



HAL
open science

Climate change impact on water resources availability – Case study of the Llobregat River basin (Spain)

Pierre-Antoine Versini, L. Pouget, S. Mcennis, E. Custodio, I. Escaler

► **To cite this version:**

Pierre-Antoine Versini, L. Pouget, S. Mcennis, E. Custodio, I. Escaler. Climate change impact on water resources availability – Case study of the Llobregat River basin (Spain). *Hydrological Sciences Journal*, 2016, <10.1080/02626667.2016.1154556>. <hal-01299399>

HAL Id: hal-01299399

<https://hal.science/hal-01299399v1>

Submitted on 11 Jan 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Climate change impact on water resources availability – Case study of the Llobregat River basin (Spain)

Versini, P.-A.^(1,2), Pouget, L.⁽³⁾, Mc Ennis, S.⁽³⁾, Custodio, E.⁽⁴⁾ and Escaler, I.⁽³⁾

¹*HM&Co-ENPC, Champs-sur-Marne, France*

²*CRAHI-UPC, Barcelona, Spain*

³*CETaqua, Water Technology Center, Spain*

⁴*UPC, Barcelona, Spain*

Corresponding author: Pierre-antoine.versini@enpc.fr

Abstract

Climate change may have significant consequences on water resources availability and management at the basin scale. This is particularly true for areas already suffering from water stress, such as the Mediterranean area. This work focuses on studying these impacts in the Llobregat basin supplying Barcelona's region. Several climate projections, adapted to the spatiotemporal resolution of the study, have been combined with a daily hydrological model to estimate future water availability.

Depending on the scenario and the time period, different assessment indicators like reliability and resilience show a future decrease in water resources (up to 40%), with drought periods more frequent. An additional uncertainty analysis has also shown a high variability of results (annual water availability ranging from 147 hm³/year to 274 hm³/year), thus making accurate projections difficult. Finally, the study illustrates how climate change could be taken into account to provide adaptative measures for the future.

Key words: climate change, water management, hydrological model, uncertainty.

1. Introduction

Human-related changes, grouped under the expression “Global Change”, could result in significant impacts on water resources quantity and quality management in the next decades. The climate component appears to be a key factor in the future water availability. The conclusions of the Intergovernmental Panel on Climate Change are unequivocal: climate change is underway and its effects within the coming half-century are at least partially inevitable (IPCC 2014). The rise of global surface temperature and changes in spatial and temporal patterns of precipitation will involve greater weather extremes, including higher intensity rainfall events or decreased streamflow conditions.

As a consequence, climate change could impact several hydrologic regimes and water resources management throughout the world (Brekke et al. 2009; Schnorbus et al., 2014; van Dam 1999). Several studies have illustrated these impacts on the hydrologic cycle at the basin scale, as was the case for the Seine River (Ducharne et al. 2010) the Rhine River (Lenderink et al. 2007) or smaller basins (Seiller and Anctil, 2014; Velasquez et al., 2013). They usually project a marked depletion of the water resources with an annual mean decrease in river discharge reaching 30% at the end of the XXI century.

It is also particularly true for Mediterranean basins where water availability is a limiting factor for socio-economic development (Cudennec et al. 2007). At the scale of the Mediterranean area, it is probable that the rise in the average annual temperature will be slightly higher than that of the world (Cabello et al. 2011; Giorgi and Lionello 2008; Hallegatte 2009): the average increase is estimated to be between about 2°C and 6.5°C by the end of the century. There will also be a reduction of the regional average precipitation, within the range of -5 % to -30 %, depending on the IPCC scenario and the season.

As a consequence, climate change could severely impact water resources (Garcia-Ruiz et al. 2011; Senatore et al. 2011) and exacerbate water availability issues that the Mediterranean basin has already faced in the past decades due to the combination of climatologic, hydrological and infrastructural factors. Here, precipitation can be subject to high inter-annual and seasonal variability and a coincidence of a dry period with the warmest temperatures during the summer months (Bonaccorso et al. 2003; Nicault et al. 2008; Piccarreta et al. 2004; Vicente-Serrano 2006). Moreover, these regions are also

subject to intense rain events characterized by several hundreds of mm in a few hours that may cause flash floods (Gaume et al. 2009; Younis et al. 2008). Consequently, water is relatively scarce throughout most of the year and mainly dependent on runoff from mountainous areas (de Jong et al. 2009; Viviroli and Weingartner 2004). The irregular distribution of precipitation in space also leads to notable disparities in water availability between different territories, aggravating the situation concerning water management. Moreover, the presence of impervious soil and the lack of aquifers increase the need for storing water when and where it is available.

In this context, the rising demand for water leads to the development of expensive and complex infrastructures, necessary to store seasonal or annual water surpluses in reservoirs later on transferred to high-demand areas, and to the intensification of the use of groundwater and its reserves (Ibanez and Prat 2003; Lopez-Moreno 2008). Unfortunately, current water management systems appear neither adapted nor flexible to changing situations. Large infrastructure developments during the 20th century were designed and constructed on the basis that water resources would be relatively stable over time, without a long-term perspective that takes into account future changes. For instance, some dams initially built to match water demand and supply appear not relevant anymore due to increasing demands coupled with a large variation in precipitation and intensification of drought periods. As a consequence, water scarcity has become particularly intense where the expansion of irrigated areas and urbanization have already caused increasing water supply difficulties.

Some supply systems are already vulnerable to climate conditions. For example, this is the case in Spain where, during the last 10 years, droughts were generalized and water reserves remained close to their warning limit of capacity on a large part of the territory (Moran-Tejeda et al. 2010). In 2007-2008, a severe drought affected Catalonia. The volume of water stored in the reservoirs, critical for the water supply of more than 3 million inhabitants, were close to the 15% threshold under which the water is considered unusable. Under pressure, local politicians organized radical solutions, like water importation by means of tankers from Tarragona (Southern Catalonia, Spain) and Marseille (Southern France), in order to contribute to the water supply of the city of Barcelona, at a cost of 22 million Euros. Since that time many plans are being considered to improve the water autonomy of Catalonia, like a sea water desalination

plant (already constructed and in standby), possible water transfer from the Rhone River or the Segre River, ...

This paper is focused on the impact of climate change on water resources availability in one of the key basins of Catalonia: the Llobregat Basin. It is a highly populated and urbanized catchment, which supplies Barcelona's region. This work particularly aims to study: (i) how could be modified water availability regarding climate change in the 21st century, (ii) how significant is the uncertainty related to these estimations, and (iii) which measures could be taken to mitigate climate change regarding these projections and the related uncertainty.

Indeed, although necessary, the integration of future changes in long-term planning is very complex. It is essentially due to the difficulty in making accurate projections of water availability. Indeed, many sources of uncertainty appear during the modelling process that can affect the conclusions and weaken the recommended standards. Essentially, they can be regrouped into two categories (Boé et al., 2009): (i) related to future climate projections (gas emission scenarios, global climate modelling and downscaling), (ii) related to hydrological modelling (structure and parameterization).

Several works have already tried to study the impact of these uncertainties on future water resources estimations. They usually adopt a "top-down" approach involving the propagation of future climate scenarios through hydrological model(s) to derive an estimate of future impact on water resources (see Wilby and Dessai, 2010; Bastola et al., 2011 for instance). Usually, an ensemble of climate simulations feed an ensemble of hydrological models of various structural complexities. The combination of climate and hydrological models generate hydro-climatic ensemble that is analysed to quantify the total related uncertainty.

Recent studies have suggested that GCM uncertainty was the largest (dominant) source of uncertainty (Kay et al., 2009; Prudhomme and Davies, 2008; Wilby et al., 2006). It is due to imperfections in the models, but essentially because anthropogenic greenhouse gas emission as well as some climate change effects and feedbacks cannot be predicted in a deterministic way (Foley, 2010). Consequently, these works recommend the use of several GCM/RCM outputs to generate impact ensembles and adopt a more cautious approach (Prudhomme et al., 2010). Uncertainty related to hydrologic models or their parameterisation often appears in second position and can also be very significant (Vaze et al., 2010; Velázquez et al., 2013). The non-stationarity in climate-runoff

relationship and dominant hydrological processes can affect the reliability of a model calibrated on historical climatological data. For these reasons, some cautions regarding the choice of model and its calibration should be taken. The use of several hydrological models is also recommended (see Gosling et al., 2011; Poulin et al., 2011 for instance).

Based on these considerations, a “top-down” approach has been established to produce hydro-climatic ensembles. Hydrological simulations using small spatial scale climatic projections have been used to estimate future water availability. It has been coupled with an uncertainty analysis focussed on both GCM and hydrologic model errors. In order to limit these errors, materials (climatic data and hydrologic model) used for this work have previously proven their relevancy in the studied area. Nevertheless, this work related to future water availability is the first one conducted on the Llobregat basin, which is a particularly strategic basin regarding Barcelona metropolitan area. It is part of the WATER CHANGE¹ project (Life+ funding) that aims to develop a methodology to evaluate global change impacts on water resources quantity and quality and define adaptation strategies based on results from different scenarios and cost-benefit analysis.

