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Sustainability of water uses in managed hydrosystems: human- and climate-induced changes for the mid-21st century

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Abstract

This paper assesses the sustainability of planned water uses in mesoscale river basins under multiple climate change scenarios, and contributes to determining the possible causes of unsustainability. We propose an assessment grounded in real-world water management issues, with water management scenarios built in collaboration with local water agencies. Furthermore we present an analysis through indicators that relate to management goals and present the implications of climate uncertainty for our results, furthering the significance of our study for water management. A modeling framework integrating hydro-climatic and human dynamics and accounting for interactions between resource and demand was developed and applied in two basins of different scales and with contrasting water uses: the Herault (2500 km^2, France) and the Ebro (85 000 km^2, Spain) basins. Natural streamflow was evaluated using a conceptual hydrological model. A demand-driven reservoir management model was designed to account for streamflow regulations from the main dams. Human water demand was estimated from time series of demographic, socio-economic and climatic data. Environmental flows were accounted for by defining streamflow thresholds under which withdrawals were strictly limited. Finally indicators comparing water availability to demand at strategic resource and demand nodes were computed. This framework was applied under different combinations of climatic and water use scenarios for the mid-21st century to differentiate the impacts of climate- and human-induced changes on streamflow and water balance. Results showed that objective monthly environmental flows would be guaranteed in current climate conditions in both basins, yet in several areas this could imply limiting human water uses more than once every five years. The impact of the tested climate projections on both water availability and demand could question the water allocations and environmental requirements currently planned for the coming decades. Water shortages for human use could become more frequent and intense, and the pressure on water resources and aquatic ecosystems could in-

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tensify. The causes of unsustainability vary across sub-basins and scenarios, and in most areas results are highly dependent on the climate change scenario.

1 Introduction

Water security was defined by the Global Water Partnership (GWP, 2000) by the following: “Water security at any level from the household to the global means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced”. This definition comprises many different concepts, which many authors have tried to define and grasp over the years (Cook and Bakker, 2012). One of the concepts included in the idea of water security is sustainability. A sustainable use of water resources implies being able to satisfy current and future human water demands while preserving functional water-dependent ecosystems (Gleick, 2000). Thus it implies the ability of users to find a long-term balance between the availability and the use of water resources, a challenge at the heart of integrated water management strategies (Vörösmarty et al., 2012). An imbalance between availability and demand can express itself through the incapacity of water supply to meet demand (be it because of insufficient water availability or excessive water demand), and/or through pressures on water-dependent ecosystems due to excessive water consumption by human use. The European Water Framework Directive (WFD) (European Commission, 2000) requires European river basins to reach a sustainable balance between human water use and ecosystem health.

In this setting water sharing plans, when not already enforced, are currently being designed in many river basins. These plans are often focused on the periods compatible with WFD requirements, i.e. the 2015, 2021 or 2027 horizons. However it is widely recognized that mid-latitude areas could experience increased water stress along the 21st century, due to climate and socio-economic changes (Heinrichs et al., 2012; Arnell and Lloyd-Hughes, 2014; Milano et al., 2013b). These projections should encourage

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decision makers and water managers to look further in time and perhaps lengthen their planning horizons (Hallegatte, 2009). Moreover as underlined by Ludwig et al. (2014) the main difference between Integrated Water Resources Management as prescribed in the WFD and climate change adaptation is the focus on current and historic issues of IWRM, compared to the future focus of adaptation.

In this context, projections of water availability and demand at the river basin scale under scenarios of climate and water use changes are essential to bring a long-term perspective to water sharing plans. To date, studies focusing on climate impacts on water management are mostly focused on projections of water resource availability (Schwank et al., 2014; Bär et al., 2015; Nkomozepi and Chung, 2014; Palazzoli et al., 2015, e.g.). However achieving a sustainable use of water resources depends on hydro-climatic factors (defining the volume of resource) but also on anthropogenic factors, such as water demand and water management infrastructures (e.g. storage and transportation capacity), determining the availability of water resources (Griffin et al., 2013; Menzel and Matovelle, 2010, e.g.). Also, climate change could have considerable impacts on irrigation requirements (Döll, 2002; Woznicki et al., 2015), which should be accounted for in prospective water balance assessments. Some studies have focused only on water demand (Grouillet et al., 2015, e.g.), on fulfilling environmental flow requirements (Donley et al., 2012, e.g.), or on the tradeoffs between environmental flow requirements and one type of demand (Kirby et al., 2014, e.g.). Wanders and Wada (2015) considered human influence in projections of future drought at a global scale; however they did not consider possible future changes in water use. A number of studies at the river basin scale assessed the impacts of hydrological changes on the capacity to satisfy current demands (López-Moreno et al., 2014; Pulido-Velazquez et al., 2011, e.g.), or future planned demands without considering the possible impact of climate change on agricultural water demand (Milano et al., 2013a, e.g.).

Studies that address the issue of water demand satisfaction at the river basin scale are scarce, even more so studies that account for consumptive use and the influence of human water use on streamflow (one example being the work of Beck and

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Bernauer, 2011). Indeed water sustainability must be assessed through the satisfaction of human water needs, the level of pressure on resources, and the respect of environmental instream uses. This implies accounting for and distinguishing water demand (i.e. the amount of water that users would withdraw without restrictions), actual withdrawals, and consumptive use, notably in complex river basins with numerous upstream-downstream relations, reservoirs and water transfers. In a number of existing papers integrating water uses, water management and water availability (Nam et al., 2015; Shamir et al., 2015, e.g.), the systems under study were elementary management units, such as individual reservoirs or an aquifer. To our knowledge fewer studies can be found addressing water balance projections in complex, mesoscale river basins, with numerous spatial and temporal interactions between water uses and water availability (Collet et al., 2013, e.g.).

Integrated modeling of water balance at the basin scale is an extremely complex task which necessarily comprises many biases and uncertainties. Questions have been raised on the confidence that can be placed into projections of hydro-climatic changes (Kundzewicz and Stakhiv, 2010; Wilby, 2010). However if projections of change cannot be considered as predictions and used directly to decide on water allocations or infrastructure dimensioning, models can be used to understand the system under study and to determine the possible causes of change (Letcher et al., 2007; Pielke, 2009, e.g.). In this way, Blöschl and Montanari (2010) recommended the use of "simple" models that will help analyze the system, rather than complex models that may never be complete enough to model the system with perfect accuracy. As stressed by Smit and Wandel (2006), "climate conditions and system dynamics that could be problematic are rarely known a priori". Modeling studies can help point out potential problems and discriminate anthropogenic and climatic impacts. While Kirby et al. (2014) found that river flows were more sensitive to the range of climate change projections than to the range of diversion reallocation scenarios considered, other studies found that anthropogenic drivers could have more impact than climatic drivers (Beck and Bernauer, 2011; Reynard et al., 2014; Vörösmarty et al., 2000, e.g.).

