Hydrol. Earth Syst. Sci. Discuss., 11, 12315–12364, 2014
www.hydrol-earth-syst-sci-discuss.net/11/12315/2014/
doi:10.5194/hessd-11-12315-2014

Hydrology and Earth System Sciences
Open Access
Discussions

Simulating long-term past changes in the balance between water demand and availability and assessing their main drivers at the river basin management scale

J. Fabre[1], D. Ruelland[1], A. Dezetter[2], and B. Grouillet[1]

[1]CNRS, HydroSciences Laboratory, Place Eugene Bataillon, 34095 Montpellier, France
[2]IRD, HydroSciences Laboratory, Place Eugene Bataillon, 34095 Montpellier, France

Received: 30 September 2014 – Accepted: 15 October 2014 – Published: 4 November 2014

Correspondence to: J. Fabre (jfabre@um2.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The aim of this study was to assess the balance between water demand and availability and its spatial and temporal variability from 1971 to 2009 in the Herault (2500 km^2, France) and the Ebro (85 000 km^2, Spain) catchments. Natural streamflow was evaluated using a conceptual hydrological model. The regulation of river flow was accounted for through a widely applicable demand-driven reservoir management model applied to the largest dam in the Herault basin and to 11 major dams in the Ebro basin. Urban water demand was estimated from population and monthly unit water consumption data. Water demand for irrigation was computed from irrigated area, crop and soil data, and climatic forcing. Finally, a series of indicators comparing water supply and water demand at strategic resource and demand nodes were computed at a 10 day time step. Variations in water stress in each catchment over the past 40 years were successfully modeled, taking into account climatic and anthropogenic pressures and changes in water management strategies over time. Observed changes in discharge were explained by separating human and hydro-climatic pressures on water resources: respectively 20 and 3 % of the decrease in the Ebro and the Herault discharges were linked to human-induced changes. Although key areas of the Herault basin were shown to be highly sensitive to hydro-climatic variability, the balance between water uses and availability in the Ebro basin appears to be more critical, owing to high agricultural pressure on water resources. The proposed modeling framework is currently being used to assess water stress under climatic and socio-economic prospective scenarios. Further research will investigate the effectiveness of adaptation policies aimed at maintaining the balance between water use and availability.

HESSD
11, 12315–12364, 2014

1 Introduction

In recent decades, climatic and anthropogenic pressures on water resources have increased in many regions of the world. According to projections of climate and socio-economic changes, mid-latitude areas could experience increased water stress in the course of the 21st century (Arnell, 2004; Heinrichs et al., 2012). Strategies are thus required to adapt water management to these changes (Hallegatte, 2009; Iglesias et al., 2011). Such strategies need to be based on a thorough understanding of the vulnerability of hydrosystems to climatic and anthropogenic pressures and of the drivers of water stress. Vulnerability to climate change is not only a consequence of a system's exposure to climatic variability but may be due to a combination of bio-physical impacts of climate change and of anthropogenic pressures (Farley et al., 2011; March et al., 2012). The vulnerability of a hydrosystem to climatic and anthropogenic pressures also depends on its ability to face particular dry events, or to adapt to new climatic conditions. Understanding vulnerability to water stress thus requires the quantitative assessment of water demand and availability, and an appropriate representation of the interactions between water uses and resource.

Many authors have underlined the need for integrative assessments of the impacts of climate change on the balance between water use and availability (e.g. Füssel and Klein, 2006; Ludwig et al., 2011), and an increasing number of studies that tackle this issue can be found in the literature. Studies at a global scale (e.g. Arnell et al., 2011) combined human and hydro-climatic data from global databases, and identified the regions that may be most vulnerable to water stress. However to assist decision making at the river basin management scale, a closer look must be taken at each hydrosystem to account for the spatial and temporal dynamics of water resources and uses (types of demand, storage capacity, etc.). In this mindset, recent studies were conducted at the river basin scale (e.g. Beck and Bernauer, 2011; Pulido-Velasquez et al., 2011; Varela-Ortega et al., 2011; Griffin et al., 2013; Koutroulis et al., 2013), which compared water

HESSD
11, 12315–12364, 2014

resources and demand with the aim of optimizing water allocation in given conditions, or for the design of water management plans, which require a long-term perspective.

Studies that compare water demand and resource at the basin scale incorporate anthropogenic and climatic drivers of water uses and availability to varying extents. The studies generally focus on simulating water resources under varying climatic conditions. In some cases, water uses are tackled by looking at population changes, without quantifying the water volumes associated (e.g. Griffin et al., 2013). In other cases, water demand is not simulated but is simply used as input data (e.g. Pulido-Velasquez et al., 2011; López-Moreno et al., 2013). This limits the possibility of analyzing the drivers of the variability of demand in space and over time, even when sufficient data on withdrawals are available to account for this variability. If water demand is simulated and its variations over time accounted for, the impact of climate variability on the demand for irrigation water is not always taken into account (Koutroulis et al., 2013). Consequently, studies that do not fully incorporate human and climatic drivers of water resources and demand may not fully grasp the ways in which hydrosystems could be affected by future anthropogenic and climate changes.

In some studies, water demand is simulated based on human and climatic factors, and is compared to water availability based on climatic variability and changing water management rules (e.g. Purkey et al., 2008; Varela-Ortega et al., 2011; Collet et al., 2013; Milano et al., 2013a). However they often take a static view of the water balance accounting for average conditions over several years (Milano et al., 2013a) or characteristic situations such as particularly dry or wet years (Varela-Ortega et al., 2011). In the context of anthropogenic and climatic changes, Krol et al. (2006) underlined the importance of correctly representing the long-term dynamics of resources and demand, which, to our knowledge, few studies have achieved so far (one exception being the study by Collet et al., 2013). Indeed before looking into complex future changes, we need to be able to represent long-term dynamics, which implies accounting for the non-stationarity of human and physical factors.

HESSD
11, 12315–12364, 2014

Finally, water stress can be considered from different perspectives. It can be represented by indicators that account for the hydrosystem's water balance and its weaknesses. Sullivan and Meigh (2005) defined indicators as a statistical concept, providing an indirect way of measuring a given quantity or state, and allowing for comparison over time. Indicators should be dynamic and account for changes in the system under study. Some studies of the water balance (Varela-Ortega et al., 2011; Collet et al., 2013; Milano et al., 2013a) included indicators that represent the ability of supply to meet demand (e.g. water demand satisfaction rates or supply reliability) and the level of anthropogenic pressure on water resources (e.g. withdrawal to resource ratios). These indicators usually account for the average water balance in a hydrosystem (Pulido-Velasquez et al., 2011). In some cases, statistical components are included in the analysis, such as the return period of undesirable events (Asefa et al., 2014).

Our review of the literature thus underlined the need to better understand the drivers and dynamics of the balance between water uses and water availability in river basins, i.e. at the scale of water management plans. To be able to adapt effectively to future climatic and anthropogenic changes, we need to understand the interactions between the different past drivers of water stress. The need to better understand and represent interactions between resources and demand and to account for the non-stationarity of human and physical factors is particularly pronounced in the Mediterranean region, which faces significant climatic variability, rapid population growth and economic development, and increasing competition between different water uses (Milano et al., 2012, 2013b). Increasing anthropogenic pressures in river basins in particular in the Mediterranean region call for both the quantification of water demand, and the understanding of its spatial and temporal dynamics.

The first step in designing appropriate adaptation strategies for water resources management is developing a modeling approach able to represent past variations in the satisfaction of water demand, in space and over time. The aim of this study was thus to: (i) combine human and hydro-climatic data in an integrative modeling framework to represent water stress and its spatial and temporal dynamics over a past multi-decadal period; and (ii) use this framework and appropriate indicators to assess the sustainability of current water uses. The integrative modeling framework was developed and applied in two contrasted Mediterranean catchments facing increasing climatic and anthropogenic pressures: the Herault basin (France) and the Ebro basin (Spain). This constrains its conception to different scales, stakes, and water management issues.

2 Study areas

2.1 Geographical context

The Herault and the Ebro catchments differ in their geographical characteristics. The Herault basin is located in the South of France (Fig. 1a). It is boarded in the north by the Cevennes Mountains. The Herault River flows 150 km from Mont Aigoual (1565 m a.s.l.) in the north, through a crystalline system of low permeability in the upstream part, a karstic system in the middle part, and an alluvial valley in the downstream part, into the Mediterranean Sea at the town of Agde.

The Ebro basin is located in the north of Spain (Fig. 1b). The Ebro River flows 910 km in a north-west to south-east direction from Fontibre in the Cantabrian Range (1027 m a.s.l.), to the town of Tortosa where it forms a large delta. It is boarded by the Pyrenean range (up to 3383 m a.s.l.) in the north, the Iberian range in the south and the Catalan coastal range in the east.

2.2 Hydro-climatic and anthropic datasets

Daily climate forcings for the Herault basin for the period 1969 to 2009 were extracted from the SAFRAN meteorological analysis system, an 8 km × 8 km grid provided by Meteo France and validated over France by Quintana-Segui et al. (2008). Potential evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith formula (Allen et al., 1998). For the Ebro basin, daily temperature and precipitation measurements from 264 and 818 stations, respectively, were interpolated on an 8 km × 8 km grid

HESSD
11, 12315–12364, 2014

using the inverse distance weighted method. Lapse rates of −6.65 °C/1000 m and of −4.16 °C/1000 m (for the Pyrenean and Cantabrian range, respectively) were applied over 1000 m a.s.l. for the interpolation of T_{MAX} and T_{MIN}, based on observations from the 1969–2009 period (Dezetter et al., 2014). Since additional data (e.g. wind and humidity) were too scarce to calculate Penman–Monteith ET_0 at the scale of the Ebro basin from 1969 to 2009, the Hargreaves empirical equation (Hargreaves and Samani, 1985) was used to calculate ET_0 at a daily time step. The calibration proposed by Martínez-Cob and Tejero-Juste (2004) in the Ebro valley was applied to the whole basin using Eq. (1). Windy areas in the Ebro basin were defined by García-Vera and Martínez-Cob (2004) based on available wind speed data.

$$ET_0 = \varpi \times (0.0864 Ra/\lambda) \times (T_{MAX} - T_{MIN})^{0.5} \times (T_{MOY} + 17.8) \quad (1)$$

where $\varpi = 0.0023$ in windy areas, $\varpi = 0.0020$ otherwise, Ra = extraterrestrial radiation, λ = latent heat flux.

Daily streamflow data were extracted from the French Ministry of Ecology and Sustainable Development's database *Banque Hydro* (MEDDE, 2010) for the Herault basin and from the *Anuario de aforos* of the Center of studies and experiments on hydraulic systems (CEDEX, 2012) for the Ebro basin. Reservoir levels and outflow data were provided by the General Council of the Herault administrative region (*Conseil Général de l'Hérault*) and by the CEDEX for the Ebro basin.

Population data were provided by national statistics institutes (INSEE for France and INE for Spain), and information concerning irrigated areas and crop dynamics was extracted from agricultural censuses. The efficiency of water supply networks and of irrigation systems and data relating to unit water consumption and industrial activities were provided by the local water management agencies.

2.3 Hydro-climatic context

The Herault catchment is characterized by a Mediterranean climate influenced by the Cevennes mountain range, with mild wet winters and hot dry summers. The temperature ranged from 6 °C in the winter to 20 °C in the summer in the period 1971–2009; average annual precipitation was 1100 mm over the basin. Temperature and precipitation follow a north-to-south gradient in the basin, ranging from under 8 to over 15 °C and from over 1600 mm yr^{-1} to less than 600 mm yr^{-1}. Climatic conditions in the Ebro basin are complex due to the contrasting influences of the Atlantic Ocean and the Mediterranean Sea, and of the three mountain ranges, particularly the Pyrenees (Vicente-Serrano and López-Moreno, 2006). Annual temperatures and precipitation range from 8 °C in the Pyrenees to 17 °C in the lower Ebro valley and from over 2000 mm yr^{-1} in the western Pyrenees to less than 400 mm yr^{-1} in the semi-arid central Ebro valley.