The paper is structured as follows: the next section presents the scope of study in more detail, including a description of the study area, the Llobregat basin, and the available hydrometeorological data. Section 3 describes the different climate scenarios used to estimate future climate change and how they are adapted to the Llobregat basin. Results obtained in terms of water availability are presented in Section 4. The uncertainty analysis studies the influence of each source of uncertainty on the future water resources projections in Section 5. Finally, Section 6 summarizes the main results and concludes on future improvements and applications of this study in water management.

2. Case study

2.1 The Llobregat basin

The Llobregat river headwaters are in the Pre-Pyrenees Mountains (2050 m), and it outflows into the Mediterranean Sea just at the western side of the city of Barcelona (Figure 1). It is 175 km long and covers a catchment of 5000 km². Most of the population is concentrated near the coast. The mountainous northern part and the central

¹ <http://www.life-waterchange.eu/>

part of the basin are covered by forest of Aleppo pines and farmland. The downstream part of the basin is more urbanized and the vegetation is almost limited to scrubland and crops (see (Arozarena Villar et al. 2006) for a detailed description of the land cover). In the central area the main activities are rainfed agriculture and animal raising in intensive farms while intensively irrigated areas are found in the lower part, constrained by the urban and service areas.

Three large dams (total capacity of 219 hm³) in the upper area regulate the river flow in the downstream part. The river's regime is characterized by high water levels in spring, with a maximum in May, and other more variable maxima in autumn in October-November, which often cause flash floods and floods. The minima are in January because of snow retention in the upstream part, dominated by highlands of over 2000 meters, and especially in August, due to the dry summer.

Average annual river flow is about 700 hm³/yr, representing approximately 20% of the total rainfall. Due to the strong temporal variability of the hydrological flows, only a fraction could be used to satisfy the water demand, explicitly the ones controlled by the dams and the river base flow downstream. The hydrological system includes five major aquifers. Two of them are located in the headwaters of the Llobregat River and its tributaries (Cardener and Anoia), and the other three are alluvial aquifers (Abrera, Sant Andreu de la Barc, and Lower Llobregat), connected to the downstream part of the river. Alternative water resources are also used to improve the system, among which the desalination plant situated in El Prat de Llobregat (in service since 2009) or the reclaimed water from the waste water treatment plant of El Prat de Llobregat.

The Llobregat basin is also a highly populated catchment, where water resources are used for different purposes, as drinking water production (around 350 hm³/yr for the conurbation of Barcelona of more than 3 million inhabitants), agricultural irrigation (around 32 hm³/yr), industry, and in-the-river hydro-electrical energy production, from urban distribution networks and private wells or direct river abstraction. Water from the Llobregat basin is conveyed to the whole Metropolitan Region of Barcelona via the water transport system of the Ter-Llobregat and SGAB systems, which also receive water from the Ter River in the north of the area. From a socio-economical point of view, this area and its surroundings are the most vulnerable in Mediterranean Spain.

2.2 Hydrometeorological data

The Llobregat watershed is covered by a quite dense measuring instrumentation network, except at the highest altitudes. Meteorological and hydrological daily data comprising precipitation, temperature and discharge have been compiled for the 1980-2010 time period from the Spanish Meteorological Agency (AEMET) and the Meteorological Service of Catalonia (SMC). They cover the whole basin with complete time series. Note that these punctual data have been interpolated at the watershed scale using a spline method. Moreover a historical database of daily precipitation fields is also available (from 1940 to 2010). Based on precipitation patterns computed from weather radar, this database is characterized by high spatial resolution (cells of 3km) that allows the representation of local variability (Versini 2012).

Daily discharge data have also been compiled from the Catalanian water agency (ACA). Time series from 1980 to 2010 have been analysed regarding related precipitation and cleaned by removing outliers for several sub-basins (See Figure 1).

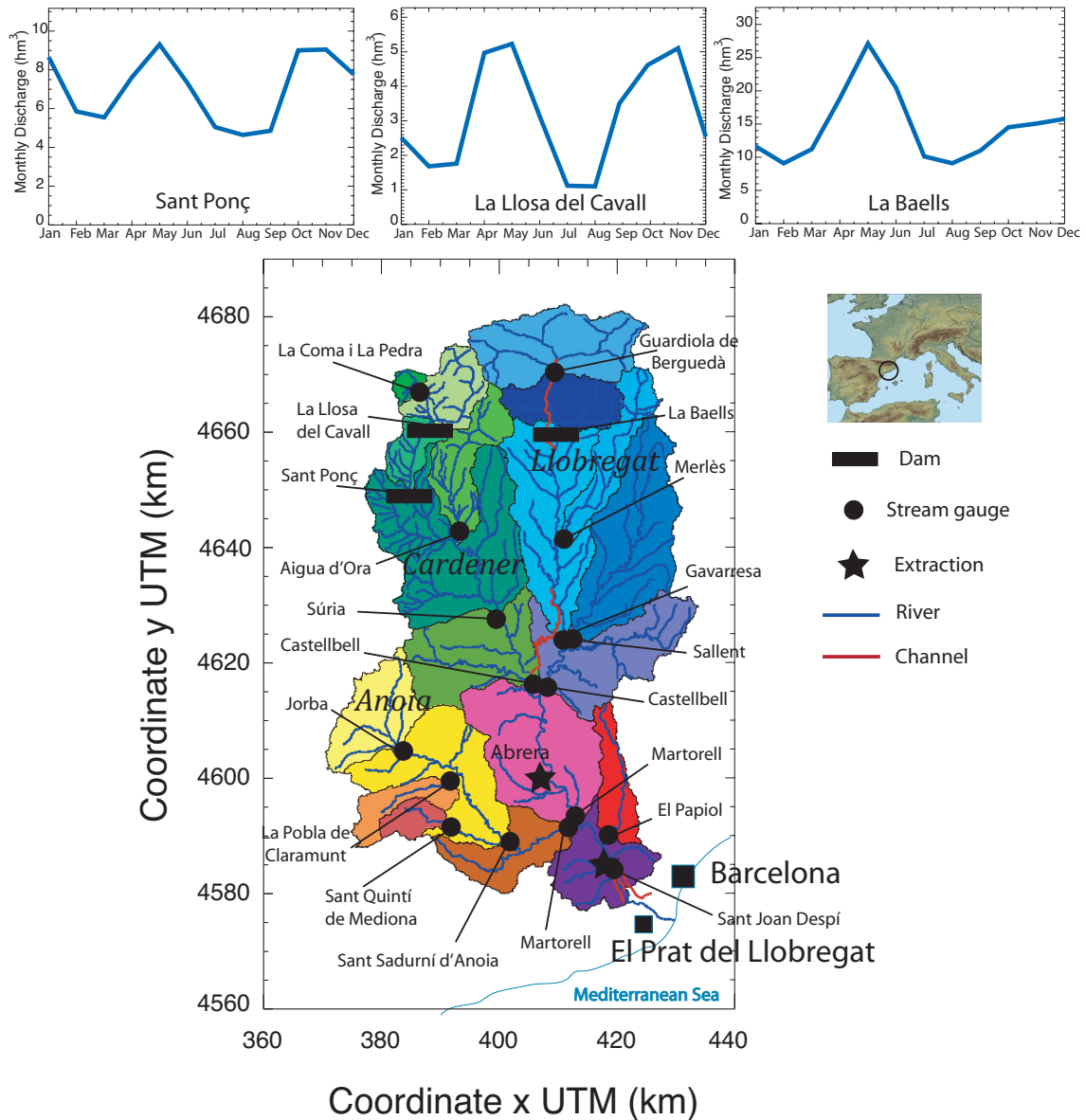


Fig. 1 The Llobregat basin disaggregated into sub-basins and the meteo-hydrographical network. Average monthly volumes (computed on the 1980-2010 time period) reaching the 3 dams are indicated.

3. Climate change scenarios

Different climate scenarios have been applied to represent as well as possible precipitation and temperature projections for the 21st century over the Llobregat basin. They combine Global Circulation Models (GCM) and a regionalization technique (called also downscaling). Downscaling is used to bridge the gap between the large-scale information provided by GCMs and the thin spatial scales required for regional and environmental impact studies. They are usually classified into two categories: statistical downscaling and dynamical downscaling (see Gutmann et al. 2012 for a detailed presentation).

Here, two different options have been used: a dynamical downscaling with the MM5 Regional Climate Model (from SMC) and a statistical technique based on analogue method (from AEMET). These scenarios have been compared and analysed on a historical time period using available observed data. They are presented in detail below.