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Uncertainties regarding anthropogenic climate change have been largely discussed in the literature. While some authors issued recommendations on how to improve modeling to better serve decision making (Milly et al., 2008, e.g.) others have stressed the importance of considering climate uncertainties in the decision process, and finding adaptation solutions despite this uncertainty (Hallegatte, 2009; Patt et al., 2005; Wilby, 2010, e.g.). Dessai and Hulme (2004) recommended testing the sensitivity of systems to changing probabilities in climate to guide adaptation. Following the framework of robust decision making (Dessai and Hulme, 2007; Dessai et al., 2009; Wilby and Dessai, 2010), we propose an approach covering a wide range of possible climate scenarios, given by a selection of global climate models. As underlined by Räisänen (2007), intermodel comparison of climate change projections may be the most pertinent currently available estimate of uncertainty.

The purpose of the present study is thus to assess the sustainability of planned water uses in complex mesoscale river basins under multiple climate change scenarios using a conceptual modelling framework, and to determine the possible causes of unsustainability. We propose an assessment grounded in real-world water management issues, with water management scenarios built in collaboration with local water agencies. Furthermore we present an analysis through indicators that relate to management goals and present the implications of climate uncertainty for our results, furthering the significance of our study for water management.

2 Study areas

2.1 Two water management units with contrasting water uses

This study was conducted in two Mediterranean water management units with contrasting geographical characteristics and water uses. The Herault basin (2500 km^2), located in the South of France (Fig. 1a), has been part of the territory managed by the *Rhône-Méditerranée Corse* water agency since 1964, and the *Syndicat Mixte du*

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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 (SMBFH, 2005). The Ebro basin (85 000 km^2), located in the North of Spain (Fig. 1b), is managed by the *Confederación Hidrográfica del Ebro* (CHE), which was created in 1926 with a strong emphasis on resource and infrastructure development but now ensures a wider role in water management, in line with Integrated Water Resources Management and planning. These two basins already have water sharing issues and could be vulnerable to climate change (Bielsa and Cazcarro, 2015; Collet et al., 2013; Milano et al., 2013a; Vargas-Amelin and Pindado, 2014). Strategies to adapt to future climate change have been designed in both basins (AERMC, 2014; García-Vera, 2013). However these strategies are lacking projections of the impacts of climate change and sustainability of planned water uses.

The Herault and the Ebro basins differ in their geographical characteristics. The Herault River flows 150 km from Mont Aigoual (1565 m a.m.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 River flows 910 km along a north-west to south-east axis from Fontibre in the Cantabrian Range (1027 m a.m.s.l.), to the town of Tortosa where it forms a large delta. It is bordered by the Pyrenean range (up to 3383 m a.m.s.l.) in the north, the Iberian range in the south and the Catalan coastal range in the east. The Herault basin is characterized by a Mediterranean climate influenced by the Cevennes mountain range, with mild wet winters and hot dry summers. Temperature and precipitation follow a north-to-south gradient in the basin, ranging from under 8 °C 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

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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.

Figure 1 shows the main anthropogenic pressures on water resources in the Herault and the Ebro basins. The upstream part of the Herault river basin is characterized by low population density and sparse agricultural areas while the downstream part has a high concentration of urban and agricultural areas (Fig. 1a). The Florensac transfer, which supplies urban water to coastal areas located outside 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 reservoir lake. The main irrigated areas are concentrated around the Gignac canal which distributes water from the Herault River to a perimeter of nearly 3000 ha of irrigable land. The Ebro is a complex and highly regulated hydrosystem with a total of 234 dams, currently amounting to a storage capacity of 60 % of total runoff (Fabre et al., 2014). Irrigated areas, covering nearly 700 000 ha in 2009, 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. The population density is mostly very low (under 10 inhab. km^{-2}) except in a few urbanized areas such as Zaragoza or Pamplona. Urban water demand and water demand for industrial use amounted to comparable volumes in 2009.

2.2 Conceptual representation of water availability and water demand

A conceptual representation of water availability and demand was set up in each basin: water uses were grouped in water demand nodes each linked to one or more water availability nodes. Water availability nodes were represented either by the surface flow at the outlet of a sub-basin, or by the volumes stored in the main dams. Thus each

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basin was divided into sub-basins, accounting for the water supply to one or more demand nodes. The conceptual mapping of both hydrosystems accounted for climatic gradients and water use contrasts (for more details see Fabre et al., 2015; Collet et al., 2014). The Herault basin was divided into six sub-basins and the Ebro into 20 (Fig. 1).

In the Herault basin the surface flow at the outlet of each sub-basin was considered to represent water availability for all water uses supplied by withdrawals inside the sub-basin (Fig. 1a). The southern section of the Herault basin (Agde) has both the highest urban withdrawals and a high level of agricultural water demand. The Gignac canal and its irrigated areas were isolated in the Herault at Gignac sub-basin. Water demand is low and mostly agricultural in the Laroque sub-basin, and minimal in the upstream sub-basins of the Saint-Laurent and Lodeve.

In the Ebro basin the links between reservoirs and irrigation systems were accounted for and eight main demand nodes, corresponding to eight main irrigation systems, were defined (Fig. 1b). In cases where the irrigation systems were directly linked to a storage dam, water availability was considered to be the volume stored in the reservoir. In other cases such as the Ebro valley, surface flow is regulated by dams upstream from the water uses, and water availability was considered to be the surface flow at the outlet of the sub-basin in which water is extracted. Note that apart from the eight main demand nodes presented here, a demand node was defined in each of the 20 sub-basins of the Ebro, grouping the water uses not connected to the large irrigation systems. In this paper we will present the balance between water demand and availability only for the eight main demand nodes.

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3 Method

3.1 Integrative modeling of the balance between water availability and demand

3.1.1 Modeling water availability and demand

Natural 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 (E_{T0}) inputs. A snow module based on mean basin temperature (T) (Ruelland et al., 2011, 2014) was 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 over the period 1981–2009 and validated over the period 1971–1980. The hydro-climatic data used in the two basins are described in Fabre et al. (2015). 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 (see Fabre et al., 2015).

At each demand node, water demand was defined for human water uses (human water demand) and for environmental requirements (environmental water demand). Three types of human water demand were considered: urban water demand (UWD), agricultural water demand (AWD), and other water demands (OWD). Human water demand was defined as the amount of water that users would withdraw without restrictions, i.e. the withdrawals that would enable users to have access to optimal amounts of water considering the efficiency of supply networks and irrigation techniques. UWD referred to water demand for domestic use and for commercial and industrial uses connected to municipal networks. AWD was defined as water demand for irrigation use. Considered negligible in the Herault basin, OWD referred to water demand for industries not connected to municipal networks in the Ebro basin. Water demand for human use was calculated according to anthropogenic drivers (e.g. population and irrigated area dynamics) and climatic drivers (only for agricultural water demand). More details on the data used and the modelling of water demands can be found in Grouillet et al. (2015) and Fabre et al. (2015).

Two types of environmental water demand were considered in this study. The first type, called Q_{MIN}, was defined as the streamflow under which withdrawals for human water use are no longer allowed. This type of minimum flow can also be enforced downstream from a dam or a pumping site, for example, to guarantee availability for other water uses downstream and a minimum flow for the aquatic environment. A second type of environmental flows was considered, in line with planning and water allocations objectives: in water sharing plans, the total volume of water allocated to the different users can be limited to guarantee a minimum monthly average flow, called objective flow or Q_{OBJ} in this study. This monthly minimum flow is not enforced as such but is used as a planning objective. In the Herault basin for example, water allocations are adjusted to guarantee the respect of this flow at least eight years out of ten.