Mean annual streamflow was 36 m^3 s^{-1} (14 L s^{-1} km^{-2}) in the Herault and 330 m^3 s^{-1} (4 L s^{-1} km^{-2}) in the Ebro between 1971 and 2009. The Herault and its tributaries have a typical Mediterranean regime, while hydrological regimes in the Ebro basin vary from nival to Mediterranean (Bejarano et al., 2010). Upstream sub-basins in the Pyrenean and the Cantabrian ranges produced an average of 47 % of the Ebro basin's natural runoff between 1971 and 2009.

Statistical breaks in temperature and discharge series were detected in both basins during the period 1971–2009. Temperature increased by 1 °C in both basins between 1971–1980 and 1981–2009 and discharge decreased by 41 and 37 % between 1971–1979 and 1980–2009 at the outlet of the Herault and the Ebro basins respectively. Although no statistically significant break was detected, annual precipitation decreased by 10 % in the Herault basin and by 12 % in the Ebro basin between 1971–1980 and 1981–2009. Seasonal disparities were identified in the precipitation trends: while winter precipitation decreased by approximately 40 % in both basins, fall precipitation increased by 21 % over the Herault basin and by 12 % over the Ebro basin. Similar hydro-climatic trends were detected by Collet et al. (2014) and Milano et al. (2013a) in the 1969–2010 and 1957–2002 periods in the Herault and Ebro basins respectively.

2.4 Water management issues

Figure 1 shows the main human pressures on water resources in the Herault and the Ebro basins. In the Herault basin, the north differs significantly from the south, with low population density and sparse agricultural areas in the north and a high concentration of urban and agricultural areas in the south (Fig. 1a). Water demands for agricultural and urban use inside and outside the basin amount to comparable volumes: 40 $hm^3 yr^{-1}$ for each type of demand on average between 1980 and 2010 (Collet et al., 2014). The Florensac transfer, which supplies urban water to coastal tourist areas located east of the basin, accounted for one third of total water demand in 2009. Water demand is highly seasonal, with irrigation demand (mostly for vineyards) and urban demand (increased because of tourism) both peaking between July and August. Of the five dams in the basin with a total storage capacity of 8 % of total runoff (Fabre et al., 2014), the main one is the Salagou dam (102 hm^3), built in 1968 to supply water for irrigation but currently mostly used for recreational activities on the lake. The main irrigated areas are concentrated around the Gignac canal which distributes water from the Herault River to an irrigable perimeter of nearly 3000 ha. According to local stakeholders, until the 1990s the efficiency of the system barely reached 7 % but increased to 20 % in the late 2000s.

The Ebro is a complex and highly regulated hydrosystem with a total of 234 dams, amounting to a storage capacity of 60 % of total runoff (Fabre et al., 2014). Irrigated areas are concentrated in the semi-arid Ebro valley and are supplied by a network of canals linked to large storage dams, most of which collect water from the Pyrenean Mountains. In 2007, agricultural water demand represented 92 % of the total water demand (CHE, 2011). The Ebro basin concentrates 60 % of Spain's fruit production and 30 % of the country's meat production (CHE, 2011) and supports a dynamic agro-industrial sector. Together with water demand for the open-air cooling systems of two nuclear power plants, industrial water demand is similar to urban water demand. The population density is mostly very low (under 10 inhab. km^{-2}) except in a few urbanized

HESSD
11, 12315–12364, 2014

areas such as Zaragoza or Pamplona. Transfers to cities outside the basin have been underway since 1927, the two main ones being urban and industrial water transfers to Bilbao and Tarragona, underway since 1975 and 1989 respectively.

In both basins, hot dry conditions in summer lead to a peak in irrigation water demand associated with low flows. In the recent past, increasing demand in both basins (since the 1970s, the population has doubled in the Herault and irrigated areas have increased by 30 % in the Ebro) and drier conditions have led to water shortage events. The EU Water Framework Directive (European Commission, 2000), which applies to both basins, has also been the source of new constraints through the regulation of environmental flows. The Herault basin has been part of the territory managed by the *Agence de l'eau Rhône-Méditerranée Corse* since 1964. The local agency *Syndicat Mixte du Bassin du Fleuve Herault* (SMBFH) was created in the 2000s to ensure more local management and in response to issues that are specific to the Herault basin, including water availability (Syndicat Mixte du Bassin du Fleuve Hérault, 2005). Studies on the balance between water demand and availability have been launched by local authorities in the Herault basin and should lead to a water sharing plan for the basin. In contrast, the *Confederación Hidrográfica del Ebro* (CHE) was created in 1926 with the aim of increasing irrigation and water resource management in the Ebro basin, with a strong emphasis on the development of the resource and of infrastructure. Nowadays the CHE has a wider role in water management, in line with Integrated water resources management and water sustainability as a whole. Since the 2000s, efforts have been underway to improve network efficiency and increase demand management (Lecina and Playán, 2002; Lecina et al., 2010; Salvador et al., 2011).

HESSD
11, 12315–12364, 2014

3 Method

3.1 Modeling approach used to assess the balance between water demand and availability

3.1.1 Integrative modeling framework

A modeling framework including hydro-climatic and anthropogenic dynamics and accounting for interactions between water resources and water demand at a 10 day time step was designed (Fig. 2). Climatic variability affects natural streamflow and water demand (mainly through crop irrigation requirements), while human activities affect water demand through population growth, industrial activity, irrigated areas and the types of irrigated crops, and the efficiency of the water supply networks. Anthropogenic drivers of water balance include local water management rules through the operation of dams and canals. These climatic and anthropogenic drivers were distributed and combined dynamically in space and over time to evaluate changes in water stress. Interactions between water resources and water demand are accounted for by the following assumptions:

- Water withdrawn from a river is no longer available for users directly downstream. Water withdrawals can also be limited in the case of insufficient water availability.
- Winter flows and spring snowmelt are kept in reservoirs for summer withdrawal, as a result, the regime of rivers downstream from storage dams may be strongly modified.
- Although water that is withdrawn is not available directly downstream, only a part of it is actually used. The remaining water returns to the river through leaks in urban and irrigation supply networks or as treated effluent.

This integrative modeling framework was applied to a long period of time to capture past variability in climatic and human conditions. The 1971–2009 period was chosen based on data availability in both basins. This nearly 40 year period includes a wetter and colder decade (1971–1980) and a warmer and drier period (1981–2009).

3.1.2 Mapping resource and demand management

The spatial distribution of resource vs. demand was mapped to correctly determine the vulnerability of each study area to water shortage. Each basin was divided into sub-basins accounting for the water supply to one or more demand nodes. The Herault basin was divided into six sections and the Ebro into 20 (Fig. 3).

Our map of the Herault hydrosystem (Fig. 3a) was adapted from the work of Collet et al. (2013). It accounted for the north–south climatic gradient separating the milder wetter upstream catchments from the warmer drier area downstream. Sub-basins were chosen based on their similar water withdrawal characteristics. Water withdrawals are low and mostly agricultural in the Laroque sub-basin, and minimal in the upstream sub-basins of Saint-Laurent and Lodeve. The Gignac canal and its irrigated areas were isolated in the Herault at Gignac sub-basin. The southern section of the Herault basin (Agde) has both the highest urban withdrawals in the basin and a high level of agricultural water demand.

Mapping the Ebro hydrosystem was mainly guided by the existence of extensive irrigation systems managed in association with large storage dams (see black triangles in Fig. 3b). The Pyrenean catchments influenced by a snowmelt hydrological regime were selected to accurately represent the corresponding freshwater availability. The two main right bank systems were also selected, as they are representative of the heterogeneous climatic and hydrological conditions in the Ebro basin.

HESSD
11, 12315–12364, 2014

3.2 Simulation of water demand and natural streamflow

3.2.1 Modeling spatial and temporal dynamics of water demand

Three types of water demand were considered: (i) urban water demand (UWD), including domestic water consumption, irrigation of parks and gardens and commercial water use, (ii) agricultural water demand (AWD) for crop irrigation and (iii) other water demands (OWD) linked to industrial processes and to power plant cooling systems. Details concerning the reconstitution of past water demand at the sub-basin scale in the Herault and the Ebro basins between 1971 and 2009 can be found in Grouillet et al. (2014a).

The UWD of each municipality was assessed by multiplying a unit water allocation per capita by the population at each 10 day time step. Unit water allocations were calculated from available urban water withdrawal and population data. These allocations depend on the water consumption rates of urban activities and on the efficiency of water supply networks, and were assumed to remain stable throughout the study period. Annual changes in population over time were taken into account, as were the seasonal dynamics due to summer tourism in the Herault basin.

Figure 4 shows how AWD was calculated based on irrigated crops, climate conditions and irrigated areas. In the case of irrigated vineyards in the Herault basin, the maximum irrigation requirement (MIR) was considered to be the water required to meet 80 % of ET_C, in accordance with deficit irrigation techniques. Data on readily available water (RAW) were extracted from the European soil database (European Commission, 2004) and averaged over each sub-basin.

OWD was not taken into account in the Herault basin because of the very limited industrial activity. In the Ebro basin, industrial demand was estimated by the CHE (2011) at the municipality scale by assigning a water allocation per employee and per year for each industrial sector. Energy demand in the Ebro basin was assumed to correspond to the volume of water evaporated by the open-air cooling system of the nuclear reactors. Hydropower demand was not accounted for in this study as data for our two

HESSD
11, 12315–12364, 2014

study areas were scarce. Moreover, in the Herault basin, the production of hydropower is limited to a few minor turbines, while in the Ebro basin dams are operated primarily to satisfy agricultural water demand.

3.2.2 Modeling spatial and temporal dynamics in natural streamflow

Streamflow was assessed in the six sub-basins in the Herault and the 20 sub-basins in the Ebro using GR4j (Perrin et al., 2003), a conceptual hydrological model run at a daily time step and calibrated/validated at a 10 day time step. The hydrological model relies on precipitation (P) and potential evapotranspiration (ET_0) inputs. A snow module based on mean basin temperature (Ruelland et al., 2011, 2014) was added and activated in the sub-basins with a snowmelt regime. GR4j relies on four parameters, and the snow module adds three more parameters. The model was calibrated using the drier period (1981–2009) and validated using the wetter period (1971–1980). Automatic calibration of the model was performed using a three-step algorithm as described in Dezetter et al. (2014). It combined a random draw of parameter sets and the succession of Rosenbrock and simplex algorithms aimed at minimizing a multi-objective function aggregating three goodness-of-fit criteria: the Nash–Sutcliffe efficiency index (NSE), the cumulative volume error (VE) and the mean annual volume error (VEM).

To assess natural runoff in each sub-basin, the model was calibrated only against runoff data that were considered to be natural, i.e. not influenced by withdrawals or dam management. Withdrawals upstream from the Pyrenean dams were considered to be negligible, so all streamflow data were used for calibration. Data on discharge entering the dams were not directly available, so streamflow upstream from the dams was computed based on a balance between inflow, variations in the reservoir level, outflow, and evaporation. Runoff produced in each downstream sub-basin was computed at a 10 day time step by subtracting the ingoing streamflow from the streamflow at the outlet of the section. The time steps for which simulated agricultural demand was greater than 0.1 hm^3 10 $days^{-1}$ were not used to calculate the goodness-of-fit criteria; hence the model was only calibrated on natural flow periods. In the downstream

HESSD
11, 12315–12364, 2014

sections, the 10 day periods left out of the calibration data correspond to low-flow periods. The model was thus calibrated on the time steps when most of the runoff is produced, which allowed for the natural flow to be simulated for the whole year.