3.1 Presentation of the different scenarios

3.1.1 SMC scenarios

SMC has provided high-resolution climate data for the 1971-2100 time period with a resolution of 15 km (Barrera-Escoda and Cunillera 2011). MM5 Regional Climate Model has been nested into ECHAM5-MPI/OM atmosphere-ocean coupled GCM outputs in order to generate the regionalised scenarios forced by two of the IPCC Special Report on Emission Scenarios (SRES) based on CO₂ emission scenarios: A2 and B1. The A2 scenario assumes a high anthropogenic impact on climate whereas in B1 the impact is assumed to be more moderate (Nakicenovic et al. 2000). In general, SMC scenarios show a reliable distribution of the simulated precipitation spatial patterns for annual and semi-annual precipitation compared to observations. They also seem to accurately reproduce the evolution of annual anomalies for Catalonia (Barrera-Escoda and Cunillera 2010b, a).

3.1.2 AEMET scenarios

These scenarios come from a statistical downscaling based on CGCM2 global circulation model output for A2 and B2 IPCC scenarios (AEMET 2008). An analogue method (called FIC analogues method, see (Brunet et al. 2007) for details) was developed and applied to rescale these climate scenarios to a higher resolution. It compares predictors at a large scale (geographic flows on the surface of 1000 and 500 hPa) and punctual observed data (predictands). The relationship linking predictors and predictands defined on the historical time period was transferred and used on the future GCM output in order to estimate future punctual values. This technique was applied for 130 rain gauges and 63 meteorological stations located in Spain.

SMC and AEMET are traditional sources of data for the Catalonian public agency in charge of water management (ACA). They provided climate projections given the opportunity to consider a larger range of possible projection (and the associated

uncertainty) in terms of SRES scenarios (A2 and B1 for SMC, and A2 and B2 for AEMET) and downscaling method (dynamical or statistical downscaling).

3.2 Results on the control period

The results obtained from the different methods on the historical time period (1970-2000) have been compared with the observed data for the Llobregat basin. Despite the fact that both methods seemed to correctly reproduce the climatological cycle over Catalonia, they fail to reproduce extreme values and seasonality at the basin scale. This is especially true for precipitation: a conspicuous underestimation of intense precipitation for AEMET data and a tendency to overestimate precipitation with a higher proportion of daily precipitation higher than 10 mm for the SMC ones. The seasonal cycle in the distribution of precipitation has been studied by representing the average monthly precipitation on the historical time period (Figure 2). It is poorly represented by all of the models. The AEMET model fails to correctly reproduce the dry period in summer and underestimates the precipitation in autumn, whereas SMC respects the seasonal variation but overestimates values from October to April and underestimates them from June to September. This could affect the hydrological results by underestimating drought period because of the overestimation of stored water in winter or precipitation in summer.

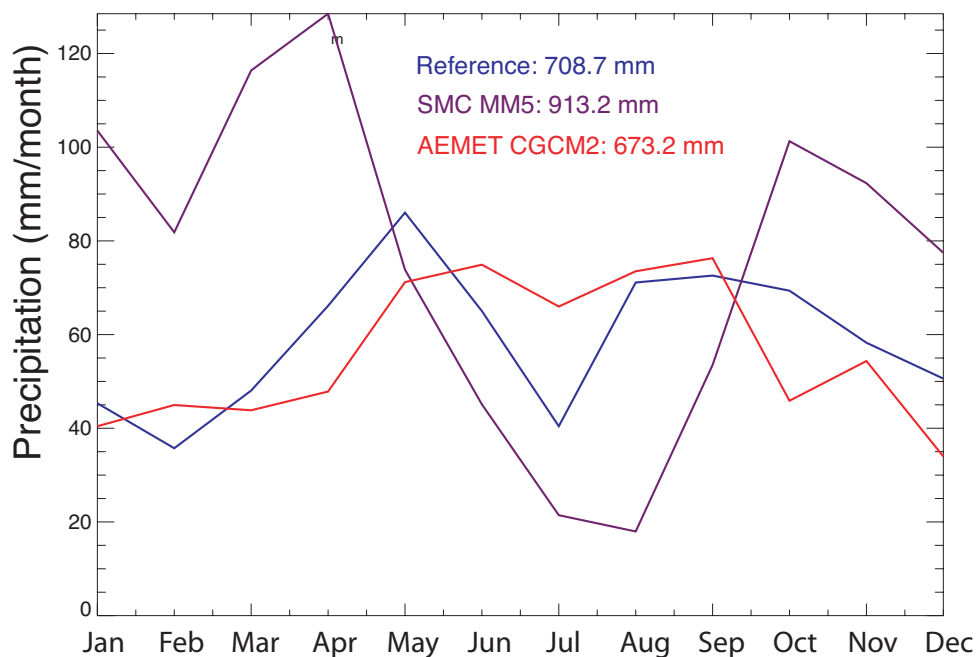


Fig. 2 Seasonal precipitation cycle (average monthly accumulation) on the control time period (1970-1990)

Concerning daily temperature, the seasonal variability (temperature increases and decreases) is correctly reproduced by all of the models, the lowest values being in winter and the highest in summer (Figure 3). Nevertheless, some bias can be noticed: AEMET data tend to shift the temperature peak in August. Moreover, a clear bias is noticed in low temperatures between observed and SMC simulated values for the hottest months. This underestimation may exceed 4°C in July and August. Conversely, temperatures are slightly overestimated in winter (between 1 and 2°C).

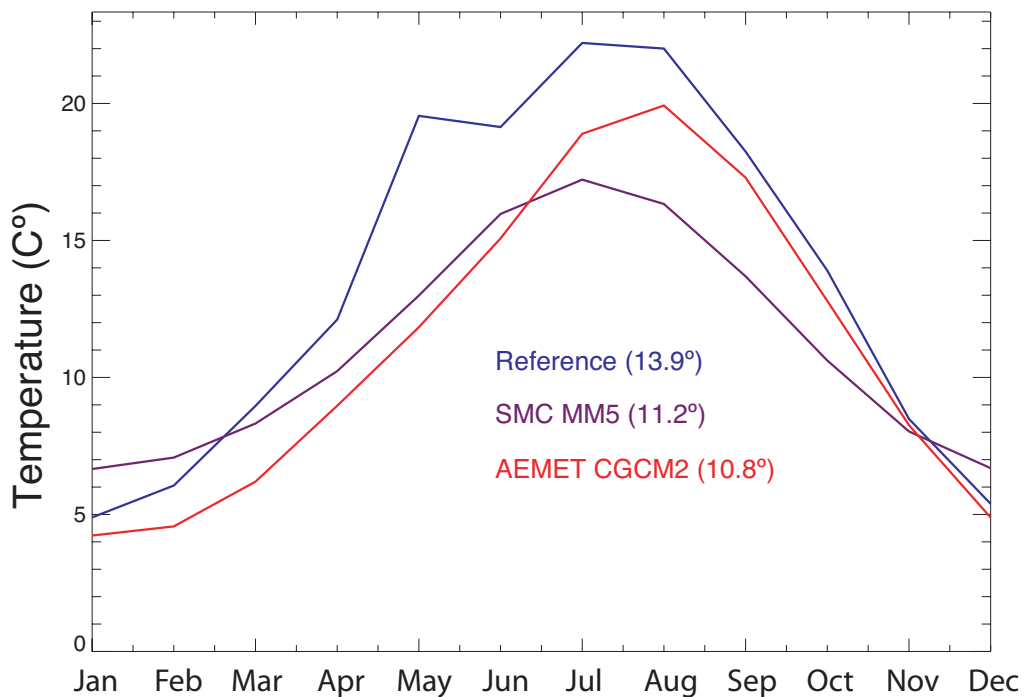


Fig. 3 Seasonal temperature cycle (average monthly value) on the historical time period

3.3 Bias correction and adaptation to the Llobregat basin

As illustrated by the results obtained from both climate projections (MM5-SMC and CGCM2-AEMET) on the past time period, GCM and RCM output may contain biases that prevent an accurate reproduction of observed meteorological conditions. Consequently, some form of bias correction is necessary, especially for precipitation (Maraun et al., 2010) but also for temperature.

Several bias correction (BC) techniques exist and are presented in Déqué (2007). They can be regrouped into two general approaches (Muerth et al. 2013): (i) extraction of deltas (differences between future and past output of the model) to be applied to on past observations, (ii) deriving scaling parameters to adjust both past and future RCM outputs to more closely fit observed climatic conditions. These technics have been

commonly used in climate change impact studies (see Ehret et al. (2012) for references) because they are attractive: ease of application, ability to allow future changes in variability and flexibility to correct the GCM outputs for the parameters of interest (Johnson and Sharma, 2012).

Nevertheless BC is far from perfect because based on numerous assumptions listed and discussed in Ehret et al. (2012). Among these assumptions, three can be put forward: (i) stationarity of the correction (correction parameters derived from past data still hold for future), (ii) suitability of GCM/RCM to predict the effect of climate change although they require severe corrections, and (iii) statistical nature of BC that can sacrifice physical coherence during the process. Ehret et al. (2012) argue that bias correction hides rather than reduces uncertainty and make some proposals to avoid or improve the use of BC.