Q_{MIN} values were defined downstream from storage dams and at specific locations (such as a 30 $\mathrm{m^3\,s^{-1}}$ constraint for the Ebro at Zaragoza and a 100 $\mathrm{m^3\,s^{-1}}$ constraint for the Ebro at Tortosa, see CHE, 2013), and threshold values were set at the outlet of each sub-basin, under which withdrawals were forbidden. The method used to define these thresholds differed between the two basins, according to the local management rules. In the Herault basin, Q_{MIN} and Q_{OBJ} values were defined by local authorities based on variations around Q_{MNA5}, the minimum monthly flow not exceeded one year out of five in past measurements. Thus in the present study the influenced streamflow as simulated by the model in each sub-basin over the period 1981–2009 (see Fabre et al., 2015) was used to calculate $Q_{\mathrm{MN}A5}$ and, accordingly, Q_{MIN} and Q_{OBJ}. For example, the minimum flow defined by local authorities for the Herault at the gauging station of Gignac is 70 % of the $Q_{\mathrm{MN}A5}$ value observed at this station. Therefore Q_{MIN} was then defined as 70 % of the the $Q_{\mathrm{MN}A5}$ as simulated by the model at the gauging station of Gignac over the period 1981–2009. In the Ebro basin Q_{MIN} (and Q_{OBJ}, considered equal to Q_{MIN}) were defined at the outlet of each sub-basin as 10 % of the mean an-

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nual natural streamflow (simulated as described in Fabre et al., 2015) over the period 1981–2009 (or 5 % of mean annual flow if it exceeded 80 $m^3 s^{-1}$).

A demand-driven dam management model adapted from Fujihara et al. (2008) presented in Fabre et al. (2015) was run to simulate streamflow regulation and storage operations of each dam (the Salagou dam in the Herault basin and 11 major dams in the Ebro basin). The model computes the water balance of the reservoirs at each 10-day time step, accounting for water demand, entering streamflow, evaporation, and the initial reservoir level. Considering minimum and target reservoir levels, it calculates the reservoir level, the volume of water released in associated canals (if applicable) and in the river downstream from the dam during each 10-day time step.

3.1.2 Comparing water availability and demand and simulating influenced streamflow

Water availability and demand were compared at each water demand node. An order of priority for water uses was considered, as defined in Fig. 2. If water availability was equal to or higher than water demand, then water withdrawals were equal to water demand for all types of human water demand. If water availability was lower than water demand, then restrictions were applied to limit withdrawals for human uses. Restrictions were first applied to AWD, then OWD, then UWD. No restrictions were imposed on industrial and urban demand before agricultural withdrawal restrictions reached 100 % of demand. Water shortage was calculated through the difference between water demand and effective water withdrawal. Only a part of the water withdrawn was considered to be actually used (consumptive use), the remaining part was considered to return to the sub-basin outlet as return flow (see Fabre et al., 2015). Thus the modeling chain simulated:

- natural water resources and their availability considering water management rules and infrastructures;

- the ability to satisfy water demands throughout the basin;

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- the influenced streamflow resulting from hydro-climatic conditions and anthropogenic pressures (water withdrawals, return flows and dam management).

The modeling chain was calibrated over the period 1981–2009 and validated over the period 1971–1980 at a 10-day time step, and simulated water supply capacity and influenced streamflow efficiently in both basins (Fabre et al., 2015).

3.2 Climate and water use scenarios for the mid-21st century

3.2.1 Climate scenarios

Climate scenarios covered a reference period (1976–2005, considered to be representative of current climatic variability) and a future period centered on 2050 (2036–2065). For each basin daily climate forcings over the period 1976 to 2005 were extracted from the 8 × 8 km grids presented in Fabre et al. (2015). For the Herault basin, climatic data came from the SAFRAN meteorological analysis system (Vidal et al., 2010) and E_{T0} 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 × 8 km grid (Dezetter et al., 2014; Fabre et al., 2015). The Hargreaves empirical equation (Hargreaves and Samani, 1985) was used to calculate E_{T0} at a daily time step.

In order to cover a wide range of possible climate projections and thus limit overreliance on a limited number of climate projections (Wilby and Harris, 2006), eighteen future climate scenarios were built based on the outputs from nine Global Climate Models (see Table 1) from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Using a large set of GCMs is indeed recommended since the dispersion between climate projections stems mainly from the climate models (Arnell et al., 2004; Dessai and Hulme, 2007). The mid-21st century (2036–2065) was chosen for projections through a compromise between local projections of water uses (generally for 2030) and the necessity to use climate projections in which a signal of climate change could be distinguished from climatic variability.

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All simulations of climate change were based on the historical Representative Concentration Pathway (RCP) over the reference period (1976–2005) and the RCPs 4.5 and 8.5 over the future period (2036–2065). The outputs from the nine GCMS were extracted from the IPCC Data Distribution Center. Climate change scenarios were then generated using a change factor method (Déqué, 2007; Milano et al., 2013b; Ruelland et al., 2012, e.g.). For each GCM grid cell, the monthly variations obtained between the reference and future climatic simulations were applied to the observed series of T and P (over the reference period 1971–2005) of the cells of the 8 × 8 km grids whose center was included within the said GCM grid cell.

3.2.2 Water use scenarios

Water uses were considered through two scenarios in each basin: current water uses and a trend scenario for 2050. Current water uses were defined with the population, irrigated areas, network efficiency, touristic activity, and unit allocations of the 2000s.

As part of planning for the respect of the European Water Framework Directive, local agencies make projections of changes in water uses by 2027. The trend scenario was built based on these projections (e.g. for irrigated areas and irrigation efficiency) and the continuation of the trends in these projections (e.g. for population growth) until 2050. The changes applied to the main drivers of water demand between the current and the trend water use scenarios are presented in Table 2. Population projections were based on the median scenarios of the national statistic institutes (INSEE in France, INE in Spain). Unit allocations for urban water demand were taken from a study of water uses in the region for the Herault and from projections by the CHE in the Ebro. In the Herault basin, Rinaudo (2011) suggested a 12 % decrease in domestic unit consumption between the 2000s and 2050, linked with forecasted behavioral changes and improved control of water consumption by household appliances. However projections also suggest an increased connection rate of small industries, parks and gardens and commercial water uses to potable water networks, inducing a total increase of urban unit allocation by 21 %. The efficiency of the potable water network

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was considered to vary in the Herault according to local objectives in line with a national policy to reduce losses, and remained constant in the Ebro, where networks are considered already efficient. A prospective study was led in the Herault basin within the water sharing plan, in which an inventory of local irrigation projects was made (regardless of available resources). These projections were used in the trend scenario. In the Ebro basin irrigated areas were considered to reach their maximum extent defined by the CHE (CHE, 2013). Changes in population (permanent and touristic) and unit urban water consumption were applied uniformly to all demand nodes, whereas changes in network and irrigation efficiency, irrigated areas and industrial activity were different for each demand node. More details on the trend water use scenarios for 2050 can be found in Grouillet et al. (2015).