3.3 Comparing resource and demand considering water management rules

3.3.1 Modeling dam management

Accurate simulation of dam management is indispensable for simulations of water availability in highly equipped hydrosystems. A demand-driven dam management model adapted from Fujihara et al. (2008) was set up and applied to the Salagou dam in the Herault basin and to 11 major dams or groups of dams in the Ebro basin (see Fig. 3). The model outputs were the reservoir level, the volume of water released into associated canals (if applicable) and into the river downstream from the dam during each 10 day time step.

As shown in Fig. 5, the water balance of the reservoir was computed at each 10 day time step, accounting for water demand, entering streamflow, evaporation, and the initial reservoir level. Infiltration was not included in the water balance. The rules guiding water release from the dams were the following: (i) after adding entering flows (V_{in} + PR) and subtracting evaporation from the initial reservoir level, water can be released to satisfy demand and/or minimum flow requirements as long as the reservoir level remains above the defined minimum level R_{min}; (ii) if the reservoir exceeds the target level R_{tar}, additional water is released from the dam into the river downstream.

Target levels were defined for each 10 day time step according to maximum observed levels over a given time period in which the dam operation rules were similar. Changes in dam operation rules were accounted for throughout the study period. Data on the level of the reservoir of the Ebro dam, for example, revealed a change in reservoir level variability after 1980, so target levels were defined separately for the periods 1971–1980 and 1981–2009. Minimum levels were provided by the stakeholders in charge of dam operations or, if the information was not available, were defined as

HESSD
11, 12315–12364, 2014

the minimum level observed over the period. The minimum levels of the reservoirs are kept as a safety reserve for a particular water use (e.g. 100 hm^3 in the Ebro dam are kept as a safety water supply to the city of Zaragoza) or to maintain reservoir levels above the elevation of a canal inlet (e.g. elevation of the Aragon and Catalunya canal inlet in the Barasona dam). In the case of the Salagou dam in the Herault basin, a minimum elevation of 137 m a.s.l. is maintained to enable tourist recreational activities on the lake.

Because dam management rules are driven by the demand associated with each individual dam, simulation of dam operations is highly dependent on accurate mapping of resources and demand. In the Herault basin, the Salagou dam supplies water for irrigation in a clearly delimited area (Fig. 1a). In the Ebro basin, dam operation rules are much more complex. Some dams, including the Ebro dam, release water into the river for downstream users. The volume of water released depends on the associated demand and on the runoff produced between the dam and the users (i.e. between the outlet of the Ebro dam and the beginning of the Lodosa canal in the Ebro system). In other cases, a canal is directly associated with the dam (e.g. the Bardenas Canal and Yesa dam) and transports water from the reservoir to irrigated areas that may be located in a different sub-basin. The volume of water released from the dam depends on the demand associated with the canal and on the capacity of the canal. This type of dam also releases water directly downstream for downstream users or to respect minimum flows. Lastly, the management of two or more dams may be coordinated to supply a particular irrigation system. The dams may be located on the same river and regulate flows from upstream to downstream (e.g. the Escales, Canelles and Santa Ana dams on the Noguera Ribagorzana River or the Mediano and Grado dams on the Cinca River, see Fig. 3b), in which case they were simulated as if they were one large dam located downstream. Two dams located in different sub-basins can also be operated jointly: if the total volume of water demand cannot be met by the first dam, it can be supplemented by the second. This is the case of two systems in the Ebro basin modeled in this study: the Alto Aragon and the Aragon and Catalunya areas (Fig. 3b).

HESSD
11, 12315–12364, 2014

3.3.2 Modeling the influence of water uses on streamflow

At each time step, water withdrawals were considered according to water availability, simulated water demand, and the following order of priority: (i) UWD (ii) OWD and (iii) AWD. Return flows were also taken into account. For UWD, two types of return flows were considered. First, 80 % of the volume actually used by domestic and more generally urban activities was considered to return to the outlet of the basin section as treated effluent. The volume actually used was calculated by subtracting losses from the supply network from withdrawals. Second, part of the losses from supply networks was considered to return to the sub-basin outlet. For OWD, 80 % of withdrawn water was considered to return to the sub-basin outlet. For AWD, only part of the losses from supply networks was considered to return to the sub-basin outlet. All the water actually available for crop irrigation was considered to be used by the crops.

The return flow rate from losses from urban and irrigation supply networks was estimated for the Herault basin as a whole and for each sub-basin of the Ebro basin, to account for soil and geological heterogeneities. Return flow rates were tested from 0 to 1 with a step of 0.1 and were calibrated by optimizing goodness-of-fit criteria including NSE on low flows (July to September included), noted NSE_{LF}, on modified streamflow.

3.3.3 Sustainability indicators for the balance between water demand and availability

First, anthropogenic and climatic pressures on water resources were assessed. Anthropogenic impacts on streamflow were estimated as the difference between natural and modified streamflow. Comparing changes in natural and modified streamflow between 1971 and 2009 enabled climate variability to be distinguished from anthropogenic pressure as causes of the decrease in streamflow observed in both basins.

Second, water shortage for each type of demand was characterized by the magnitude, frequency, and average length of withdrawal restrictions (see Fig. 2). These indicators were calculated for each demand node considering hydro-climatic and anthropic variability between 1971 and 2009. The percentage of water demand that could not be satisfied due to lack of available water was computed for each type of demand at a 10 day time step. According to the local stakeholders, withdrawal restrictions were acceptable as long as they did not exceed 50 % of AWD and 95 % of UWD. Water shortage analysis concentrated mostly on agricultural demand since it was last in order of priority (Fig. 2). The frequency of withdrawal restrictions (F) was expressed by the number of years out of five including at least one time-step in which restrictions on irrigation water withdrawals exceeded 50 % of the demand. The average length of a water shortage event (L) was represented by the average number of consecutive time steps with restrictions exceeding 50 % of the demand. Years with urban water shortage exceeding 5 % of the demand during at least one 10 day time step were also identified. These years corresponded to critical situations in which withdrawal restrictions also applied to non-agricultural users, pointing to potential water sharing conflicts. When restrictions are applied to urban water withdrawals, this means that all three types of demands faced water shortage, including industrial demands.

Last, the current sensitivity of the two basins to water stress was evaluated: water demand corresponding to the size of the population, the irrigated areas, and industrial activity in the year 2009 was compared to water availability under the prevailing hydro-climatic conditions in the period 1971–2009, using the dam management rules applied in 2009. Five indicators (see Fig. 2) were computed at each demand node to characterize the balance between water uses and water availability in the Herault and Ebro basins with their current human activities and water management practices, and faced with the climate variability of the recent past. Maximum shortage (MS) was defined as the maximum simulated annual irrigation water shortage rate and reliability (Rel) and was considered to be the rate of occurrence of satisfactory years, i.e. years with an annual irrigation water shortage below 50 %. Shortage frequency (F) indicates the frequency of occurrence of irrigation water withdrawal restrictions of more than 50 % at a 10 day time step, and resilience (Res), computed as the inverse of the average length of withdrawal restrictions, shows how quickly withdrawal restrictions were lifted.

HESSD
11, 12315–12364, 2014

The definitions of maximum shortage (also called vulnerability in the literature), reliability, and resilience were based on the metrics used in previous studies to evaluate the performance of water supply systems (Hashimoto et al., 1982; Fowler et al., 2003). The final indicator was the frequency of occurrence of water sharing conflicts (C). For each indicator, an acceptable range of values was defined according to management criteria in the local basin agencies.

4 Results

4.1 Efficiency of the modeling chain

4.1.1 Simulation of natural streamflow

Calibration and validation results for the simulation of natural streamflow are presented in Table 1. Overall, the results were satisfactory except for some downstream sections in which discharge was significantly modified and few calibration data were consequently available on natural streamflow. However, the sections of the basin where the model performed poorly generally produced only a small proportion of total streamflow in the basin.

In the Herault basin NSE values were over 0.80 and volume error (VE) was negligible over the calibration period in all sub-basins except in the Agde section. In the upstream Saint-Laurent and Laroque sub-basins, NSE values over the validation period were slightly lower (0.79 and 0.72 respectively), and volume errors tended to increase slightly. The lack of observed streamflow in the 1970s in the Gignac, Salagou and Agde sub-basins prevented validation of natural streamflow simulations in these areas.

The simulated natural streamflow in the Ebro basin was in good agreement with observed streamflow in the sub-basins that contribute most to discharge at the outlet, i.e. the Pyrenean sub-basins and the Ebro upstream from the Aragon River. In these sub-basins, NSE values were above 0.60 and VEM and absolute values of VE were below

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

18 % over the calibration and validation periods, with the exception of the Noguera Ribagorzana sub-basin upstream from the Santa-Ana dam. In this sub-basin the three dams (Escales, Canelles and Santa Ana) were simulated as one large dam in the location of Santa Ana (see Sect. 3.3.1), thus multiplying possible errors in the calculation of the natural discharge at Santa Ana. In sub-basins 13, 14 and 20 (Ebro at Zaragoza, Mequinenza and Tortosa, see Table 1) results indicated poor calibration and validation scores. This can be explained by the high level of influence of withdrawals on streamflow, leaving very few data for calibration. The simulation of natural streamflow in these three sub-basins of the semi-arid Ebro valley was thus considered to be unreliable. However, the climatic and topographic conditions of the middle and lower Ebro valley suggest that the contribution of these areas to total discharge is minor. For the rest of the study, the contributions of sub-basins 13, 14 and 20 to the natural discharge of the Ebro River were set to zero.

4.1.2 Simulation of dam management

Figure 6 shows the results of the simulation of reservoir levels in the two basins. Seasonal dam operations were well represented for the majority of dams. Moreover, simulated interannual variability of the reservoir levels were in rather good agreement with observations (e.g. the Ebro, Sotonera or Tranquera dams). Despite the complexity of their management, the variations in the levels of the Yesa and Grado dams were well reproduced, with NSE values of 0.68 and 0.56 respectively, and mean volume errors of 9 and 8 %.

Simulations of the Salagou reservoir level led to scores of 0.53 for NSE and 1 % for VEM for the period 1990–2009 (reservoir level data were only available after 1990). As can be seen in Fig. 6a, the reservoir level started showing significant seasonal variability in 1986, which is consistent with the start-up of a hydropower turbine and with increasing water demand for irrigation since the 1990s.

HESSD
11, 12315–12364, 2014

The functioning of some dams was less well simulated. In the case of the Caspe and Talarn dams, this may be due to the existence of other dams that regulate streamflow further upstream, which were not included in this study.

4.1.3 Simulation of influenced streamflow

Influenced streamflow was accurately reproduced in the Herault basin (see Fig. 7) with NSE values above 0.80 in all sub-basins for the calibration and validation periods, except at the outlet of the Salagou dam where the outflow was only moderately well simulated by the dam management model. However, the contribution of the Salagou dam to streamflow at the outlet of the basin is very low.

Results at the outlet of the Ebro basin (see Fig. 8) showed that the influenced discharge in this complex hydrosystem was rather well simulated: aggregated simulations at the basin outlet led to NSE and volume error scores of 0.68 and −6 % respectively over the calibration period, and of 0.64 and −12 % over the validation period. The influenced discharge in the Cinca and Segre systems was moderately well reproduced, with NSE values under 0.50 and negative low flow NSE (NSE_{LF}, see Sect. 3.3.2) values over the calibration period. Streamflow in the downstream Segre sub-basin is influenced by outflows from the Santa Ana, Talarn and Oliana dams, which have complex management rules.

4.2 Changes in water demand and natural streamflow

4.2.1 Variations in water demand under anthropogenic and climate variability

Total water demand in the Herault basin doubled between the 1970s (24 $hm^3\,yr^{-1}$) and the 2000s (53 $hm^3\,yr^{-1}$) mainly because of a significant increase in UWD (from 18 $hm^3\,yr^{-1}$ in the 1970s to 36 $hm^3\,yr^{-1}$ in the 2000s over the whole basin), particularly for the Florensac transfer in the Agde section where UWD more than doubled (see Fig. 10a). Total AWD also increased (from 6 to 17 $hm^3\,yr^{-1}$ between the 1970s and the

2000s) with heterogeneities throughout the basin. In the Laroque upstream section, AWD decreased in the 1990s due to agricultural decline and stabilized in the 2000s. In the other upstream sections, AWD increased significantly, but volumes nevertheless remained very low. The simulated increase in AWD over the Herault basin is mostly due to warmer and drier conditions from the 1980s on, which led to a threefold increase in AWD in the Gignac area (see Fig. 10a).