Based on these considerations, a BC procedure has however been implemented to adapt projected data to the Llobregat basin: seasonal variability has been corrected for both models, SMC intense precipitation have been reduced, whereas temperatures have been increased.

In order to separate the impact of bias correction from downscaling procedure and to properly represent the seasonal variability, a monthly correction has been performed as in Muerth et al. (2013). A multi-linear interpolation based on past data relationships was applied to correct future scenarios. The following methodology was applied for both precipitation and temperature fields:

- On the historical time period, daily simulated and observed data (averaged over the Llobregat basin) are ordered and compared for each month of the year.
- On the future time period, the areal daily data is calculated over the Llobregat basin. It is corrected using a multi-linear interpolation based on past data relationship.
- Ten historical precipitation/temperature fields characterized by the closest resulting average value are selected.
- The distances between the original future field and the 10 selected historical fields are calculated. The field with the lowest distance is selected. It represents the best field in terms of spatial variability.

Finally, the corrected scenarios are supposed to respect the seasonal cycle but also the spatial variability provided by the initial scenario and the accuracy of actual measurements. Assuming the seasonal cycle will not be modified in the future, it will be possible to detect future evolution of climate.

3.4 Results on the future time period

Based on the previous methodology, precipitation and temperature scenarios issued by SMC and AEMET have been corrected and adapted to the Llobregat basin. Future seasonal variability of precipitation and temperature are shown in Figures 4 and 5 for 3 different time periods (2011-2040, 2041-2070, and 2071-2100). They represent areal values for the whole basin. The different 30-year periods have been defined in order to be comparable with the historical period characterized by the same duration.

Concerning precipitation, SMC scenarios appear to be more pessimistic than AEMET scenarios, and among them, the worst are those based on the A2 IPCC scenario. They forecast a general decrease in precipitation, especially during wet periods (spring and autumn). AEMET scenarios are quite similar to the reference one and reproduce very few future changes. Nevertheless, both types of scenario show the same tendency of average total precipitation to decrease during the 21st century.

The resulting seasonal variability of temperature shows a general increase of temperature during the year for every scenario. Whatever the future time period and the IPCC scenario, the average temperature will increase between 2 and 8°C during the XXI century. The worst case is represented by the A2 scenario for the 2071-2100 period, with a temperature increase reaching 8°C in summer.

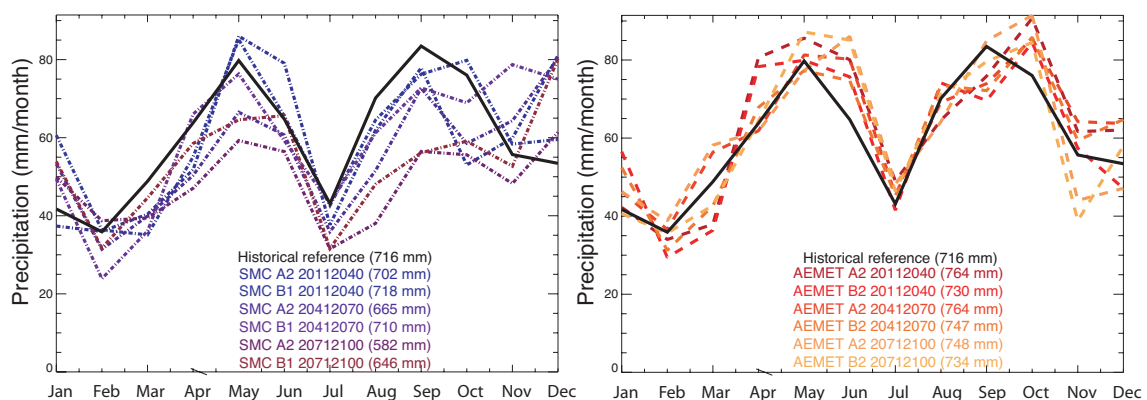


Fig. 4 Seasonal precipitation cycle (average monthly accumulation) on the future time period for downscaled precipitation scenarios (2010-2100)

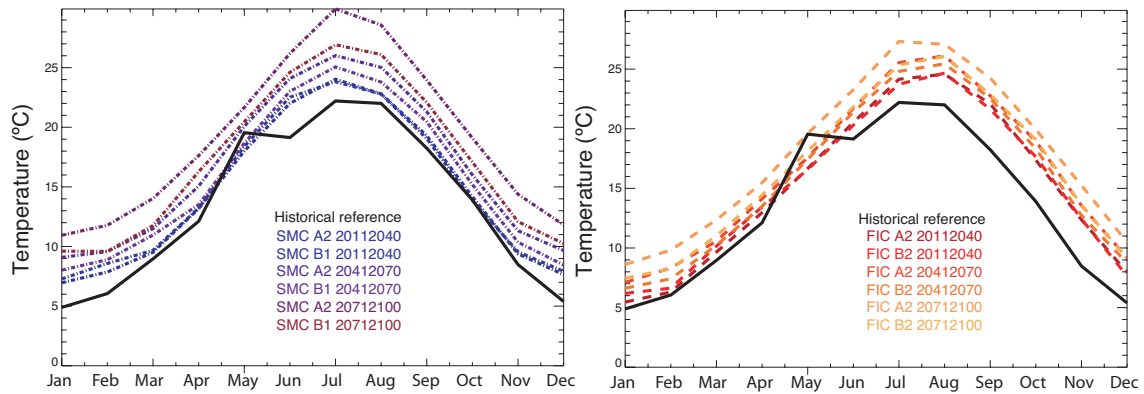


Fig. 5 Seasonal temperature cycle on the future time period for downscaled temperature scenarios (2010-2100)

4. Water availability simulation

4.1 Presentation of the hydrological model

The HBV rainfall-runoff model (Bergström 1992) has been used to simulate future water availability in the Llobregat basin. In different model versions, HBV was applied in more than 40 countries all over the world (Jin et al. 2009; Lidén and Harlin 2000; Zhang and Lindström 1997). It was also already used in several climate change studies to estimate future discharge modifications (Akhtar et al. 2008; Jiang et al. 2007; Leander and Buishand 2007; Merritt et al. 2006; Steele-Dunne et al. 2008). HBV is commonly used as a semi-distributed model by dividing the catchment into sub-watersheds and running on daily rainfall and air temperature values. At the sub-basin scale, the HBV model is divided into several routines depending on the process to be represented: direct runoff, soil moisture, upper and lower reservoir filling and emptying, and flow transfer.

4.2 Calibration on historical data

In order to simulate the water available for water supply, the HBV model has been especially applied to the upstream sub-basins, comprising those located upstream the three dams. These sub-basins (La Llosa del Cavall, Sant Ponç, Aigua d’Ora, Guardiola de Berguedà, La Baells, Merlès, Gavarresa, see Figure 1) are called contributor basins. They are those which are integrated in the management model used by the ACA to simulate natural contributions to the Llobregat system. A set of parameters has been adjusted for each of these sub-basins comparing daily simulated and observed discharges (when they were available).

Hydrological model calibration is a key issue in climate change impact studies. The underlying assumption of this approach is the stability of the dominant hydrological processes under a changed climatic condition (Vaze et al., 2010). The commonly used procedure (split-sample test with calibration and validation of a set of parameters on two historical time periods) may face to two significant issues: (i) equifinality issue (multiple sets produce acceptable simulations), and (ii) non-stationarity issue (difficulty to identify model parameters that are suitable for both current and future conditions). The first point is studied in Section 5.3. Concerning the second point, it is clear that calibration on present conditions may become invalid for the evaluation of climate change impacts (Mauser and Bach, 2009).

To study the effect of a change in climate, Klemes (1986) suggests the use of a differential split-sample test with the definition of two periods with different values of climate parameters of interest. This procedure has been applied on the available data with the definition of two sub-periods climatologically different. The first one (1980-2000, used for calibration) is considered as a wet (normal) period with an average annual amount of precipitation of 690 mm on the Llobregat basin and 4 occurrences of dry year (< 600mm). The second one (2001-2010, used for validation) is supposed to be similar to climate change with an average annual amount of precipitation of 560 mm and 6 occurrences of dry year.

The optimization criterion (f_0) used to evaluate the performance of the model combines The Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970) and absolute error between observed and simulated volumes:

$$\begin{aligned}
 f_0 &= 0.5 \times (1 - Nash) + 0.5 \times Error \\
 &= 0.5 \times \frac{\sum_{t=0}^n (Q_{obs}(t) - Q_{sim}(t))^2}{\sum_{t=0}^n (Q_{obs}(t) - \overline{Q_{obs}})^2} + 0.5 \times \frac{\sum_{t=0}^n |Q_{obs}(t) - Q_{sim}(t)|}{\sum_{t=0}^n Q_{obs}(t)} \quad (Eq. 1)
 \end{aligned}$$

Where $Q_{sim}(t)$ represents the simulated discharges, $Q_{obs}(t)$ the observed discharges, $\overline{Q_{obs}}$ the average observed discharge, and n the number of days of the calibration period for which observations are available.