3.3 Analysis of the relative impact of climate and water use scenarios

3.3.1 Combinations of climate and water use scenarios

The modeling framework was applied under four combinations of climate and water use scenarios to differentiate the impacts of climatic and anthropogenic changes on water supply capacity. These combinations and their corresponding objectives are presented in Table 3.

Natural streamflow in the reference climate was simulated by running the hydrological model with climate input data from 1976 to 2005. For the simulation of natural streamflow over the period 2036–2065, the hydrological model was run with climate input data from each of the 18 climate scenarios described in Sect. 3.2.1. The parameters obtained by calibration over 1981–2009 were kept identical in all simulations.

The dam management model was run with the hydro-climatic and water demand inputs corresponding to each combination of scenarios. Future water use scenarios also include changes in dam management such as the doubling of the Yesa dam's storage capacity, a project currently under way in the Ebro basin. Thus target reservoir levels were changed accordingly in combinations regarding the trend water use sce-

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nario (future uses under past climate and future uses under future climate). Target and minimum levels remained unchanged for the other dams.

3.3.2 Indicators of water demand satisfaction and anthropogenic pressure on water resources

As detailed in Sect. 3.1.2, water shortage was calculated at each demand node and for each type of demand, at a 10-day time step. The satisfaction of urban and agricultural water demand was then characterized by three indicators:

- F: frequency of years with at least one significant deficit at a 10-day time step (> 5 % of UWD or AWD);
- D_{10}: average deficit at a 10-day time step;
- D_{AN}: average annual deficit.

These indicators inform us on the frequency and magnitude of water shortages. D_{10} was calculated by averaging the non-null deficits (i.e. water shortage as a percentage of water demand) computed at a 10-day time step over the whole period. Water shortages were summed for each year and the annual deficit was defined as the percentage of total annual demand that could not be satisfied by available resources. D_{AN} was then calculated by averaging the non-null annual deficits over the whole period. The three indicators were computed separately for urban water demand (UWD) and agricultural water demand (AWD).

For each combination of scenarios the level of anthropogenic pressure on water resources was calculated: the difference between natural and influenced streamflow was calculated at the outlet of each basin at a 10-day time step, and averaged over the 30 year period. The level of anthropogenic pressure was expressed as a percentage of natural streamflow. Finally, influenced monthly streamflow was compared for each combination of scenarios to the monthly environmental flows Q_{OBJ} described in

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Sect. 3.1.1 and the frequency of non-compliance with these monthly environmental flows was calculated.

4 Results

4.1 Hydro-climatic and water demand changes

4.1.1 Projections of hydro-climatic changes for the mid-21st century

Figure 3 shows the changes in temperature, precipitation and natural discharge projected by the nine GCMs and two RCPs for the period 2036–2065 in comparison to the 1976–2005 reference period in the Herault and the Ebro basins. Temperature projections show a clear increasing trend, particularly marked in the summer (up to +4.8 °C in the Herault basin and +4.6 °C in the Ebro basin). Precipitation projections are more uncertain and differ among the 18 scenarios. Annual precipitation changes range from −13 to +7 % in the Herault and from −15 to +5 % in the Ebro basin. Nevertheless, spring and summer precipitation are projected to decrease or slightly increase in both basins; in the already dry months of June, July and August all scenarios project a decrease in precipitation.

These climatic scenarios result in changes in simulated natural discharge: while scenarios diverge in fall, winter and spring, all 18 scenarios result in a decrease in summer low flows, slightly more marked in the Herault (−14 to −57 %) than in the Ebro (−4 to −36 %) basin. In the Ebro basin discharge changes at the beginning of spring (April) are uncertain, with a possible increase in discharge due to increased and earlier snowmelt, while all scenarios lead to a decrease in spring discharge in the Herault basin.

4.1.2 Water demand changes under water use and climate scenarios

In the Herault basin projections of water demand for the mid-21st century are contrasted between the upstream and downstream sections (see Fig. 4a). Although demand is expected to increase in some upstream sections such as Laroque and Lodeve, projected agricultural demand remains low relatively to the downstream sections of Gignac and Agde. Depending on the water use scenario considered, the highest AWD is found in the downstream sections of Gignac or Agde. In the Gignac section the increase in efficiency in the water use trend scenario leads AWD to decrease by 50 % despite a 65 % increase in irrigated areas, whereas AWD in the Agde section doubles in the trend scenario because of a 90 % increase in irrigated areas. In both sections the impact of projected climate change on AWD is comparable to the impact of projected anthropogenic changes (in the most pessimistic climate change scenarios). Note the UWD increase (+57 % or 14.8 hm^3, of which 10.4 hm^3 are linked to an increase in demands outside the basin) in the Agde section, which concentrates 83 % of the basin's UWD in the water use trend scenario. In the upstream sections the impacts of projected climate and anthropogenic changes on agricultural water demand are of the same order of magnitude. In the Saint Laurent and Salagou sections, the water use trend scenario causes a slight decrease in AWD (−15 %); however changing climate conditions have a dominant impact and cause an increase in AWD (up to +40 and +57 % in the Saint Laurent and Salagou sections respectively). UWD is pojected to increase in the upstream sections, from +11 % in the Laroque section to +53 % in the Salagou section.

AWD is projected to increase in all sections of the Ebro basin and in all scenarios, except in the Bardenas, Alto Aragon and Ebro Valley irrigated areas where some of the climate change scenarios lead to a decrease in AWD with current water uses. In the water use trend scenario, irrigated areas are projected to increase in all basins, particularly in the Segre and Lower Ebro areas. In these areas the impact of the trend scenario is stronger than the impact of some scenarios of climate change (see Fig. 4b). In the Bardenas, Aragon y Catalunya, Jalon and Guadalope areas climate change is projected to have as much or more impact on AWD than the changes in water use in the trend scenario. The uncertainty on the impact of climate change on AWD is largest in the Aragon and Catalunya, Segre, Jalon and Guadalope areas; it is lowest in

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the Lower Ebro area. Although AWD stays dominant in all scenarios, UWD and OWD are also projected to increase in all areas in the trend scenario. The highest UWD increases are found in the Aragon and Catalunya (+30 %), Segre (+45 %) and Lower Ebro (+50 %) areas. OWD is projected to double or more in all sections except the Segre and Lower Ebro (from +100 % in Aragon and Catalunya to +185 % in the Ebro Valley).

4.2 Water demand satisfaction under climate and water use scenarios

4.2.1 Water demand satisfaction in the Herault basin

Considering current water uses in the reference climate variability, water shortages appear less than once every five years in all sections of the Herault basin except in the Gignac and Agde areas, where agricultural water shortage occurs two years out of five (Fig. 5a). In the Saint Laurent and Lodeve sections the average restriction on agricultural water demand at a 10-day time step reaches nearly 100 %, while restrictions are less severe in the other sections. The annual deficit is highest in Saint-Laurent and Agde, nearing 20 % of agricultural water demand.