Total demand in the Ebro basin increased from 4330 $hm^3 yr^{-1}$ in the 1970s to 6820 $hm^3 yr^{-1}$ in the 2000s, with the biggest increase in the 1970s and the 1980s. As shown in Fig. 10b, the main increase in AWD occurred in the Bardenas and Alto Aragon irrigation systems (from 400 to 880 $hm^3 yr^{-1}$ and from 320 to 950 $hm^3 yr^{-1}$ respectively between the 1970s and the 2000s). In the Ebro valley, Aragon and Catalunya and Segre systems, AWD increased between the 1970s and the 1980s and stabilized (or even slightly decreased in the case of the Ebro valley) after 1990. On the right bank, AWD remained almost unchanged, with a peak in the 1980s in the Jalon sub-basin.

4.2.2 Impact of climatic variability on natural streamflow

Simulated changes in natural streamflow at the outlet of the Herault and the Ebro basins are illustrated in Fig. 9. The 1980s and 2000s appear to have been particularly dry compared to the 1970s, mainly in the Herault basin. In both basins, natural streamflow at the outlet decreased by approximately 20 % between 1971–1980 and 1981–2009.

At Agde, the natural streamflow of the Herault river decreased in the winter, spring and summer (−52, −30 and −39 % respectively) and increased in the fall (+36 %). Similar changes were observed in upstream sections, with a bigger decrease in the streamflow in summer at Laroque and Gignac (47 and 48 % respectively). The natural streamflow of the Ebro river at Tortosa also decreased in the winter, spring and summer (−21, −29 and −23 % respectively) and increased slightly (+8 %) in the fall. In sub-basins influenced by a snowmelt regime such as the Cinca and Segre catchments, peak flow occurred one month earlier (May instead of June) after 1980, and streamflow decreased in spring and summer.

The changes in natural streamflow simulated in both basins are in agreement with the climatic trends described in Sect. 2.3., i.e. a decrease in winter precipitation and an increase in fall precipitation between 1971–1980 and 1981–2009, associated with a 1 °C annual increase in temperature.

4.2.3 Relative impact of anthropogenic and climatic conditions on streamflow

Figure 9 also shows that the impact of water use on streamflow increased between 1971 and 2009 in both basins. Average total water consumption increased from 11 to 27 $hm^3 yr^{-1}$ (1 to 2 % of mean annual natural runoff) in the Herault basin and from 3830 to 5000 $hm^3 yr^{-1}$ (24 to 38 % of mean annual natural runoff) in the Ebro basin between 1971–1980 and 2000–2009. Annual water consumption in both basins stabilized in the 2000s.

Although the annual anthropogenic impact was higher in the Ebro basin, it reached 30 % of natural flow at a 10 day time step in the Herault basin between mid-July and mid-August in the 2000s (Fig. 9a). While the impact of human activities was highest in the summer in the Herault basin, the storage role of reservoirs in the Ebro basin is clearly visible in Fig. 9b: in the Ebro basin, anthropogenic impacts decreased in July and August, when withdrawals were made from reservoirs.

Simulating natural and modified streamflow made it possible to distinguish anthropogenic impacts on streamflow variability from the impact of climate variability. In the upstream sections of the Herault basin (Saint-Laurent, Laroque and Lodeve, data not shown) the decrease in streamflow between 1971–1980 and 1981–2009 was due to a natural decrease in streamflow only, whereas in Gignac and Agde, respectively 1 and 3 % of the decrease in annual influenced streamflow was linked to anthropogenic impacts. Eighty percent of the decrease in discharge at the outlet of the Ebro basin between 1971–1980 and 1981–2009 was due to a natural decrease in streamflow and 20 % to an increase in anthropogenic pressure, and these proportions varied

HESSD
11, 12315–12364, 2014

throughout the basin (75–25 % in the Aragon sub-basin, 50–50 % in the Cinca sub-basin and a decrease in anthropogenic pressure in the Segre sub-basin).

4.3 Sustainability of the hydrosystems: balance between water demand and availability

4.3.1 Simulation of water shortages over the period 1971–2009

Figure 10 shows the water shortages simulated between 1971 and 2009 in the Herault and the Ebro basins. Results are only presented for the Gignac and Agde sections of the Herault basin, as they concentrate most of the water uses and our simulations did not identify any water shortage in the other sub-basins. Figure 9a shows the frequent occurrence of agricultural water shortages in the Gignac area from the 1980s on. Although AWD decreased slightly in the 2000s due to recent efforts to improve the efficiency of the Gignac canal, water shortage events continued to occur three years out of five. In Agde, increasing UWD and AWD continued to be satisfied until the 2000s. Restrictions on agricultural and urban water withdrawals appeared in 2005, a dry year. These results are consistent with the information provided by local stakeholders on the occurrence of water supply problems in the Herault basin in the past 40 years: the main stakes concerning the supply of agricultural water are concentrated around the Gignac canal, while user conflicts may appear in the downstream Agde area. The year 2005 was indeed notable for tensions around water resources, with strict regulations concerning the use of water and special negotiations that led to the release of additional water from the Salagou dam to compensate for low flows in the Herault River.

Figure 10b shows the results of the simulation of water shortage for the eight main management systems in the Ebro basin. The systems on the right bank are very exposed to water shortage, particularly the Guadalope sub-basin. Although some agricultural water withdrawal restrictions may have been applied in all areas except the lower Ebro, between 1971 and 2009, only the Ebro valley, Bardenas and Alto Aragon areas faced shortages exceeding 50 % of demand. In the case of the Bardenas irrigation

HESSD
11, 12315–12364, 2014

system, the increase in water shortage mirrored an increase in water demand. The storage capacity of the Yesa dam is currently being increased by about 600 hm^3. In the Alto Aragon system, the Sotonera and Grado dams have been managed together since 1982, which helped improve the balance between water demand and availability despite a significant increase in demand (from 320 to 950 $hm^3\,yr^{-1}$ between the 1970s and the 2000s). However agricultural water shortage periods did occur in the 2000s. The construction of new storage facilities to increase the storage capacity by about 400 hm^3 is planned in this area.

4.3.2 Sustainability of current water uses in the hydro-climatic conditions of the recent past

In the Gignac area of the Herault basin, the impact of the improved efficiency of the canal in the 2000s (see Sect. 2.3.) is clear: while AWD reached 13 $hm^3\,yr^{-1}$ on average and shortages occurred in three years out of five in the 1990s (see Fig. 10a), AWD would only have been 4 $hm^3\,yr^{-1}$ with shortages one year out of five on average, with the same irrigated areas and efficiency as today and under the same climate conditions (Fig. 11a). However water shortages would have become more frequent and intense with the warmer and drier conditions of the 2000s, owing both to an increase in demand due to increasing evapotranspiration and decreasing precipitation, and to a reduction in available water resources (see Fig. 9a). Figure 12 shows that, on the whole, water use and availability are better balanced in the Herault than in the Ebro hydrosystem. Apart from the Salagou area with a maximum shortage of 70 % and resilience of 0.3 and the Agde area with a resilience of 0.3, the indicators remain in an acceptable range in all demand nodes of the Herault basin.

According to the results shown in Fig. 12, the Aragon and Catalunya, Ebro valley, Segre-Urgel and Lower Ebro sections in the Ebro basin appear to have found a sustainable balance between water use and availability if climatic conditions remain in the range of variability as that observed in the recent past. Comparison of Figs. 10b and 11b shows an improvement in the water balance in the Segre-Urgel irrigation

HESSD
11, 12315–12364, 2014

system due to the construction of the Rialb dam in the early 2000s, which was added to the storage capacity of the Oliana dam. The combined operation of the two dams reduces annual agricultural water shortage rates (Fig. 11b) compared to the Oliana dam without the additional storage capacity of Rialb (Fig. 10b). On the other hand, the expansion of irrigated areas in the Bardenas and Alto Aragon systems appears to have contributed to the increase in water stress revealed in Fig. 10b. Figure 11b shows that the current uses of water in the Bardenas system would not match water availability in the hydro-climatic conditions of the recent past. With its current water use and water management and under unchanged climate variability, in the future, this area could face many long severe shortage events (MS = 75 % and Res = 0.2), even though, generally speaking, the system can still be considered to be reliable since years with a total deficit over 50 % occur in our simulations less frequently than once every five years (see Fig. 12). Finally, the Jalon and Guadalope areas appear to be particularly unbalanced (see Fig. 12), even though no conflicts between users have arisen in the Jalon (C = 0) due to very low UWD.

5 Discussion and conclusion

5.1 Outcome

The purpose of this study was to (i) combine human and climatic drivers to represent water stress and its dynamics in space and over time in a past 40 year period, and (ii) assess the balance between water uses and availability and its sustainability in two contrasted catchments subject to anthropogenic and climatic variability. The approach presented in this paper enables better identification of the drivers of water stress in basins that are likely to face rapid climatic and anthropogenic changes in the coming decades.

A combination of human and hydro-climatic data based primarily on the mapping of resource and demand nodes enabled us to account for heterogeneities in water uses

HESSD
11, 12315–12364, 2014

and management practices in the two basins. The main heterogeneities in resource availability were identified by isolating the catchments that contributed most in the Herault basin and the snowmelt dominated catchments in the Ebro basin, and by defining the dams most important for the satisfaction of water demands. Local water management was taken into account. Our maps of the Ebro basin isolated management units for the main irrigation systems: resource management in the basin is currently organized in 17 sub-units, the *Juntas de Explotación* (CHE, 2011); in each unit, a local water management committee adjusts water allocations on a yearly basis. Thus, the demand nodes in our study represent actual management units, the scale at which water allocation is discussed.

We were able to distinguish between hydro-climatic and human-induced dynamics by simulating natural streamflow and the influence of regulations and withdrawals. Despite the complexity of the systems represented, particularly in the Ebro basin, the simulation of influenced streamflow produced satisfactory results. Distinguishing between the types of pressure gave us a better understanding of observed changes in discharge in both basins, which confirmed the preliminary works of Collet et al. (2014) who attributed the observed decrease in discharge of the Herault River to a decrease in precipitation and an increase in evapotranspiration over the Herault catchment. In contrast, studies that focused on only a few years in the past and/or future projections (Pulido-Velasquez et al., 2011; Varela-Ortega et al., 2011) did not distinguish between hydro-climatic and human dynamics, which hindered their understanding of the long-term drivers of water stress.

One may note that integrated tools for the simulation of water balance at a basin scale have already been developed and described in the literature, such as AQUATOOL (Andreu et al., 1996), WEAP (Sieber and Purkey, 2007) or Mike BASIN (DHI, 2003). However, beyond the use of a particular integrated modeling tool, the core issue in assessing water stress lies more in spatial and temporal processing and in combining data to build a dynamic representation of water uses and availability over a long period of time. For example, the added value of the simulation of agricultural water

HESSD
11, 12315–12364, 2014

demand stems from the processing of raw data on irrigated crops and areas at the municipal scale, to provide input data for the model at a 10 day time step and per demand node. The *Confederación Hidrográfica del Ebro* also has an operational model of the Ebro basin using Aquatool. It takes into account all the storage dams and canals, and can simulate demand satisfaction at a fine spatial scale. Nevertheless data availability would not enable a thorough calibration of water resource simulation over a period of several decades at the fine scale used in this operational model.