Sub-basin	Nash efficiency	Error V (%)
La Llosa del Cavall	0.50/0.45	5.0/6.0
Sant Ponç	0.58/0.52	6.0/4.0
Guardiola de Berguedà	0.63/0.58	5.5/5.2
Sallent	0.60/0.62	7.1/6.4

Table 1. Results of the calibration for the gauged sub-basins. The Nash efficiency is reported as the absolute volume error (Error V) by comparing observed and simulated time series on the calibration period (left) and the validation period (right).

Details on the calibration results are given in Table 1. Absolute errors between observed and simulated volumes calculated on both periods (around 5%) illustrate the ability of the model to reproduce correctly water availability. Although Nash-Sutcliffe efficiencies are quite low (but similar to those obtained in Velasquez et al. (2013)), the simulated discharges match well with the observed ones at the daily time scale. The difference between observations and simulations is usually due to an underestimation of peak discharge. From a water management point of view this is not a major issue. It has to be noted that the drought period of 2007-2008 is particularly well reproduced. Some testes have already been conducted to verify stationarity (calibration on 1990-2010 and validation on 1980-1989) and have provided similar results.

4.3 Simulation of future water availability

Future water availability has been computed applying the HBV model for the different climate scenarios, the future precipitation and temperature considered as inputs, and the different time periods.

First, the main tendencies have been calculated for each configuration, including average precipitation, temperature, and mean, minimum and maximum annual water availability for the contributor basins (accumulated simulated volume). These results are summarized in Table 2.

	1980-2000	2011-40				2041-70				S
	Ref.	SMC		AEMET		SMC		AEMET		
		A2	B1	A2	B2	A2	B1	A2	B2	
p	770 mm/year	-1%	+3%	+9%	+2%	-5%	+2%	+8%	+5%	-19%
T	11.8 °C	+8%	+9%	+9%	+10%	+25%	+16%	+20%	+16%	+47%
WA_mean	317 hm ³ /year	-14%	-7%	+1%	-13%	-17%	-7%	-4%	-8%	-40%
WA_min	151 hm ³ /year	+22%	+12%	+47%	0%	-18%	+10%	+38%	+41%	-62%
WA_max	653 hm ³ /year	-29%	-23%	-33%	-43%	+42%	-9%	-23%	-25%	-32%
Reliability	65%	66%	63%	80%	66%	30%	56%	76%	70%	26%
Resilience	57%	50%	45%	50%	50%	14%	30%	57%	44%	22%

Table 2. Main results of future water availability simulations: mean, minimum and maximum values, annual reliability and resilience for SMC and AEMET climate scenarios for the contributor sub-basins. The reference values are computed for the historical period (1980-2000). The bold value of +42% results from an extreme event (precipitation of 150 mm over the basins)

Although total precipitation seems to be less affected by climate change in the upstream sub-basins, the results follow the general trends defined over the entire Llobregat basin and presented in the previous section. Concerning SMC scenarios, no modification in precipitation and an increase in temperature are noticed for the first part of the 21st century. In terms of water availability, A2 scenario is always worse than B1, with a very strong intensification of climate change during the last period and a decrease, from 7% up to 40% in the worst case. With few exceptions (an extreme episode occurring during the second future period for which daily rainfall reaches 150 mm over every contributor basins), minimum and especially maximum water availability tend to decrease with time. Future drought and wet periods seem to be dryer.

Conversely, AEMET scenarios show a slight increase of precipitation compared to the historical reference. Combined with a temperature (and evapotranspiration) increase, they yield a general water availability decrease (up to 13% for B2 scenario). This almost invariance of average precipitation leads to limited variations of water availability, with minimum values higher and maximum values lower, closer to the mean values.

In a second step, some indicators have been computed to assess how the Llobregat basin will be able to supply sufficient water in the future. First a “reliability” indicator has been calculated, which represents the ability of the system to perform and maintain its functions in routine circumstances (business as usual), as well as hostile or unexpected circumstances. Here, the reliability of the system is defined as the number of values in a satisfactory state divided by the total number of values in the time series (see Equation 2). In this study a value is considered as satisfactory if annual water availability is over a 250 hm³ threshold that represents a state of drought. It is considered as unsatisfactory when annual water availability fails to reach this value:

$$Annual_reliability = 1 - \frac{Number\ of\ annual\ fails}{Total\ number\ of\ years} \quad (Eq. 2)$$

Secondly, a “resilience” indicator has been calculated to evaluate the capacity of the system to respond to a perturbation or disturbance by resisting damage or recovering quickly. In this context, resilience is defined as the probability that when a system fails, the next state will be satisfactory. The resilience cannot be defined if the system never reaches an unsatisfactory state. Here, the resilience is calculated as follows:

$$Annual_resilience = \frac{Number\ of\ annual\ fails\ followed\ by\ non\ fail}{Total\ number\ of\ fails} \quad (Eq. 3)$$

Compared with previous results, those obtained for AEMET and SMC scenarios are significantly different. Because of the absence of significant variations, water availability values computed from AEMET scenarios are quite optimistic and similar to the historical situation. The reliability indicator is almost equal or higher than the past value (65%), limiting the number of droughts in the future. Similarly, the resilience indicator illustrates a moderate capacity of recovery (around 50%), equal to the past one. It illustrates that 50% of the time, an annual drought situation is followed by another one. Water availability values computed from SMC scenarios are more pessimistic. Both reliability and resilience indicators significantly decrease with time whatever the considered emission scenarios. From year 2041, reliability decreases under 60% to reach 26% in the worst case, indicating enhancement of drought and deficit periods. Resilience above 30% shows that such perturbation is usually followed by another similar situation more than two out of three times, which may cause long dry periods of several years.

To study this kind of situation, 3-year water availability accumulations (total amount of water volume computed on 3-year time windows) have been computed for each 30-year time period. The evolution of these 3-year accumulations are represented in Figure 6. On the past period, the lowest 3-year accumulations were 450 hm³. It occurred in 2007-2008 during the intense period of drought that severely affected Catalonia. In coordination with the management services, the value of 700 hm³ has been used as critical reference to evaluate the severity of future droughts.

The 3-year accumulations of water availability for the first future period (2011-2040) based on SMC scenarios are similar to the situation that occurred during the last 30 years. The occurrence of values lower than 700 hm³ is very close, with 4 or 5 years of drought over this period depending on the IPCC scenario. This phenomenon increases during the 21st century, with around 10 dry situations per 30-year period, a number reaching 20 for the most pessimistic situation (A2 scenario for the 2071-2100 time period). They show that drought periods could be more frequent but also more intense in the future.

As AEMET precipitation and temperature scenarios are less variable from one year to another, the 3-year accumulations variation is less pronounced. Whatever the time period or the IPCC scenario, the number of drought situations varies between 0 and 2 times over the 30-year periods.

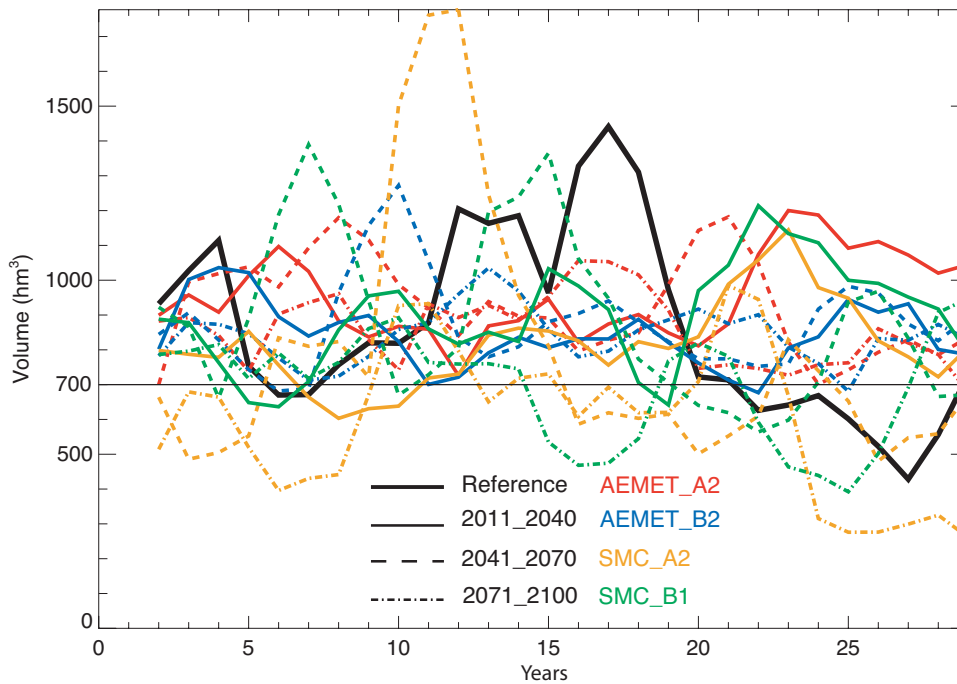


Fig. 6 3-year accumulation computed by the HBV model for SMC and AEMET climate scenarios

5. Uncertainty analysis

As presented above, computed results have a large uncertainty due to different sources of error that appear during the modelling process. These numerous sources of uncertainty can be regrouped into two categories: related to future climate calculations or to hydrological modelling.