The trend water use scenario in a reference climate only impacts the satisfaction of AWD in the Agde area. Despite a significant decrease in AWD in the Gignac area, the frequency of withdrawal restrictions is not projected to decrease, due to the high UWD increase in the Agde area. Indeed UWD was considered of first priority over AWD and no upstream priority was given to AWD in Gignac over UWD in Agde. Thus if streamflow was insufficient to meet water demand in the downstream sub-basin, agricultural withdrawals upstream were limited.

Considering current water use in climate change scenarios, water demand and availability become out of balance in all sections of the Herault basin. However results are highly dependent on the climate scenario, particularly regarding the frequency of water shortages: depending on the climate scenario, the frequency of agricultural water shortages in the Gignac area reaches three to eight years out of ten. Despite some

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possible high increases in the frequency of water shortages, the average annual deficit are not affected by climate change except in the Gignac area, where the annual agricultural water deficit reaches 30 % under the most pessimistic climate change scenarios.

Finally, results for planned water uses under climate change scenarios show that projected climate change has a higher impact than the water use trend scenario in all sections of the Herault basin. In the sections of Gignac and Agde, the water use trend scenario amplifies the impact of the different climate change scenarios.

4.2.2 Water demand satisfaction in the Ebro basin

In the combination of current water uses and reference climate variability, results show that the Bardenas, Ebro Valley and right bank systems (Jalon and Guadalope) are out of balance, with agricultural water shortages every year and annual deficits of 30 % in the Ebro Valley and Bardenas, and 60 and 70 % in the Jalon and Guadalope areas respectively (see Fig. 5b). Also, shortages at a 10-day time step are higher in the right bank systems. Urban water shortages also appear frequently in these areas.

Combined with current water uses, climate change scenarios induce an increase in the frequency of shortages in the Alto Aragon and Lower Ebro areas for AWD, and in the Bardenas, Ebro valley and right bank systems for UWD. Projected climate change also increases the magnitude of annual deficits except in the Ebro Valley and Lower Ebro. The impacts are most uncertain in the Alto Aragon and Lower Ebro areas. Note that water demand satisfaction in the Segre is not be impacted by climate change if no changes in water uses occur. It is also hardly impacted in the Aragon and Catalunya area.

The water use trend scenario under reference climate variability results in a significant improvement of the balance between water demand and availability in the Bardenas system, for both urban and agricultural water uses. The increase of the Yesa dam's storage capacity is projected to lead to a decrease in the frequency of agricultural water shortages, from every year to three years out of ten. In the already out of balance systems of Guadalope, Jalon, and the Ebro Valley, and in the balanced systems of

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Segre and Aragon and Catalunya the water use scenario has little to no impact on water demand satisfaction. Finally the increase in AWD in the Alto Aragon area and the increase in all types of water demand in the Lower Ebro in the trend scenario induces an increase in the frequency of AWD shortage in Alto Aragon and causes AWD and UWD shortages to appear in the Lower Ebro.

The combination of the water use trend scenario and climate change scenarios lead to significant water shortages in the entire Ebro basin, with marked differences between the areas. The benefits of the dam enlargement in the Bardenas area are partly offset by climate change in some of the scenarios. Thus the range of climate change scenarios tested in this study makes the efficiency of this adaptation strategy quite uncertain. In the Ebro valley and the right bank systems, projected climate change causes an increase in the magnitude of water shortages and an increase in the frequency of urban water shortages. However in these areas the main causes of imbalance seem to reside in the current conditions, water use and climate changes only causing a slight deterioration in already imbalanced systems. In the Lower Ebro and Segre areas the combination of projected water use and climate changes lead to frequent agricultural water shortages in both areas (every year in the Lower Ebro, eight years out of ten in the Segre) and to urban water shortages in the Lower Ebro.

4.3 Anthropogenic pressure on water resources

In the Herault basin simulated anthropogenic pressure on water resources remains low at an annual time step: it increases from 2 to 3 % between the current water use and the trend water use scenario, and it reaches 2 to 3 % under climate change scenarios and 3 to 4 % under a combination of water use trend and climate scenarios. In the combination of current water uses and reference climate, anthropogenic pressure on water resources at the outlet of the Herault basin reaches 20 % of natural streamflow at the end of July (Fig. 6a). Anthropogenic pressure increases and reaches 27 % of natural streamflow at the same period under the water use trend scenario. Under climate change scenarios consumptive use is projected to increase slightly earlier in the year,

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with an earlier and more marked peak than in the reference climate. This peak reaches 25 to 45 % (depending on the climate change scenario) with climate change only, and 30 to 50 % with the water use trend scenario under climate change.

Figure 6b shows the high impact of storage on streamflow in the Ebro basin: the anthropogenic impact is highest in spring and fall, and decreases in summer when water withdrawals are at their highest. This can be due to withdrawals being made mostly in the reservoirs, and to the operation of the Mequinenza, Ribaroja and Flix dams which aims at securing a flow of 100 $m^3 s^{-1}$ for the Ebro delta. This environmental flow constraint also explains the decrease of anthropogenic impact under climate change scenarios: although natural streamflow decreases in the climate change scenarios, the outflow from the dams was kept at a minimum of 100 $m^3 s^{-1}$, thus leaving a larger percentage of natural flow at the outlet. Anthropogenic pressure on water resources reaches 38 % of annual flow under current conditions and increases to 45 % of annual natural streamflow under the water use trend scenario. Climate change scenarios result in an increase in anthropogenic pressure, ranging from 36 to 44 % with current water uses and from 43 to 52 % when combined with the water use trend scenario.

Figure 7 shows that monthly environmental flows Q_{OBJ} are reached more than eight years out of ten in all sub-basins of the Herault and Ebro basins, under current water uses and reference climate variability. However the water use trend scenario causes an increase in the frequency of unsatisfactory years (when influenced streamflow is inferior to environmental objectives) at the outlet of the Ebro basin. Conversely, it improves the respect of environmental flows in the Gignac (Fig. 7a) and Bardenas (Fig. 7b) areas. Climate change scenarios lead to a non-compliance with monthly environmental flows in the Lodeve, Saint-Laurent and Gignac areas of the Herault basin and in all areas except the Cinca and the Segre sub-basins in the Ebro basin. Finally, the combination of the trend water use scenario and climate change scenarios is projected to have a high impact on the compliance with environmental flows in the Ebro at Tortosa.

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5 Discussion and conclusion

5.1 Significance for water management

The purpose of this study was to assess the sustainability of planned water uses under an ensemble of climate change scenarios using a conceptual modeling framework, and to determine the possible causes of unsustainability. The sustainability of water uses was appraised through the risk of imbalance between water availability and demand over the long term (several decades), i.e. the possibility to satisfy demands for human water use while keeping withdrawals and consumptive use at environmentally sustainable levels. The sustainability of planned water uses was assessed by simulating water demand satisfaction and the pressures of water uses on resources considering climate variability over 30 year periods, in water use and climate scenarios. Results showed that objective monthly environmental flows would be guaranteed in current climate conditions in both basins. Yet in several areas this could imply limiting human water uses more than once every five years, which implies a need to adapt water uses to lower water availability, or "doing better with what we have" as suggested by Molle et al. (2010). Moreover the impact of the tested climate projections on both water availability and demand could question the water allocations and environmental constraints currently planned for the coming decades. Indeed, under climate change and water use scenarios water shortages for human use could become more frequent and intense, and the pressure on water resources and aquatic ecosystems could intensify.