Because the indicators used to measure water stress were defined with local stakeholders, they were appropriate for water management issues. These indicators are sensitive to the spatial and temporal dynamics of anthropogenic pressures, and should help anticipate undesirable situations and/or make projections, as recommended by Juwana et al. (2012). Threshold values were set to define undesirable situations in each hydrosystem. The indicators can be seen as a way of interpreting simulation results to characterize the dynamics of the balance between demand and availability over four decades. Including human and physical drivers in a spatially and temporally distributed modeling approach enabled us to correctly reproduce changes in water demand satisfaction in the Herault and the Ebro basins: the simulated trends matched the situations described by local managers. Our simulation results made it possible to analyze the impacts of climate variability and variations in water uses and water management practices on the balance between demand and availability.

In the Herault basin, the irrigation needs of vineyards increased and were subject to great variability (standard deviation reached 60 % of the mean water demand over 1971–2009). Urban water demand also increased significantly, and water use conflicts started to appear in the basin. AWD satisfaction in the Gignac area appears to be sensitive to hydro-climatic variability (the 1970s were wetter whereas the 1980s and the 2000s were warmer and drier). However the improvement in irrigation efficiency in the 2000s succeeded in limiting agricultural water shortages in the Gignac area. In the Agde section, an imbalance between demand and availability appeared in the 2000s because of the combined increase in AWD and UWD and the decrease in natural

HESSD
11, 12315–12364, 2014
Simulating long-term past changes in the balance between water demand and availability
J. Fabre et al.

streamflow. Although UWD also increased in the Ebro basin, it remained very low compared to AWD. The main driver of the decrease in water demand satisfaction in the Ebro was the increase in demand triggered by the expansion of irrigated land, which exceeded the water supply capacity in some areas (under current management and storage capacity).

Although key areas of the Herault basin were highly sensitive to hydro-climatic variability, the balance between water uses and availability in the Ebro basin appears to be more critical, owing to high agricultural pressure on water resources. All the same, water demand and availability were shown to be in balance in large systems of the Ebro basin such as the Ebro Valley, Aragon and Catalunya, Segre, and Lower Ebro, which concentrate 60 % of the water demand from the large irrigation systems in the basin. In comparison, water demand in the Gignac area represented, on average, 70 % of total AWD over the Herault basin over the past 40 years. What is more, the vineyards in the Herault basin may be more vulnerable to an unreliable water supply than the cereal and fodder crops grown in the Ebro basin, where cropping patterns can be adjusted on a yearly basis to adapt them to the hydro-climatic conditions. The spatial distribution of our integrative approach enabled us to identify the most vulnerable areas: the main stakes for maintaining or reaching water balance are concentrated in the Gignac and Agde areas in the Herault basin, and on the right bank and the Bardenas and Alto Aragon systems in the Ebro basin.

5.2 Limitations

Our integrative modeling chain includes uncertainties stemming from data use and interpretation, and modeling uncertainties. In the Ebro basin, widespread anthropogenic influence on streamflow made calibration and validation of natural streamflow difficult. Setting the contribution of the semi-arid Ebro valley sub-basins at zero led to a general improvement of the simulations but also to the underestimation of total volumes, as would be expected. Although the long-term reconstitution of past water demands produced valuable information that was not available using regular data sources, accurate

HESSD
11, 12315–12364, 2014

validation of water demand simulations in space and over time was not possible due to the lack of appropriate data on withdrawals. Nonetheless, the orders of magnitude, seasonal distributions, and past dynamics appear to be in agreement with the data that were available as well as with the knowledge of local managers (see Grouillet et al., 2014b).

Simulations of water shortages at a 10 day time step should be interpreted with caution, as no real-time water management adjustments were considered in this modeling framework. Indeed, the order of priority for the supply of water to different uses was fixed in our model, and no restrictions were imposed on industrial and urban demand before agricultural withdrawal restrictions reached 100 % of demand. In real life, water use restrictions can be decided on in advance, to limit non-essential urban uses before supplies to irrigators are entirely cut off. Likewise, in the Ebro basin each *Junta de Explotación* can decide on the water volumes allocated to different users at the beginning of the irrigation season, based on the filling level of the associated reservoirs. Thus, if the irrigation season begins with low reservoir levels, withdrawals can be partially restricted throughout the season instead of waiting until the reservoirs are at their minimum level before limiting withdrawals. Sometimes farmers decide on their cropping patterns according to the reservoir level and/or snow cover (Salvador et al., 2011). In systems with no storage capacity like the Gignac canal or the Agde section in the Herault basin, water shortages may be more irregular. In future studies, anticipated water reallocation should be incorporated in the model to better integrate the human aspects of water management.

Finally, the simulation of UWD, OWD and AWD does not provide a comprehensive view of water uses. Notably the demand for hydropower production was only partly accounted for through reserved flows at the dams concerned for the satisfaction of AWD. This could be a major source of bias in the modeling of influenced streamflow, as the operation of dams for the production of hydropower can have a major impact on the downstream streamflow and hence significantly affect downstream users. Also, despite the increasing attention paid to environmental flows, these flows were not included in this study, except for reserved flows at dam outlets in the Ebro basin. However considering the time depth of the study, one could argue that water withdrawals would not have been limited by environmental concerns during the majority of the study period. In future studies, environmental flows should be taken into account when assessing the sustainability of a hydrosystem's water balance.

5.3 Prospects

Despite the limitations mentioned above, the approach described in this paper will enable the identification of the drivers of water stress in basins that are likely to face rapid climatic and anthropogenic changes in the coming decades. Such information will be extremely useful to policy makers when designing water plans for coming decades. The next step of this work, which is currently being conducted in the framework of the GICC-REMedHE project, consists in using the proposed integrative modeling chain to simulate and compare the impacts of socio-economic trend scenarios and a wide range of possible future climates. Further research will assess the effectiveness of adaptation measures in reducing water stress and achieving a sustainable balance between water uses and availability.

Acknowledgements. This work was carried out as part of the GICC REMedHE project funded by the French Ministry of Ecology, Sustainable Development and Energy for the period 2012–2015. The authors thank the *Syndicat Mixte du Bassin du Fleuve Hérault* and the *Confederación Hidrográfica del Ebro* for providing the necessary data and documents for this study as well as for sharing their knowledge of water resources management in the studied basins. Climatic data for the Ebro basin was provided by the *Agencia Estatal de Meteorología* (AEMET).

HESSD
11, 12315–12364, 2014

References

Allen, R., Pereira, L., Raes, D., and Smith, M.: Crop evapotranspiration – guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, FAO, 1998. 12320

Andreu, J., Capilla, J., and Sanchìs, E.: AQUATOOL, a generalized decision-support system for water resources planning and operational management, J. Hydrol., 177, 269–291, 1996. 12341

Arnell, N.: Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environ. Change, 14, 31–52, 2004. 12317

Arnell, N., van Vuuren, D., and Isaac, M.: The implications of climate policy for the impacts of climate change on global water resources, Global Environ. Change, 21, 592–603, 2011. 12317

Asefa, T., Clayton, J., Adams, A., and Anderson, D.: Performance evaluation of a water resources system under varying climatic conditions: reliability, resilience, vulnerability and beyond, J. Hydrol., 508, 53–65, 2014. 12319

Beck, L. and Bernauer, T.: How will combined changes in water demand and climate affect water availability in the Zambezi river basin?, Global Environ. Change, 21, 1061–1072, 2011. 12317

Bejarano, M., Marchamalo, M., de Jalon, D. G., and del Tánago, M. G.: Flow regime patterns and their controlling factors in the Ebro basin (Spain), J. Hydrol., 385, 323–335, 2010. 12322

CEDEX – Centro de estudios y experimentacion de obras publicas: Anuario de Aforos, available at: http://www.hercules.cedex.es/anuarioaforos/default.asp (last access: February 2014), 2012.

CHE: Propuesta de Proyecto de Plan Hidrológico de la cuenca del Ebro, Memoria, available at: www.chebro.es (last access: October 2014), 2011. 12323, 12327, 12341

Collet, L., Ruelland, D., Borrell-Estupina, V., Dezetter, A., and Servat, E.: Integrated modeling to assess long-term water supply capacity of a meso-scale Mediterranean catchment, Sci. Total Environ., 461–462, 528–540, 2013. 12318, 12319, 12326

Collet, L., Ruelland, D., Borrell-Estupina, V., and Servat, E.: Assessing the long-term impact of climatic variability and human activities on the water resources of a meso-scale Mediterranean catchment, Hydrolog. Sci. J., 59, 1457–1469, 2014. 12322, 12323, 12341

Dezetter, A., Fabre, J., Ruelland, D., and Servat, E.: Selecting an optimal climatic dataset for integrated modeling of the Ebro hydrosystem, in: Hydrology in a changing world: environmental and human dimensions, Proc. 7th FRIEND Int. Conf., 7–10 October 2014, Montpellier, France, IAHS-AISH Publ., 363, 355–360, 2014. 12321, 12328
DHI: MIKE BASIN 2003: A versatile decision support tool for integrated water resources management planning (guide to getting started tutorial), Danish Hydraulic Institute, Horsholm, Denmark, 2003. 12341
European Commission: Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, Brussels, 2000. 12324
European Commission: European Soil Database (distribution version V2.0), Brussels, 2004. 12327
Fabre, J., Collet, L., Milano, M., Ruelland, D., Dezetter, A., Ardoin-Bardin, S., and Servat, E.: Assessing the long-term evolution of water supply capacity: comparison of two Mediterranean catchments, in: Hydrology in a changing world: environmental and human dimensions, Proc. 7th FRIEND Int. Conf., 7–10 October 2014, Montpellier, France, IAHS-AISH Publ., 363, 203–208, 2014. 12323
Farley, K., Tague, C., and Grant, C.: Vulnerability of water supply from the Oregon Cascades to changing climate: linking science to users and policy, Global Environ. Change, 21, 110–122, 2011. 12317
Fowler, H., Kilsby, C., and O'Connel, P.: Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system, Water Resour. Res., 39, 1222, doi:10.1029/2002WR001778, 2003. 12333
Fujihara, Y., Tanaka, K, Watanabe, T., Nagano, T., and Kojiri, T.: Assessing the impacts of climate change on the water resources of the Seyhan River basin in Turkey: use of dynamically downscaled data for hydrologic simulations, J. Hydrol., 353, 33–48, 2008. 12329
Füssel, H.-M., and Klein, R.: Climate change vulnerability assessments: an evolution of conceptual thinking, Climatic Change, 75, 301–329, 2006. 12317
García Vera, M. A. and Martínez-Cob, A.: Revisión de las necesidades hídricas netas de los cultivos de la Cuenca del Ebro, Zaragoza, Confederación Hidrográfica del Ebro, 2004, Informe, Trabajo de consultoría y asistencia – Convenio Colaboración CSIC-CHE, 8 vols., 2004. 12321

Griffin, M., Montz, B., and Arrigo, J.: Evaluating climate change induced water stress: a case study of the Lower Cape Fear basin, NC, Appl. Geogr., 40, 115–128, 2013. 12317, 12318

Grouillet, B., Fabre, J., Ruelland, D., Collet, L., and Boyer, J.-F.: Assessing past and future water demands under climate change and anthropogenic pressures in two Mediterranean basins, in: Hydrology in a changing world: environmental and human dimensions, Proc. 7th FRIEND Int. Conf., 7–10 October 2014, Montpellier, France, IAHS-AISH Publ., 363, 185–190, 2014a. 12327

Grouillet, B., Fabre, J., Ruelland, D., and Dezetter, A.: Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments, J. Hydrol., submitted, 2014b. 12344

Hallegatte, S.: Strategies to adapt to an uncertain climate change, Global Environ. Change, 19, 240–247, 2009. 12317

Hargreaves, G. and Samani, Z.: Reference crop evapotranspiration from temperature, Appl. Eng. Agric., 1, 96–99, 1985. 12321