5.1 Methodology

The methodology chosen to estimate and represent the remaining sources of uncertainty is based on an “uncertainty cascade” (Wilby and Harris 2006). During the different steps of the modelling process, some sets of equiprobable inputs are used to produce an ensemble of several water availability time series. It is assumed that each member of the ensemble represents a possible state of the considered variable by taking into account the uncertainty from corrected climate scenarios and hydrological modelling.

Here, the following sources of uncertainty have been considered:

- Related to future climate scenarios: in order to take into account gas emission scenarios, global climate modelling and downscaling uncertainties, several ensembles

have been created. As climate projections provided by AEMET and SMC calculated from gas emission scenarios (IPCC) are very different depending on the selected hypothesis and model, four different climate scenario configurations have been used: SMC-A2, SMC-B1, AEMET-A2, and AEMET-B2. The uncertainty related to bias-correction method proposed to correct and adapt climate scenarios to the Llobregat basin is also considered. 10 historical fields have now been selected (for which the distance between the projected and corrected maps are the lowest) in the historical database to represent future climate. As these selected analogues are characterized by some very similar distance with the original fields (in terms of average values not spatial distribution), it has been assumed they all have the same probability of occurrence.

- Hydrological modelling: Here only the uncertainty due to model parameterization has been considered. Different approaches have been proposed to quantify the uncertainty of model parameter estimation (Matott and Purucker 2009), including Bayesian methods (Kuczera et al. 2006) and simulation-based approaches (Vrugt et al. 2003). A common principle of these methods is the equifinality assumption, which assumes that there are multiple sets of model parameters that produce acceptable simulations of the observed discharges, based on the resulting objective function. Equifinality is the basis of the Generalized Likelihood Uncertainty Estimation method (GLUE), a Monte Carlo-based method that allows performing the uncertainty analysis of model parameter estimation (Beven and Binley 1992).

In order to implement the GLUE methodology, a total of 5000 parameter sets were produced from uniform distributions for each parameter. The Nash efficiency was selected as a likelihood function for the evaluation of the simulation results. For each sub-basin where the method was applied, the best Nash efficiency was selected. A threshold was defined for the selection of acceptable parameter sets. It represents a 5% decrease of this best Nash efficiency values. As a consequence, the parameter sets producing values lower than this threshold in the Nash efficiency values have been rejected and excluded from the acceptable parameter sets. M acceptable parameter sets are selected, between 9 and 15 depending on the basin.

Model accuracy and structure (its ability to represent past and future hydrological processes) have not been considered. This point is discussed in section 6. The

uncertainty due to hydrometeorological (precipitation, temperature, discharge) measurements used to calibrate the models has also not been taken into consideration.

The uncertainty impact on the water availability simulations and the sensibility to each source of uncertainty has been assessed by the use of a dispersion function (Disp):

$$Disp = \frac{\max(WA) - \min(WA)}{\text{mean}(WA)} \times 100 \quad (\text{Eq. 4})$$

Where $\min(WA)$, $\max(WA)$ and $\text{mean}(WA)$ are the minimum, maximum and mean values of average annual water availability for the 10 ensemble members.

5.2 Future climate scenario uncertainty

The water availability results from these 10 modified climate scenarios are summarized in Table 3. They were calculated using the calibrated parameters defined in Section 4.2. Dispersion for both AEMET and SMC scenarios are similar from one time period to another: between 10% and 20% for SMC, and close to 10% for AEMET. This difference is quite similar to the difference between historical and projected water availability whatever climate scenario is chosen (see Table 3). That means that the step of climate scenarios correction represents a significant source of uncertainty in the water availability simulation. The difference between AEMET and SMC scenarios comes from the initial variation in climate scenarios, the data provided by the SMC being the most fluctuating.

	SMC						AEMET					
	2011-40		2041-70		2071-00		2011-40		2041-70		2071-00	
Scenario	A2	B1	A2	B1	A2	B1	A2	B2	A2	B2	A2	B2
Annual water availability												
Mean (hm ³ /year)	207	224	219	231	179	190	239	211	239	224	236	220
Max (hm ³ /year)	224	246	248	251	200	208	256	222	255	239	254	231
Min (hm ³ /year)	198	211	204	221	169	177	227	202	229	210	224	209
Dispersion (%)	12	15	20	13	17	16	12	9	11	13	12	10

Table 3. Annual water availability computed for the ensemble of modified climate scenarios

5.3 Hydrological model uncertainty

Similarly, as in the previous section, the dispersion indicator is computed for the ensemble of simulated water availability computed from the acceptable parameter sets. Results are presented in Table 4. The dispersion and the uncertainty caused by the hydrological model parameterization are higher than those computed from downscaled climate scenarios: dispersion varies between 16% and 24%, depending on the scenario and the time period. Although the choice of future climate scenarios remains the highest source of uncertainty, these results confirm that hydrological model parameterization represents a significant source of uncertainty. Due to equifinality, several parameter sets lead to similar results in terms of Nash efficiency on the historical period. Applied to the future scenarios, they cause a large variability between the different simulations.

Annual water availability	SMC						AEMET					
	2011-40		2041-70		2071-00		2011-40		2041-70		2071-00	
Scenario	A2	B1	A2	B1	A2	B1	A2	B2	A2	B2	A2	B2
Mean (hm ³ /year)	201	224	231	227	183	189	248	212	248	231	252	224
Max (hm ³ /year)	228	252	256	255	200	211	268	231	268	250	274	243
Min (hm ³ /year)	179	201	210	204	167	170	226	194	228	212	234	206
Dispersion (%)	24	22	20	22	18	21	17	17	16	16	16	16

Table 4. Water availability computed for the ensemble of HBV parameters

5.4 Combination

The different ensembles defined above (climate scenario configurations, downscaled fields, model parameters) have been combined to study the propagation of uncertainty during the modelling process. An ensemble of N climate members (N=10 in this case) and M acceptable parameter sets, depending on the sub-basin, are used to simulate NxM time series of discharge.

Water availability has been computed for each member of this ensemble by combining HBV parameters and climate scenarios. The results are summarized in Table 5. Regarding the results obtained in the two previous sections, the dispersion indicator seems to be quite linear, the total dispersion being very similar to the sum of the dispersion values obtained for both climate scenarios and HBV model uncertainties. This dispersion can reach almost 40% for the SMC scenarios and around 30% for the

AEMET scenarios. These results illustrate that deterministic projections of WA are characterized by an error, which is higher than the climate change consequences calculated in Section 4.3, in most of the cases.

	SMC						AEMET					
	2011-40		2041-70		2071-00		2011-40		2041-70		2071-00	
Average annual water availability												
Scenario	A2	B1	A2	B1	A2	B1	A2	B2	A2	B2	A2	B2
Mean (hm ³ /year)	190	209	208	213	169	177	234	206	236	220	236	215
Max (hm ³ /year)	228	252	256	254	200	212	268	237	274	253	274	249
Min (hm ³ /year)	160	177	177	180	147	149	203	177	206	187	208	191
Dispersion (%)	36	35	38	34	31	35	28	30	29	30	28	27

Table 5. Water availability computed for the ensemble of climate scenarios and HBV parameters

6. Discussion and Conclusion

The impact of climate change on water availability has been studied for the Llobregat basin, for which water resources management is a critical issue since it has been frequently affected by severe droughts in the recent past. Climate change, which may amplify the current situation in the future, has to be taken into account to assess and improve water management in the future.

For this reason, future water availability has been estimated by combining climate change scenarios and hydrological modelling. These different climate projections were provided by the Spanish and Catalanian weather agencies (AEMET and SMC) and based on greenhouse gas emission hypotheses. They both combine a Global Circulation Model, a downscaling technique and a bias-correction method to obtain climate data adapted to the spatiotemporal scale of the study.

Resulting water availability simulations have been assessed by indicators like reliability and resilience. These projections appear to vary significantly from a scenario to another and from a time period to another. Those based on AEMET climate scenarios lead to a future situation similar to the current one, characterized by a moderately worse context (decrease of annual volume about 10%) but with less pronounced extremes. Whereas

water availability projections based on SMC scenarios are more pessimistic (decrease of annual volume reaching 40%) with an increase in deficit situations that could be more frequent and more intense (every 2 years during the 21st century for the worst case).