In some areas the plans to increase water use, rather than the decrease in availability under climate change scenarios, should cause an imbalance between water use and availability: in four areas of the Ebro basin (Alto Aragon, Aragon and Catalunya, Segre and Lower Ebro), current water uses could be sustainable under climate change scenarios. In these areas if water uses change according to local plans, water demands should be satisfied in current climate conditions. Yet a risk of water stress could appear over a longer term, under a changing climate. However note that it may be harder by then to reduce water demand, than to curb its increase from now on. In other ar-

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eas water stress should be induced mainly by climate change, notably in the Herault basin. Our results showed that the fixed environmental flows could frequently be unsatisfied, even with also frequent limitations of water withdrawals. Facing decreasing natural low flows, the question arises whether regulatory minimum flows can be kept at their current level. Then again, increased consumptive use as shown by simulations under climate change scenarios could further impact ecosystems already perturbed by warmer temperatures, lower flows, and quickly changing conditions.

The comparison of the Herault and Ebro basins shows that the regulated systems on the left bank of the Ebro could be only slightly impacted by climate change, up to a certain level in agricultural water demand, whereas systems with limited streamflow regulation such as the Herault basin should be directly affected by any decrease in summer low flows. Although anthropogenic pressures on resources were shown to be much higher in the Ebro than in the Herault basin, some of the main water uses could remain in balance with water availability. However in the Ebro basin only the large, regulated demand nodes were studied; water stress within each area may be quite heterogeneous, in the same way as the different areas of the Herault basin. Nevertheless both scales of study remain pertinent, since they each match a scale of water management and planning.

In most areas, results were highly dependent on the climate change scenario. Although this may induce some difficulties in the analysis of results, the breadth of uncertainty in future climates must be considered, and characterizing the range of possible climate change scenarios is essential to limit the risk of over-reliance on one uncertain projection and thus the risk of maladaptation (Pielke, 2001; Wilby, 2010). Also, the sensitivity to climate uncertainties was shown to vary between the demand nodes. For example in the Herault basin, the areas of Laroque, Saint-Laurent and Lodeve, which have comparable frequencies of water shortage in reference conditions, exhibited different sensitivities to climate uncertainties (see Fig. 5).

5.2 Contributions of the integrated modeling framework

The integrated modeling framework enabled us to account for many interactions within the two studied hydrosystems. Upstream-downstream interactions were considered through the simulation of water withdrawals, return flows and consumptive use. Interactions between water uses were also accounted for: while water demand in the Ebro is mostly agricultural and thus water shortages are mostly caused by a hydro-climatic deficit, in the Herault basin agricultural water withdrawals can be limited because of the priority given to UWD. In this way the increase in irrigation efficiency in the Gignac area should not lead to an improvement of AWD satisfaction if it occurs concurrently with the increase in UWD of the Agde area, as suggested in the trend water use scenario. Finally by differentiating the impacts of climate change from those of socio-economic and demographic trends, the modeling framework helped assess the cause of the hydrosystems' vulnerability to water stress, which, as underlined by Blöschl and Montanari (2010), is an essential value of climate change impact studies. The identification of the drivers of water stress in basins facing rapid climatic and anthropogenic changes is also at the heart of the challenges put forward in the Panta Rhei hydrological scientific decade of the IAHS (International Association of Hydrological Sciences) (Montanari et al., 2014).

The indicators used in this study to characterize the balance between availability and demand were sensitive to the dynamics of anthropogenic pressures, and should help anticipate undesirable situations, as recommended by Juwana et al. (2012). They enabled us to assess the frequency and magnitude of deficits, and thus helped to qualify the vulnerability of the studied hydrosystems to water stress. The impacts of future changes will indeed be different in areas experiencing more frequent years of shortage of the same magnitudes (see the upstream areas of the Herault basin), than in areas exposed to increased annual deficits (such as the Gignac and Agde areas of the Herault basin or the Alto Aragon area of the Ebro basin) or to shortage events with an increased deficit (such as the Gignac area).

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5.3 Limitations and uncertainties

Although efforts were made to account for uncertainty in future water stress by using a wide range of climate scenarios, the full range of uncertainties was far from being completely covered in this study. Different downscaling techniques, hydrological models (Jiang et al., 2007; Jones et al., 2006, e.g.), or water use scenarios (Purkey et al., 2008; Reynard et al., 2014; Shamir et al., 2015, e.g.) could be used, for example, to cover a wider range of uncertainty. Note that only one water use scenario was compared to many climate change scenarios. However the trend water use scenario should be seen here not as a projection for water managers of what water uses could be at the 2050 horizon, but rather as a quantification (with the expected modeling uncertainties) of water demand associated with the demographic and socio-economic trends that local managers included in their planning documents for the mid-term. Thus the trend water use scenario should be considered as a reference state on which to base the design of adaptation measures.

This prospective study was based on debatable assumptions regarding the stationarity of hydrological processes and of water management, which may be seen as partly unrealistic. Notably, keeping the parameters of the hydrological model obtained by calibration over 1981–2009 in all simulations raises the question of hydrological non-stationarity. The robustness of conceptual hydrological models under changing climatic and anthropogenic drivers is an essential question for impact studies. According to published research, it seems in the range of climate change studied here, hydrological model parameters could be transposable (Coron et al., 2012; Vaze et al., 2010). Moreover, climate projections at the 2050 horizon only accounted for mean monthly changes, due to the downscaling method. Also, note that the water use scenarios were built with constant anthropogenic drivers over 30 years, while simulations over the past 40 years (Fabre et al., 2015) showed that the non-stationarity of anthropogenic forcings was a key element to be considered in hydrological modeling. However one could argue that since the sequence of wet and dry years from the reference period was

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kept in climate projections, it might not make more sense to consider varying population and irrigated areas, considering that the climate variability over the 30 year period is unpredictable. Thus to account for the variability of anthropogenic pressures in future scenarios, it would seem more pertinent to use a large range of stationary water use scenarios and to confront them to different climate scenarios over multi-decadal periods.