Hashimoto, T., Stedinger, J., and Loucks, D.: Reliability, resiliency, and vulnerability criteria for water resources system performance evaluation, Water Resour. Res., 10, 14–20, 1982. 12333

Heinrichs, T., Lehner, B., and Alcamo, J.: An integrated analysis of change in water stress in Europe, Integr. Ass. Stud., 3, 15–29, 2012. 12317

Iglesias, A., Garrote, L., Diz, A., Schlickenrieder, J., and Martin-Carrasco, F.: Re-thinking water policy priorities in the Mediterranean region in view of climate change, Environ. Sci. Policy, 14, 744–757, 2011. 12317

Juwana, I., Muttil, N., and Perera, B.: Indicator-based water sustainability assessment – a review, Sci. Total Environ., 438, 357–371, 2012. 12342

Koutroulis, A., Tsanis, I., Daliakopoulos, I., and Jacob, D.: Impact of climate change on water resources status: a case study for Crete Island, Greece, J. Hydrol., 479, 146–158, 2013. 12317, 12318

Krol, M., Jaeger, A., Bronstert, A., and Güntner, A.: Integrated modeling of climate, water, soil, agricultural and socio-economic processes: a general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil, J. Hydrol., 328, 417–431, 2006. 12318

Lecina, S. and Playán, E.: Mejora del regadío de la Comunidad de Regantes V del Canal de Bardenas, in: Actas del XX Congreso Nacional de Riegos y Drenajes (AERYD), Ciudad Real., 99–101, 2002. 12324

Lecina, S., Isidoro, D., Playán, E., and Aragües, R.: Irrigation modernization and water conservation in Spain: the case of Riegos del Alto Aragón, Agr. Water Manage., 97, 1663–1675, 2010. 12324

López-Moreno, J., Zabalza, J., Vicente-Serrano, S., Revuelto, J., Gilaberte, M., Azorin-Molina, C., Morán-Tejeda, E., García-Ruiz, J., and Tague, C.: Impact of climate and land use change on water availability and reservoir management: scenarios in the Upper Aragón River, Spanish Pyrenees, Sci. Total Environ., 493, 1222–1231, 2013. 12318

Ludwig, R., Roson, R., Zografos, C., and Kallis, G.: Towards an inter-disciplinary research agenda on climate change, water and security in Southern Europe and neighboring countries, Environ. Sci. Policy, 14, 794–803, 2011. 12317

March, K., Therond, O., and Leenhardt, F.: Water futures: Reviewing water-scenario analyses through an original interpretative framework, Ecol. Econ., 82, 126–137, 2012. 12317

Martínez-Cob, A. and Tejero-Juste, M.: A wind-based qualitative calibration of the Hargreaves ET0 estimation equation in semiarid regions, Agr. Water Manage., 64, 251–264, 2004. 12321

Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., and Servat, E.: Facing global changes in the Mediterranean Basin: How could the current water stress evolve by the medium-term?, C. R. Geosci., 344, 432–440, 2012. 12319

Milano, M., Ruelland, D., Dezetter, A., Fabre, J., Ardoin-Bardin, S., and Servat, E.: Modeling the current and future capacity of water resources to meet water demands in the Ebro basin, J. Hydrol., 500, 114–126, 2013a. 12318, 12319, 12322

Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., Fritsch, J.-M., Ardoin-Bardin, S., and Thivet, G.: Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes, Hydrolog. Sci. J., 58, 498–518, 2013b. 12319

Ministère de l'Ecologie du Développement Durable et de l'Energie: Banque Hydro, available at: http://www.hydro.eaufrance.fr/selection.php, last access: October 2010.

Perrin, C., Michel, C., and Andreassian, V.: Improvement of a parsimonious model for streamflow simulation, J. Hydrol., 10, 282–290, 2003. 12328

HESSD

11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Pulido-Velasquez, D., Garrote, L., Andreu, J., Martin-Carrasco, F.-J., and Iglesias, A.: A methodology to diagnose the effect of climate change and to identify adaptive strategies to reduce its impacts in conjunctive-use systems at basin scale, J. Hydrol., 405, 110–122, 2011. 12317, 12318, 12319, 12341

Purkey, D., Joyce, B., Vicuna, S., Hanemann, M., Dale, L., Yates, D., and Dracup, A.: Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley, Climatic Change, 87, 109–122, 2008. 12318

Quintana-Segui, P., Moigne, P. L., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas, C., Franchisteguy, L., and Morel, S.: Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France, J. Appl. Meteorol. Clim., 47, 92–107, 2008. 12320

Ruelland, D., Brisset, N., Jourde, H., and Oyarzun, R.: Modelling the impact of climatic variability on groundwater and surface flows from a mountainous catchment in the Chilean Andes, Cold regions hydrology in a changing climate, proceedings of Symposium H02 held during IUGG 2011, July 2011, Melbourne, Australia, IAHS Publ., 346, 171–179, 2011. 12328

Ruelland, D., Dezetter, A., and Hublart, P.: Sensitivity analysis of hydrological modeling to climate forcing in a semi-arid mountainous catchment, in: Hydrology in a changing world: environmental and human dimensions, Proc. 7th FRIEND Int. Conf., 7–10 October 2014, Montpellier, France, IAHS-AISH Publ., 363, 145–150, 2014. 12328

Salvador, R., Martínez-Cob, A., Cavero, J., and Playán, E.: Seasonal on-farm irrigation performance in the Ebro basin (Spain): crops and irrigation systems, Agr. Water Manage., 98, 577–587, 2011. 12324, 12344

Sieber, J. and Purkey, D.: User Guide for WEAP 21 (Water Evaluation and Planning System), Stockholm Environment Institute (SEI), US Center, USA, 2007. 12341

Sullivan, C. and Meigh, J.: Targeting attention on local vulnerabilities using an integrated index approach: the example of the Climate Vulnerability Index, Water Sci. Technol., 51, 69–78, 2005. 12319

Syndicat Mixte du Bassin du Fleuve Hérault: Gestion quantitative de la ressource, Etat des lieux version 4, SAGE du bassin du fleuve Hérault, France, www.sage.herault.fr (last access: August 2014), 2005. 12324

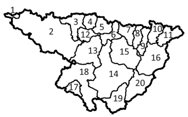
Varela-Ortega, C., Blanco-Gutiérrez, I., Swartz, C., and Downing, T.: Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: an integrated hydro-economic modeling framework, Global Environ. Change, 21, 604–619, 2011. 12317, 12318, 12319, 12341

HESSD
11, 12315–12364, 2014

Vicente-Serrano, S. and López-Moreno, J.: Influence of atmospheric circulation at different spatial scales on winter drought variability through a semiarid climatic gradient in North-East Spain, Int. J. Climatol., 26, 1427–1453, 2006. 12322

HESSD
11, 12315–12364, 2014

Table 1. Calibration and validation results of the simulation of natural streamflow in the Herault and the Ebro basins. Optimal values of NSE, VE and VEM are 1, 0 and 0 respectively.

		Calibration			Validation			Simulated annual streamflow ($m^3 s^{-1}$)
		NSE	VE	VEM	NSE	VE	VEM	1971–2009
Herault								
	1-Vis at St-Laurent	0.88	0 %	11 %	0.79	19 %	16 %	10
	2-Herault at Laroque	0.80	0 %	21 %	0.72	−15 %	22 %	9
	3-Herault at Gignac	0.83	0 %	19 %	NA	NA	NA	8
	4-Lergue at Lodeve	0.84	0 %	26 %	0.94	−5 %	9 %	4
	5-Salagou	0.95	0 %	6 %	NA	NA	NA	1
	6-Herault at Agde	0.34	0 %	60 %	NA	NA	NA	11
Ebro								
	1-Ebro at Arroyo	0.83	0 %	8 %	0.73	−13 %	12 %	10
	2-Ebro at Castejon	0.76	0 %	5 %	0.64	−10 %	10 %	123
	3-Arga	0.82	0 %	9 %	0.72	−11 %	18 %	38
	4-Irati at Liedena	0.85	0 %	9 %	0.87	0 %	7 %	29
	5-Aragon at Yesa	0.83	0 %	7 %	0.78	−15 %	15 %	38
	6-Gallego at Ardisa	0.73	0 %	12 %	0.62	−2 %	12 %	25
	7-Cinca at Grado	0.80	0 %	5 %	0.83	3 %	4 %	42
	8-Esera	0.71	0 %	7 %	0.67	−6 %	7 %	21
	9-Noguera Ribagorzana	0.34	0 %	10 %	0.57	−6 %	28 %	20
	10-Noguera Pallaresa	0.66	0 %	12 %	0.72	−13 %	14 %	31
	11-Segre at Oliana	0.73	0 %	11 %	0.72	−17 %	17 %	26
	12-Aragon at Caparroso	0.39	0 %	20 %	0.16	−46 %	44 %	6
	13-Ebro at Zaragoza	0.13	0 %	21 %	−1.55	25 %	2 %	28
	14-Ebro at Mequinenza	0.02	0 %	5 %	−1.15	5 %	+0 %	13
	15-Cinca at Fraga	0.61	0 %	3 %	0.18	−53 %	18 %	13
	16-Segre at Seros	0.30	−20 %	60 %	0.13	−24 %	51 %	11
	17-Piedra	0.62	0 %	9 %	0.16	−12 %	16 %	3
	18-Jalon en Grisen	0.76	0 %	24 %	−0.91	−52 %	10 %	4
	19-Guadalope	0.71	0 %	43 %	NA	NA	NA	2
	20-Ebro at Tortosa	0.07	0 %	83 %	−0.59	39 %	124 %	30

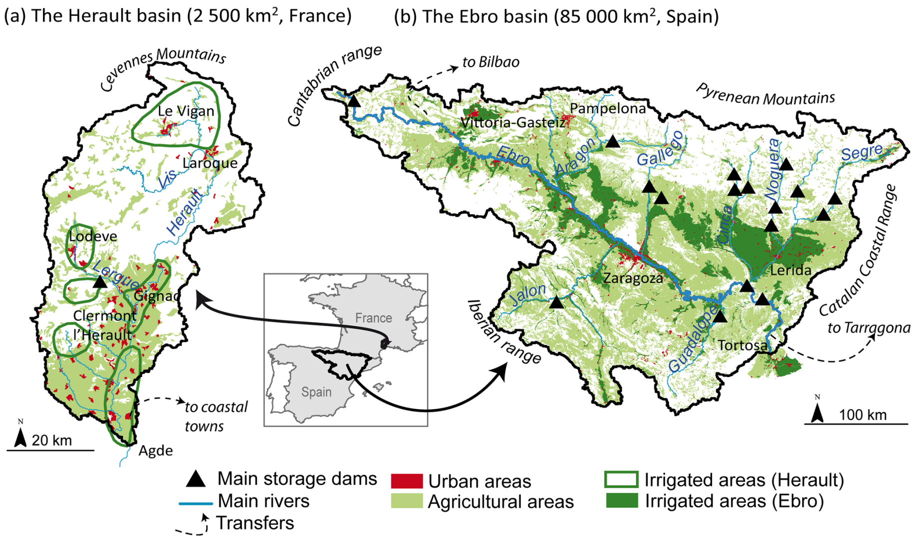


Figure 1. The Herault and the Ebro basins: location of the main human pressures on water resources (urban and agricultural areas, main storage dams and water transfers).