In parallel, an uncertainty analysis has been conducted regarding the different internal sources of error appearing during the whole modelling process. Climate scenarios bias-correction method and hydrological model uncertainties have been represented using an ensemble method. Both sources of uncertainty appear to have significant impact on water availability projections. The combination of both sources of uncertainty gives an error reaching approximately more or less 15%.

Considering the whole set of simulations, by combining the different climate scenarios provided by AEMET and SMC with the ensembles resulting from the uncertainty analysis, the water availability projections vary significantly (an average annual WA ranging from 147 hm³/year to 274 hm³/year). The large spectrum of results, from maintaining the current situation to a very pessimistic scenario (WA divided by two) in which the drought periods are doubled, complicates their use in terms of decision-making.

These interesting results provided by the chosen modelling approach are based on a number of implicit hypotheses and limitations that can be discussed:

- Climate model downscaled scenarios: As suggested by Ehret et al. (2012), some cautions have been taken to apply bias correction in the production of downscaled climate scenarios adapted to impact studies. First, a multi-model ensembles approach has been adopted as two different GCM were used, including a nested approach (use of RCM to downscale GCM output, MM5). Second, a monthly correction has been performed to separate the impact of bias correction from downscaling procedure. Although bias correction does not represent the main source of uncertainty (regarding climate and hydrological models), some critical points still remain. For instance, the assumption that the correction parameters computed in the past period will remain the same for future periods is a questionable hypothesis and should be studied. The use of bias correction could be avoided if some significant improvements are done in climate projection from global and regional models but also from downscaling methods. Especially, the explicit representation of convection (representing a

key-factor for precipitation in Mediterranean area) should enhance model accuracy.

- Hydrological model structure: Only uncertainty related to model parameterization has been considered in this study. It has been assumed that HBV model was able to reproduce correctly present and future water processes in the Llobregat basin. As it is surely true regarding past data (HBV has already been used in other studies on this site, see Velasco et al. (2013), and satisfactory results were obtained regarding water availability on past data), it could be not the case in the future. As mentioned by Teng et al. (2012), hydrological modelling results could be different if potential changes in climate-runoff relationship and land-vegetation-atmosphere feedback are modelled. As land-use of the Llobregat contributor basins are supposed to not be modified in the future (Cabello et al., 2011), a conceptual model has been chosen. As Jones et al. (2006) suggested, conceptual and physical based models have a different role in impact assessment: the former can be used to rapidly assess the impact of different climate scenarios, while the latter can assess the joint impacts of land-use and climate change. Nevertheless, the approach to simulate evapotranspiration (here Thornthwaite formulation) could be very influenced by a changing climate and are thus an additional source of uncertainty. Consequently, as low flow simulation is an important challenge and need to be improved, it could be interesting to use an additional hydrological model in the future to compare its results to those obtained with HBV.

Despite the limitations mentioned above, this study supports some interesting elements for water resources management. The awareness of the possible impacts of future changes could help stakeholders in defining more resilient measures, and therefore avoiding or minimizing adverse social, economical and environmental consequences. If these projections are not accurate enough to justify investment in important infrastructures, at least it could help anticipate and implement small permanent measures (modernisation of irrigation, construction of water reclamation plants, rules for sustainable construction ...) or punctual measures (awareness-raising campaigns, reduction of non-essential uses, improved interlinking of water networks, potential water markets, point operation of desalination plants,...).

When developing sustainable and long term planning of water resources in the same direction as the Water Framework Directive specifies, it becomes necessary to consider Global Change. This was one of the objectives of the WATER CHANGE project by combining climate change with other human-related changes. It aimed to develop a methodology and a tool to assess the Global Change impacts on water resources, thus helping river basin agencies and water companies in their long-term planning and in the definition of adaptation measures. The outcomes of this project enable the definition and testing of different sets of adaptation measures for the basin that can be further evaluated through cost-benefit analysis. The integration of the results contributes to an efficient decision-making on how to adapt to Global Change impacts.

References

- AEMET, 2008. Generación de escenarios regionalizados de cambio climático para España. Agencia Española de Meteorología, Madrid
- Akhtar, M., Ahmad, N., and Booij, M.J, 2008. The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios. *Journal of Hydrology* 355 (1-4), 148-163
- Arozarena Villar, A., Del Bosque González, I., Porcuna Fernández Monasterio, A., and Villa Alcázar, G., 2006. Mapa de Ocupación del Suelo en España. Corine Land Cover-Proyecto I&CLC2000. Centro Nacional de Información Geográfica,
- Barrera-Escoda, A., and Cunillera, J., 2010a. Generació d'escenaris climàtics per a Catalunya durant el segle XXI a partir d'una tècnica dinàmica de regionalització climàtica. In: 2nd Congrés de Meteorologia i Climatologia de la Mediterrània Occidental, Valencia, Spain, 2010a. p 4
- Barrera-Escoda, A., and Cunillera, J., 2010b. Study of the precipitation evolution in Catalonia using a mesoscale model (1971–2000). *Advances in Geosciences* 26:1-6. doi:10.5194/adgeo-26-1-2010
- Barrera-Escoda, A., and Cunillera, J., 2011. Climate change projections for Catalonia (NE Iberian Peninsula). Part I: Regional climate modeling. *Tethys Journal of Mediterranean Meteorology and Climatology*, 8, 75-87. doi:10.3369/tethys.2011.8.08
- Bastola, S., Murphy, C., and Sweeney, J., 2011. The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. *Adv Water Resour*, 34(5), 562–576.
- Bergström, S., 1992. The HBV model—its structure and applications. SMHI Reports RH no. 4. Norrköping, Sweden
- Beven, K., and Binley, A., 1992. The future of distributed models: Model calibration and uncertainty prediction. *Hydrological Processes*, 6 (3), 279-298
- Boé, J., Terray, L., Martin, E., and Habets, F., 2009. Projected changes in components of the hydrological cycle in French river basins during the 21st century, *Water Resour. Res.*, 45: 1–15,
- Bonaccorso, B., Bordi, I., Cancelliere, A., Rossi, G., and Sutera, A., 2003. Spatial variability of drought: An analysis of the SPI in Sicily. *Water Resources Management*, 17 (4), 273-296
- Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., and White KD, 2009. Climate Change and Water Resources Management – a Federal Perspective.
- Brunet, M., Casado, M.J., de Castro, M., Galan, P., Lopez, J.A., Martin, J.M., Pastor, A., Petisco, E., Ramos, P., Ribalaygua, J., Rodriguez, E., Sanz, I., and Torres, L., 2007. Generación de escenarios regionalizados de cambio climático para España AAgencia Estatal de Meteorología (AEMET) Madrid, Spain
- Cabello, A., Velasco, M., Barredo, J.I., Hurkmans, R.T.W.L., Barrera-Escoda, A., Sempere-Torres, D., and Velasco, D., 2011. Assessment of future scenarios of climate and land-use changes in the IMPRINTS test-bed areas. *Environmental Science and Policy* 14 (7):884-897. doi:10.1016/j.envsci.2011.03.003
- Cudennec, C., Leduc, C., and Koutsoyiannis, D., 2007. Dryland hydrology in Mediterranean regions - a review. *Hydrological Sciences Journal*, 52 (6), 1077-1087. doi:10.1623/hysj.52.6.1077

- de Jong, C., Lawler, D., and Essery, R., 2009. Mountain hydroclimatology and snow seasonality - Perspectives on climate impacts, snow seasonality and hydrological change in mountain environments. *Hydrological Processes*, 23 (7), 955-961
- Déqué, M., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values, *Global Planet. Change*, 57, 16–26
- Ducharne, A., Habets, F., Pagé, C., Sauquet, E., Viennot, P., Déqué, M., Gascoïn, S., Hachour, A., Martin, E., Oudin, L., Terray, L., and Thiéry, D., 2010. Climate change impacts on water resources and hydrological extremes in northern France. Paper presented at the XVIII International Conference on Water Resources, Barcelona (Spain)
- Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J., 2012. Should we apply bias correction to global and regional climate model data? *Hydrology and Earth System Sciences*, 16(9), 3391-3404
- Foley, A.M., 2010. Uncertainty in regional climate modelling: A review, *Prog. Phys. Geogr.*, 34, 647–670
- Garcia-Ruiz, J.M., Lopez-Moreno, J.I., Vicente-Serrano, S.M., Lasanta-Martinez, T., and Begueria, S., 2011. Mediterranean water resources in a global change scenario. *Earth-Science Reviews*, 105 (3-4), 121-139
- Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaskovicova, L., Bloschl, G., Borga, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D., and Viglione, A., 2009. A compilation of data on European flash floods. *Journal of Hydrology*, 367 (1-2), 70-78
- Giorgi, F., and Lionello, P., 2008. Climate change projections for the Mediterranean region. *Global and Planetary Change*, 63 (2-3), 90-104
- Gosling, S.N., Taylor, R.G., Arnell, N.W., and Todd, M.C., 2011. A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models, *Hydrol. Earth Syst. Sci.*, 15, 279-294
- Gutmann, E.D., Rasmussen, R.M., Liu, C., Ikeda, K., Gochis, D.J., Clark, M.P., Dudhia, J., and Thompson, G., 2012. A Comparison of Statistical and Dynamical Downscaling of Winter Precipitation over Complex Terrain. *Journal of Climate* 25 (1), 262-281. doi:10.1175/2011jcli4109.1
- Hallegatte, S.P., 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change*, 19 (2), 240-247
- Ibanez, C., and Prat, N., 2003. The environmental impact of the Spanish National Hydrological Plan on the lower Ebro River and Delta. *International Journal of Water Resources Development*, 19 (3), 485-500
- IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp
- Jiang, T., Chen, Y.D., Xu, C.-Y., Chen, X., Chen, X., and Singh, V.P., 2007. Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China. *Journal of Hydrology* 336 (3-4):316-333
- Jin, X., Xu, C.-Y., Zhang, Q., and Chen, Y.D., 2009. Regionalization study of a conceptual hydrological model in Dongjiang basin, south China. *Quaternary International*, 208(1-2),129-137