Finally, some authors have questioned the use of indicators to assess and predict water stress (Molle and Mollinga, 2003, e.g.), arguing that indicators tend to aggregate reality and even out spatial and temporal heterogeneities. Although the authors concede that indicators calculated at a local level and resulting from a complete study may give accurate information, they argue that the added value of using indicators is unclear. In the present study we used indicators to facilitate the comparison of different scenarios: rather than the absolute values of the indicators in each scenario, it is the changes in their values between different scenarios that counts the most. Nevertheless the question remains of the use of these indicators to represent the vulnerability of hydrosystems to water stress. The indicators used in this paper could in fact be considered as harm indicators, quantifying changes in the frequency and magnitude of water shortage for human use. They do not completely grasp the notion of vulnerability, which, according to Hinkel (2011), cannot be measured. Complementary studies using a bottom-up approach, focusing on social vulnerability and adaptive capacity (Bhave et al., 2014; Burton et al., 2002; Farley et al., 2011; Wilby and Dessai, 2010, e.g.) would be needed to assess the vulnerability of these two river basins to water stress. Indeed different systems may not react in the same way to similar water shortage frequency or intensities. In the Laroque area of the Herault basin, for example, summer low flows are sensitive to climatic variability, with no storage capacity to lessen the pressure of summer withdrawals. Furthermore, aquatic ecosystems in this area are fragile and of high value, therefore environmental flows are of particular interest. However, the local agriculture and thus economic activity is highly dependent on irrigation, and frequent limitations of water withdrawals may question this activity.

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5.4 Prospects

Applying this integrated modelling framework in different combinations of climate and water use scenarios helped to answer the question of the sustainability of water uses under climate- and human-induced changes, and to determine the causes of water shortage risks. This study enables us to approach possible adaptation options to improve the sustainability of water uses for each study area. In the Herault basin, water managers will have to address the satisfaction of UWD, while accounting for interactions between water uses and between upstream and downstream. For instance this study showed that the efforts regarding irrigation efficiency in Gignac would not necessarily induce an increase in the satisfaction of local agricultural demand because of the priority given to the satisfaction of urban water demand further downstream. In the Ebro adaptation will most likely relate to agricultural water demand. Modifying dam management could have an impact on the balance between demand and availability, however caution is needed while considering long term investments, which may not be effective over the long term in non-stationary climate conditions (Hallegatte, 2009). This was well illustrated in this study by the case of the Yesa dam in the Bardenas area of the Ebro basin, where the benefits of the dam enlargement could be partly offset by climate change.

The next step of this work, currently underway, is thus to assess the sensitivity of future changes in water demand satisfaction to variations in the water use scenarios, and to propose scenarios of sustainable changes in water uses, both effective in reducing the gap between water demand and availability and robust to climate uncertainties.

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Table 1. Selected GCMs from the IPCC Data Distribution Center: model name, modeling center, atmospheric resolution and main reference. Source: IPCC (2013).

Model name	Modeling Center (Country)	Atmospheric resolution	Reference
CanESM2	Canadian Centre for Climate Modelling and Analysis (Canada)	1.875° × 1.875°	von Salzen et al. (2013)
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (France)	1.4° × 1.4°	Voldoire et al. (2013)
CSIRO-MK3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence (Australia)	1.875° × 1.875°	Rotstayn et al. (2012)
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory (USA)	2.5° × 2°	Dunne et al. (2012)
HADGEM2-CC	Met Office Hadley Centre (UK)	1.875° × 1.25°	Collins et al. (2011), Martin et al. (2011)
HADGEM2-ES	Met Office Hadley Centre (UK)	1.875° × 1.25°	Collins et al. (2011), Martin et al. (2011)
IPSL-CM5A-MR	Institut Pierre-Simon Laplace (France)	1.25° × 1.25°	Dufresne et al. (2013)
MIROC5	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Japan)	1.40625° × 1.40625°	Watanabe et al. (2010)
MPI-ESM-MR	Max Planck Institute for Meteorology (Germany)	1.8° × 1.875°	Stevens et al. (2013)

Table 2. Main drivers of water demand at the scale of the Herault et and Ebro basins in the current and the trend water use scenarios. NA: Non Applicable.

		Herault			Ebro		
		2000s	2050s	Trend	2000s	2050s	Trend
UWD	Permanent population (inhab.)	350 417	440 651	+39 %	468 675	554 241	+18 %
	Touristic activity			+74 %	NA	NA	NA
	Transfers (inhab. outside the basins)	186 620	234 676	+38 %			+27 %
	Unit allocation (m^3 $inhab.^{-1}$ yr^{-1})	97	117	+21 %	109	111	+4 %
	Network efficiency (%)	75	80	+5 %	NA	NA	+0 %
OWD	Industrial water allocation	NA	NA	NA	NA	NA	+95 %
AWD	Irrigated areas (ha)	4754	8502	+80 %	658 500	961 400	+46 %
	Network and irrigation efficiency (%)	60	75	+22 %	60	65	+9 %

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Table 3. Four combinations of climate and water use scenarios applied in the Herault and the Ebro basins.

Combination	Water uses	Climate	Aim of the assessment
Current uses under past climate	2000s	1976–2005	Sustainability of current water uses under reference climate variability
Current uses under future climate	2000s	2036–2065	Sustainability of current water uses under climate change
Future uses under past climate	2050	1976–2005	Sustainability of planned water uses under reference climate variability
Future uses under future climate	2050	2036–2065	Sustainability of planned water uses under climate change

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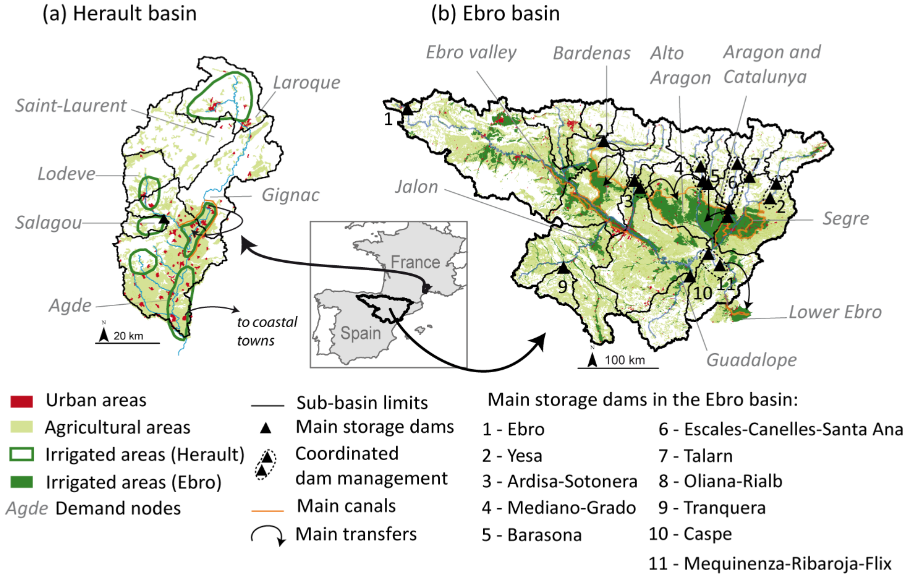

Figure 1. Location, main water uses and water management characteristics of **(a)** the Herault and **(b)** the Ebro basins. In the Herault basin, 6 sub-basins matching 6 demand nodes were defined. In the Ebro basin, 20 sub-basins were selected for the simulation of water resources and 8 demand nodes matching the main irrigation systems were defined.