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄| |►
◄ ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

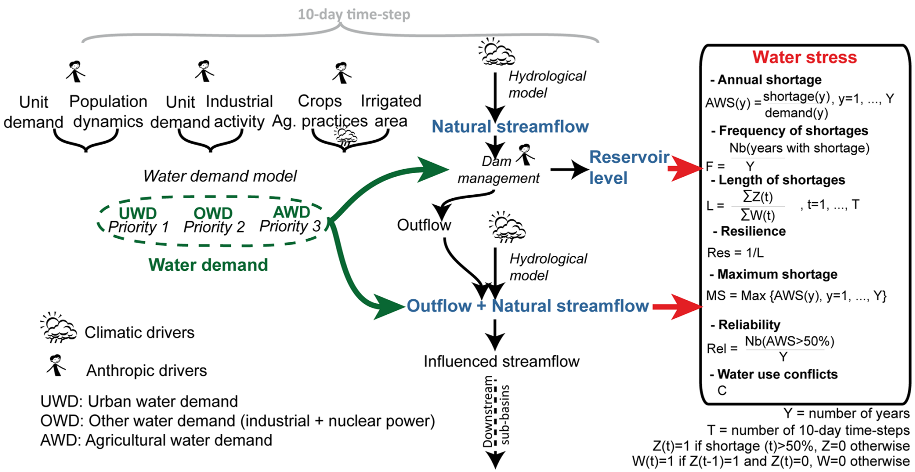


Figure 2. General framework for the integrative modeling chain developed and applied to the Herault and the Ebro basins at a 10 day time step over the 1971–2009 period.

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

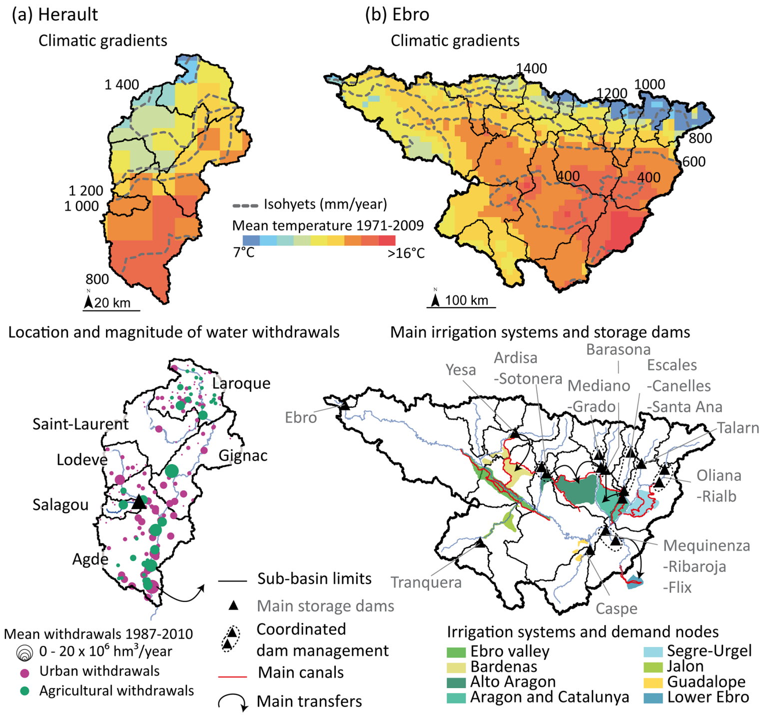


Figure 3. Maps of the main physical and human spatial characteristics of the two basins: **(a)** 6 sections were selected for simulation of water resources and water demand nodes in the Herault basin; **(b)** 20 sectionsfor simulation of water resources and 8 demand nodes that matched the main irrigation systems were selected in the Ebro basin.

HESSD
11, 12315–12364, 2014

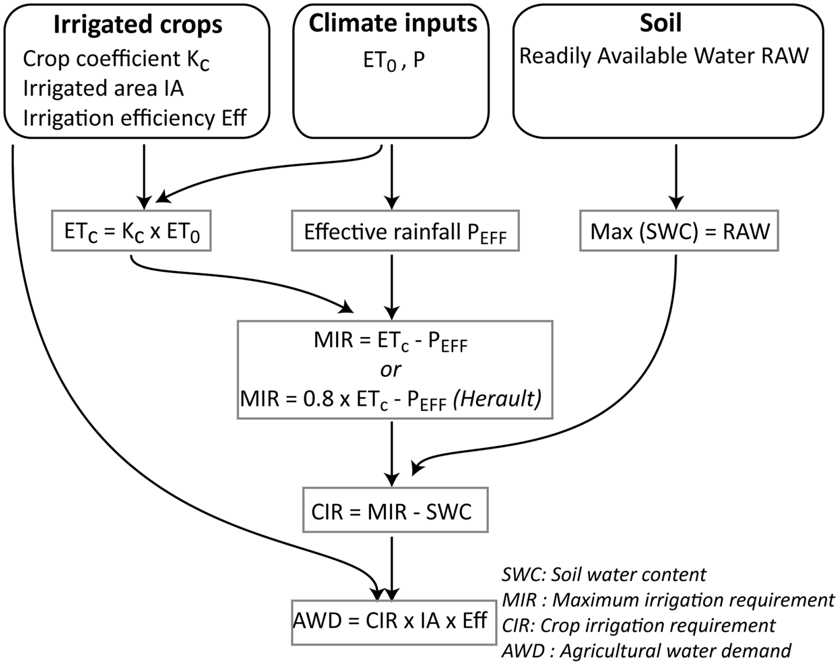


Figure 4. Agricultural Water Demand (AWD) simulation model.

HESSD
11, 12315–12364, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

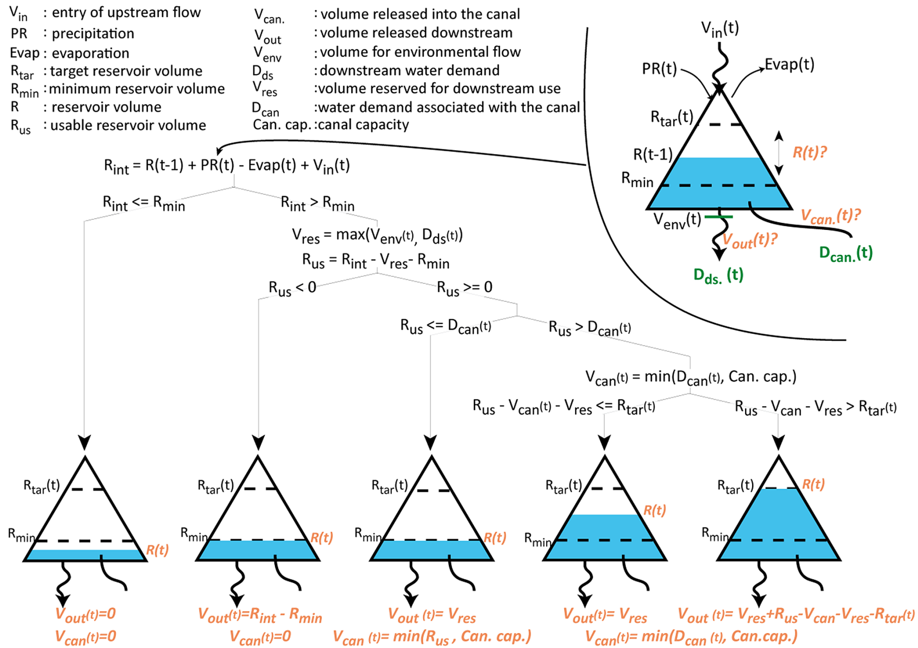


Figure 5. Demand driven dam management model. The reservoir level (R) and volumes released downstream (V_{out}) and into the canal (V_{canal}, if applicable) were calculated at a 10 day time step t.

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

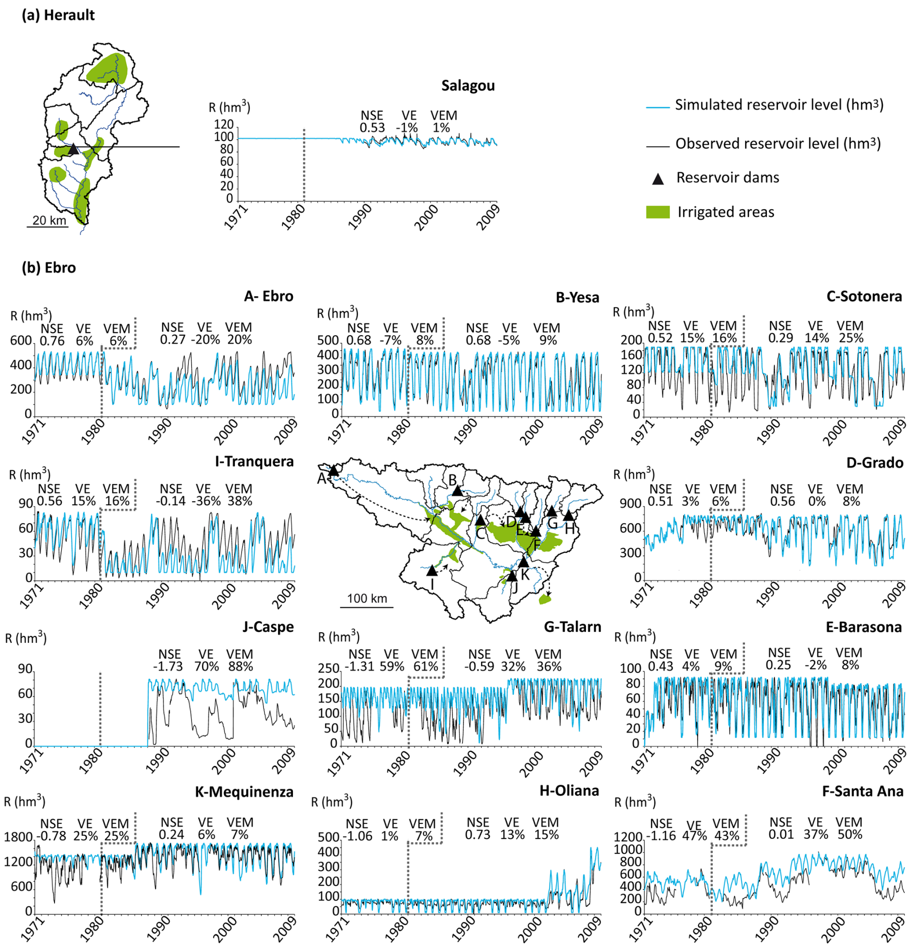


Figure 6. Simulated and observed reservoir levels of the main dams in **(a)** the Herault basin and **(b)** the Ebro basin. Optimal values of NSE, VE and VEM are 1, 0 and 0 respectively.

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

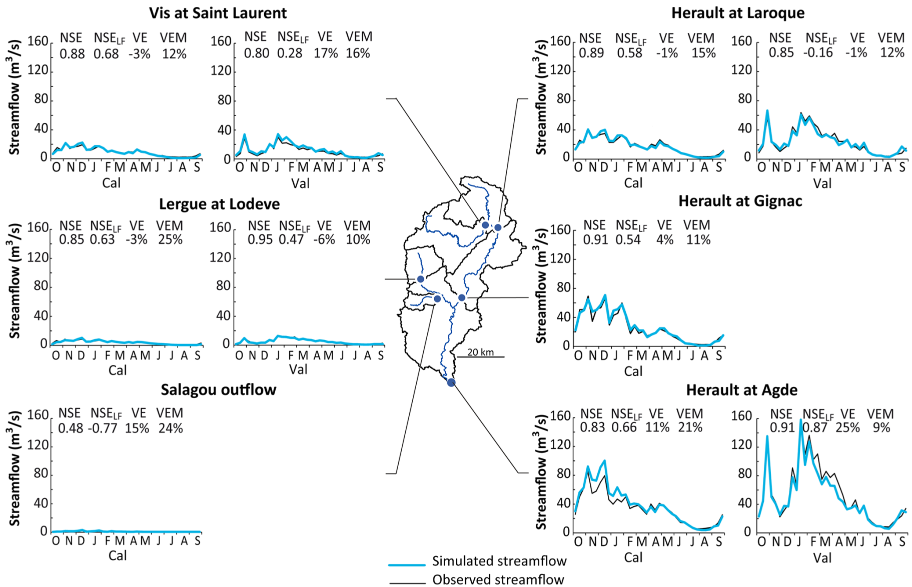


Figure 7. Simulation of influenced streamflow in the Herault basin from 1971 to 2009: results for calibration (Cal: 1981–2009) and validation (Val: 1971–1980) periods. Optimal values of NSE (Nash–Sutcliffe efficiency index), NSE_{LF} (low flow NSE), VE (cumulative volume error), and VEM (mean annual volume error) are 1, 1, 0 and 0 respectively.