- Johnson, F. and Sharma, A., 2012. A nesting model for bias correction of variability at multiple time scales in general circulation model precipitation simulations, *Water Resour. Res.*, 48
- Jones, R.N., Chiew, F.H.S., Boughton, W.C., and Zhang, L., 2006. Estimating the sensitivity of mean annual runoff to climate change using selected hydrological models, *Adv. Water Resour.*, 29, 1419–142.
- Kay, A.L., Davies, H.N., Bell, V.A., and Jones, R.G., 2009. Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Climatic Change*, 92(1-2), 41–63.
- Kuczera, G., Kavetski, D., Franks, S., and Thyer, M., 2006. Towards a Bayesian total error analysis of conceptual rainfall-runoff models: Characterising model error using storm-dependent parameters. *Journal of Hydrology*, 331 (1-2), 161-177
- Leander, R., and Buishand, T.A., 2007. Resampling of regional climate model output for the simulation of extreme river flows. *Journal of Hydrology*, 332 (3-4), 487-496
- Lenderink, G., Buishand, A., and van Deursen, W., 2007. Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrology and Earth System Sciences*, 11 (3), 1145-1159. doi:10.5194/hess-11-1145-2007
- Lidén, R., Harlin, J., 2000. Analysis of conceptual rainfall-runoff modelling performance in different climates. *Journal of Hydrology*, 238 (3-4), 231-247
- Lopez-Moreno, J.I., 2008. Estimacion de perdidas de agua por evaporacion en embalses del Pirineo. Cuadernos de Investigacion Geografica, 34, 61-81
- Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., Brienen, S., Rust, H.W., Sauter, T., Themeßl, M., Venema, V.K.C., Chun, K.P., Goodess, C.M., Jones, R.G., Onof, C., Vrac, M., and Thiele-Eich, I., 2010. Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user, *Rev. Geophys.*, 48
- Matott, L.S., and Purucker, B.J., 2009. Evaluating uncertainty in integrated environmental models: A review of concepts and tools. *Water Resources Research*, 45:W06421
- Merritt, W.S., Alila, Y., Barton, M., Taylor, B., Cohen, S., and Neilsen, D., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. *Journal of Hydrology*, 326 (1-4), 79-108
- Moran-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J.M., 2010. Hydrological response of Mediterranean headwaters to climate oscillations and land-cover changes: The mountains of Duero River basin (Central Spain). *Global and Planetary Change*, 72, 39-49
- Muerth, M.J., Gauvin St-Denis, B., Ricard, S., Velázquez, J.A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwig, R., and Turcotte, R., 2013. On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences*, 17, 1189-1204.
- Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H.M., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S.J., Swart, R., van Rooijen, S., Victor, N., and Dadi, Z., 2000. Special Report on Emissions Scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. PBD. Cambridge University Press,

- Nash, J.E., and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I - A discussion of principles. *Journal of Hydrology*, 10 (3), 282-290
- Nicault, A., Alleaume, S., Brewer, S., Carrer, M., Nola, P., and Guiot, J., 2008. Mediterranean drought fluctuation during the last 500 years based on tree-ring data. *Climate Dynamics*, 31(2-3), 227-245
- Piccarreta, M., Capolongo, D., and Boenzi, F., 2004. Trend analysis of precipitation and drought in Basilicata from 1923 to 2000 within a southern Italy context. *International Journal of Climatology*, 24 (7), 907-922
- Poulin, A., Brissette, F., Leconte, R., Arsenault, R., and Maloet, J.-S., 2011 Uncertainty of hydrological modelling in climate change impact studies in a Canadian, snow-dominated river basin, *J. Hydrol.*, 409, 626–636
- Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L., and Reynard, N.S., 2010 Scenario neutral approach to climate change impact studies: application to flood risk. *J Hydrol*, 390, 198–209.
- Prudhomme, C., and Davies, H.N., 2008. Assessing uncertainties in climate change impact analyses on river flow regimes in the UK. Part 2: future climate. *Climatic Change*, 93, 197-222
- Schnorbus, M., Werner, A. and Bennett, K., 2014. Impacts of climate change in three hydrologic regimes in British Columbia, Canada. *Hydrological Processes*, 28(3), 1170–1189
- Seiller, G., and Anctil, F., 2014. Climate change impacts on the hydrologic regime of a Canadian river: comparing uncertainties arising from climate natural variability and lumped hydrological model structures. *Hydrology and Earth System Sciences*, 18, 2033-2047
- Senatore, A., Mendicino, G., Smiatek, G., and Kunstmann, H., 2011. Regional climate change projections and hydrological impact analysis for a Mediterranean basin in Southern Italy. *Journal of Hydrology*, 399 (1-2), 70-92
- Steele-Dunne, S., Lynch, P., McGrath, R., Semmler, T., Wang, S., Hanafin, J., and Nolan, P., 2008. The impacts of climate change on hydrology in Ireland. *Journal of Hydrology*, 356(1-2), 28-45
- Teng, J., Vaze, J., Chiew, F.H.S., Wang, B., and Perraud, J.-M., 2012. Estimating the Relative Uncertainties Sourced from GCMs and Hydrological Models in Modeling Climate Change Impact on Runoff, *J. Hydrometeorol.*, 13(1), 122–139
- van Dam, J.C, 1999. Impacts of climate change and climate variability on hydrological regimes. Delft (Netherlands)
- Vaze, J., Post, D.A., Chiew, F.H.S., Perraud, J.M., Viney, N., and Teng, J., 2010. Climate nonstationarity – Validity of calibrated rainfall-runoff models for use in climate change studies, *J. Hydrol.*, 394, 447–457
- Velasco, M., Versini, P.-A., Cabello, A., and Barrera-Escoda, A., 2013. Assessment of flash floods taking into account climate change scenarios in the Llobregat River basin, *Nat. Hazards Earth Syst. Sci.*, 13, 3145-3156
- Velázquez, J.-A., Schmid, J., Ricard, S., Muerth, M.J., Gauvin St-Denis, B., Minville, M., Chaumont, D., Caya, D., Ludwig, R. and Turcotte, R., 2013. An ensemble approach to assess hydrological models' contribution to uncertainties in the analysis of climate change impact on water resources, *Hydrol. Earth Syst. Sci.*, 17(2), 565–578
- Versini, P-A, 2015. Reconstruction of historical precipitation based on radar fields: application on Catalonia region (Spain). *Journal of Hydrology*, submitted
- Vicente-Serrano, S.M., 2006. Spatial and temporal analysis of droughts in the Iberian Peninsula (1910-2000). *Hydrological Sciences Journal*, 51(1), 83-97

- Viviroli, D., and Weingartner, R., 2004. The hydrological significance of mountains: From regional to global scale. *Hydrology and Earth System Sciences* 8 (6), 1016-1029
- Vrugt, J.A., Gupta, H.V., Bouten, W., and Sorooshian, S., 2003. A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters. *Water Resources Research*, 39(8), 1201. doi:10.1029/2002wr001642
- Wilby, R.L., and Dessai, S., 2010. Robust adaptation to climate change. *Weather*, 65(7), 180–185.
- Wilby, R.L., and Harris, I., 2006. A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resources Research*, 42(2):W02419. doi:10.1029/2005wr004065
- Wilby, R.L., Whitehead, P.G., Wade, A.J., Butterfield, D., Davis, R.J., and Watts, G., 2006. Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *J Hydrol* 330, 204–220
- Younis, J., Anquetin, S., and Thielen, J., 2008. The benefit of high-resolution operational weather forecasts for flash-flood warning. *Hydrology and Earth System Sciences*, 5, 345-377
- Zhang, X., and Lindström, G., 1997. Development of an automatic calibration scheme for the HBV hydrological model. *Hydrological Processes*, 11 (12), 1671-1682