HESSD
11, 12315–12364, 2014

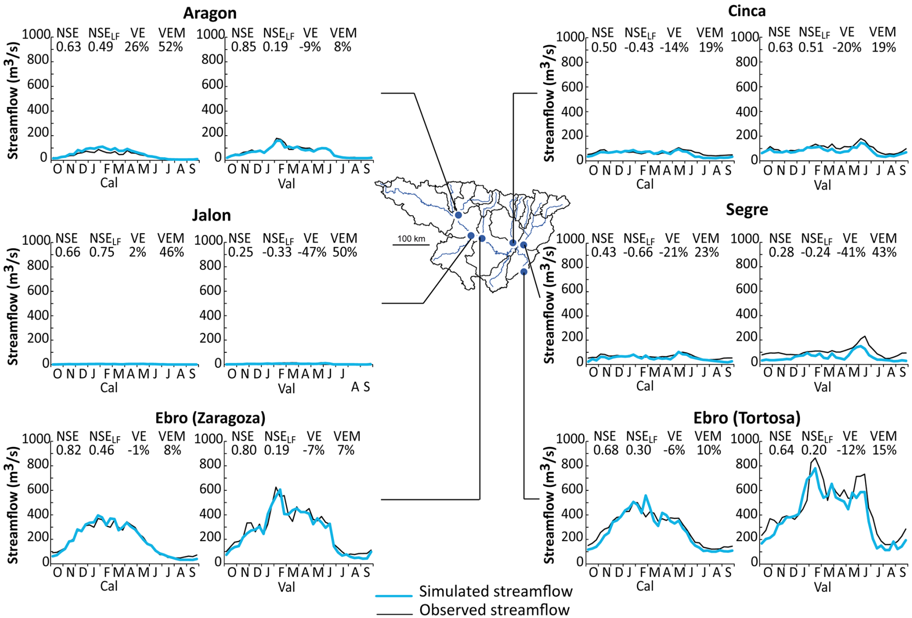


Figure 8. Simulation of influenced streamflow in the Ebro basin from 1971 to 2009: results for calibration (Cal: 1981–2009) and validation (Val: 1971–1980) periods. Optimal values of NSE (Nash–Sutcliffe efficiency index), NSE_{LF} (low flow NSE), VE (cumulative volume error), and VEM (mean annual volume error) are 1, 1, 0 and 0 respectively.

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◄ ►
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

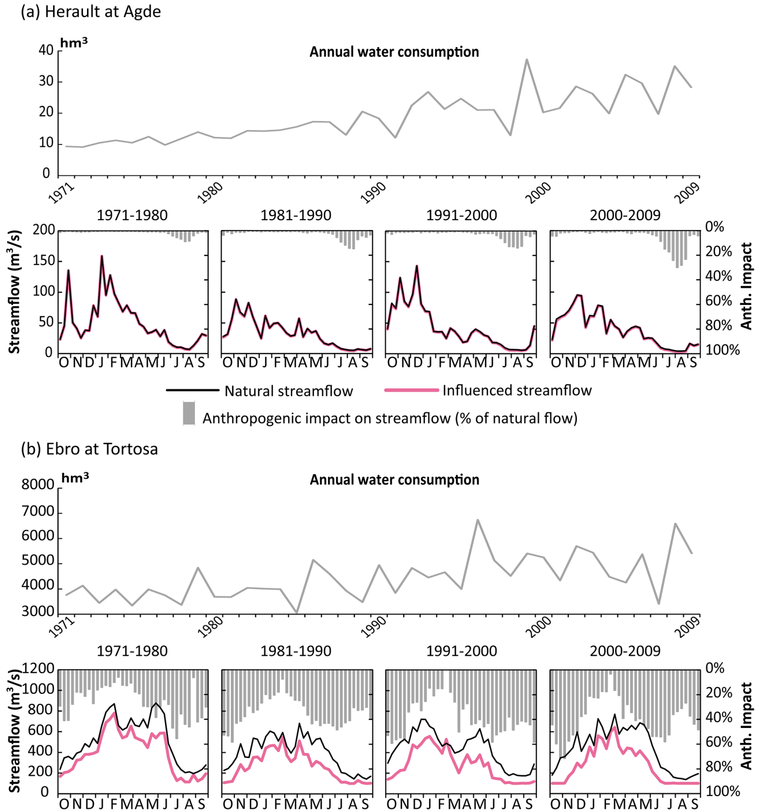


Figure 9. Comparison of natural vs. influenced streamflow: anthropogenic impacts (water consumption and water storage) on **(a)** the Herault river and on **(b)** the Ebro river.

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

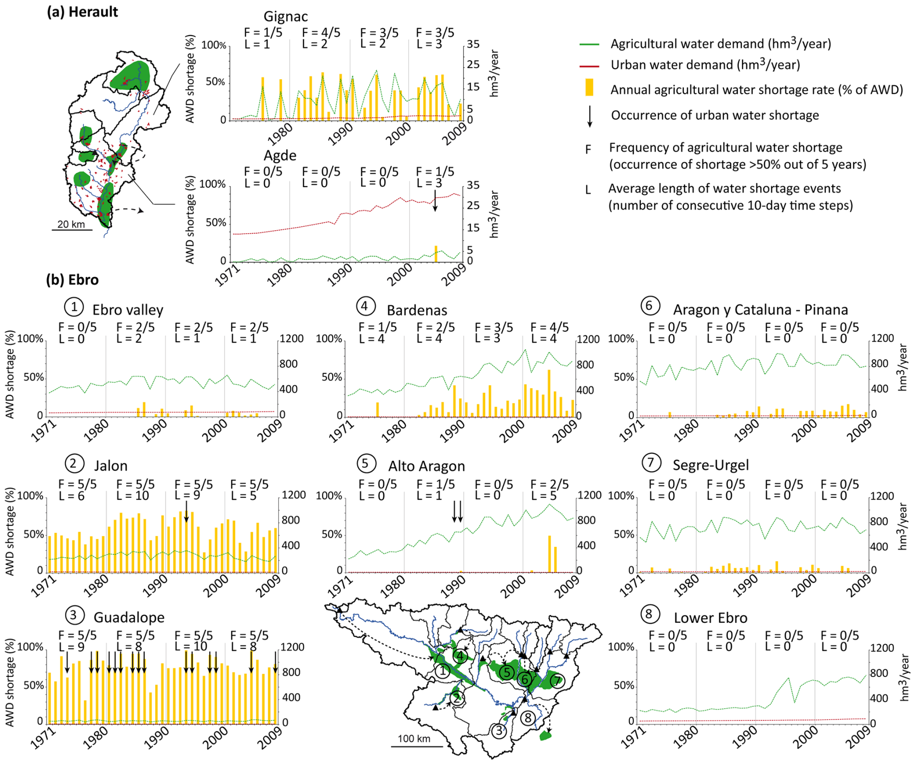


Figure 10. Frequency and intensity of agricultural and urban water shortage in the period 1971–2009 considering the spatial and temporal dynamics of water uses and hydro-climatic conditions **(a)** in the Herault basin and **(b)** in the Ebro basin.

HESSD
11, 12315–12364, 2014

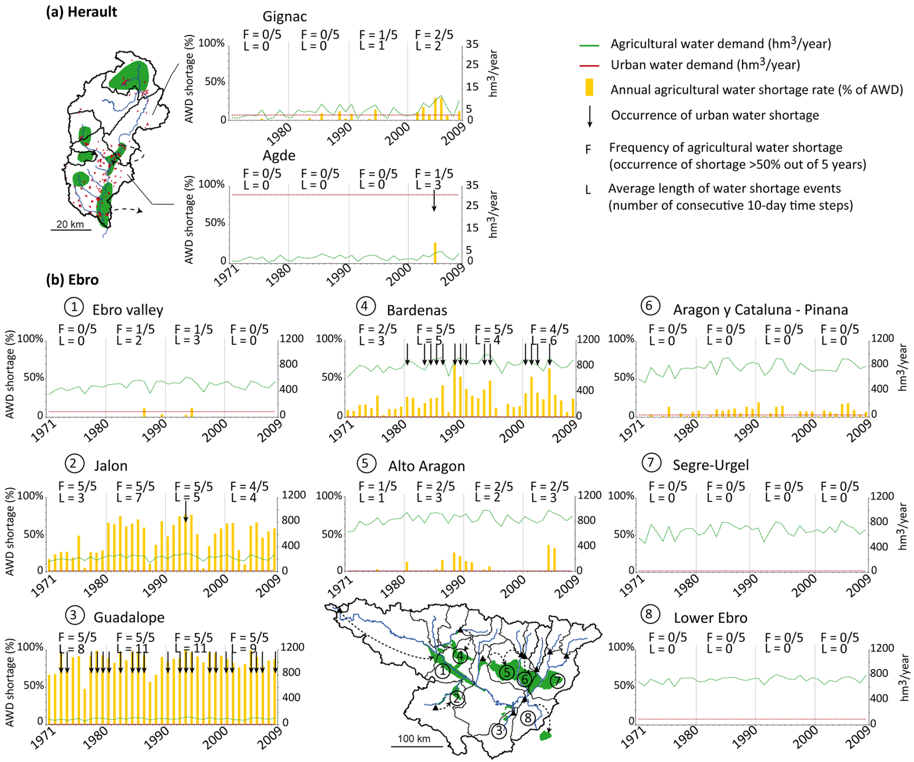


Figure 11. Frequency and intensity of agricultural and urban water shortage under current water uses (2009) and hydro-climatic conditions in the period 1971–2009 **(a)** in the Herault basin and **(b)** in the Ebro basin.

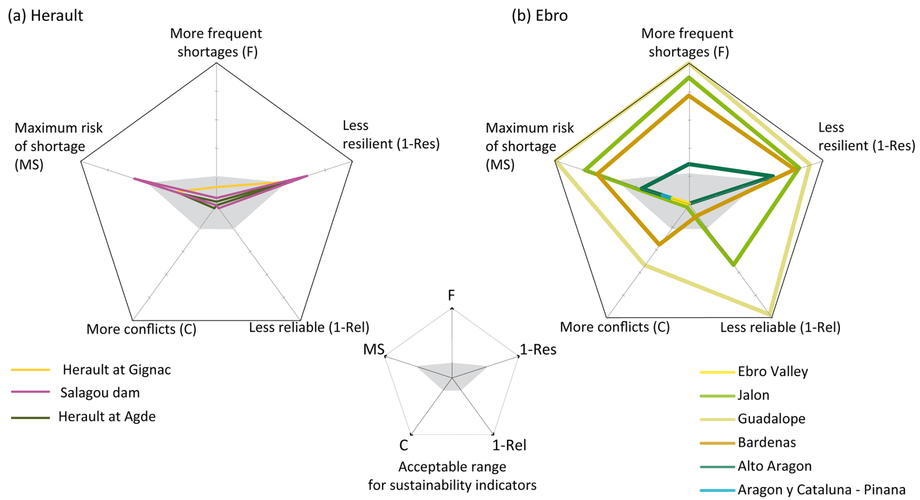


Figure 12. Sustainability of current water uses (2009) under the hydro-climatic conditions of the recent past (1971–2009) for **(a)** the Herault and **(b)** the Ebro basins: frequency of agricultural water shortage (F) and of water use conflicts (C) in years out of 5 years, resilience (Res), maximum agricultural water shortage (MS), reliability (Rel) at the main demand nodes of each catchment. Only demand nodes with at least one non-null indicator value are represented in the radar charts.

HESSD
11, 12315–12364, 2014

Simulating long-term past changes in the balance between water demand and availability

J. Fabre et al.