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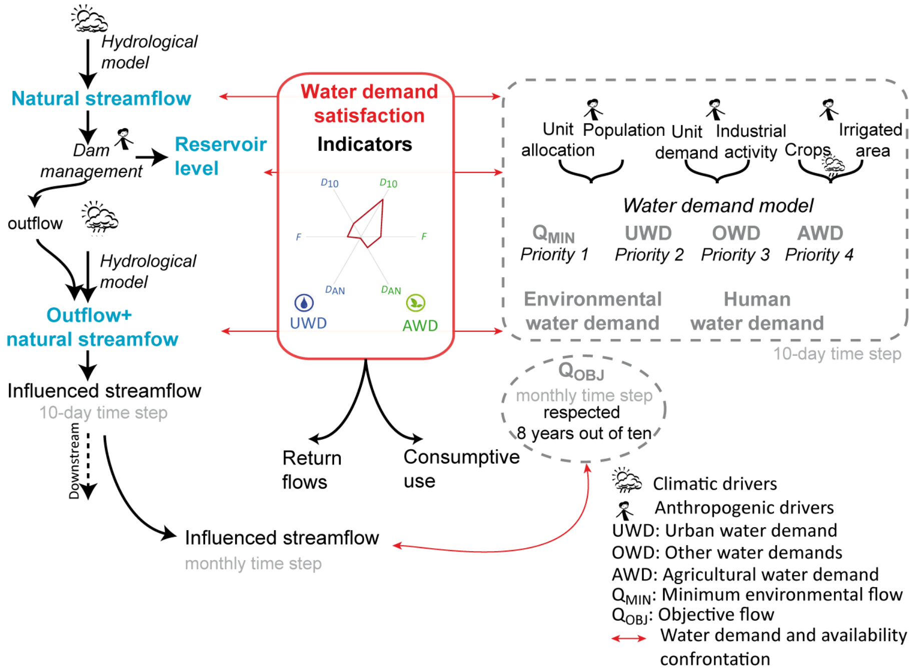

Figure 2. Integrative modelling framework applied at each resource and demand node of the Herault and the Ebro basins. Water demand and natural streamflow were simulated based on climatic and anthropogenic drivers. Anthropogenic influence on streamflow was assessed through the simulation of demand-driven dam management and consumptive use. Water demand satisfaction was assessed by comparing demand to availability.

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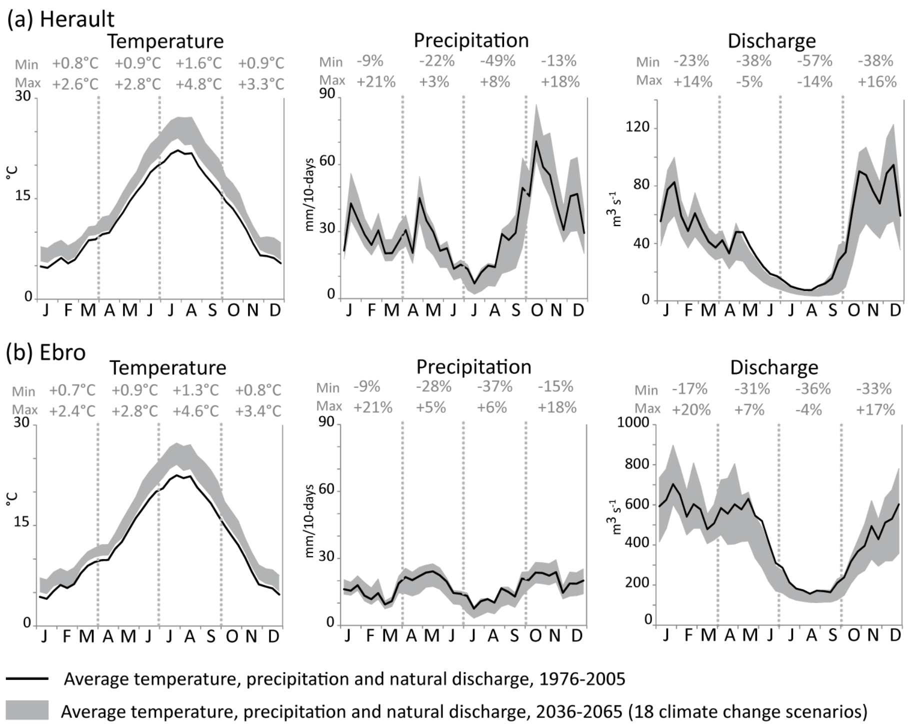

Figure 3. Average temperature, precipitation and natural discharge over the reference period 1976–2005 and under 18 climate change scenarios at the 2050 horizon in **(a)** the Herault and **(b)** the Ebro basins. Natural discharge is simulated with the hydrological model over the reference and future period.

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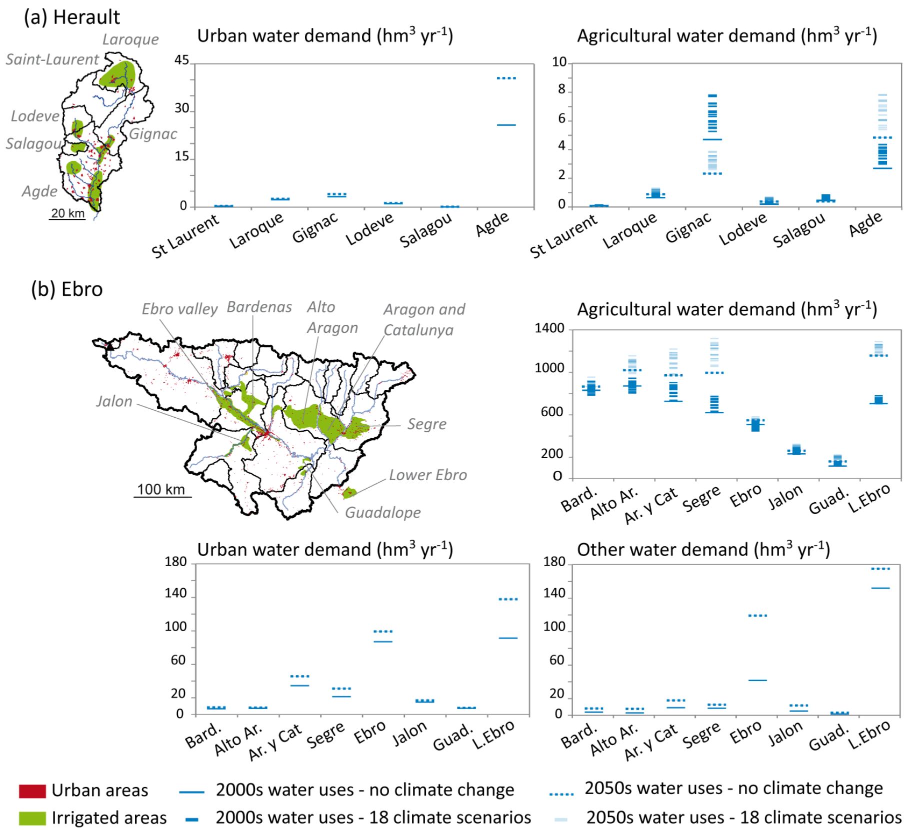

Figure 4. Water demands for human activities in **(a)** the Herault and **(b)** the Ebro basins under four combinations of water use and climate scenarios.

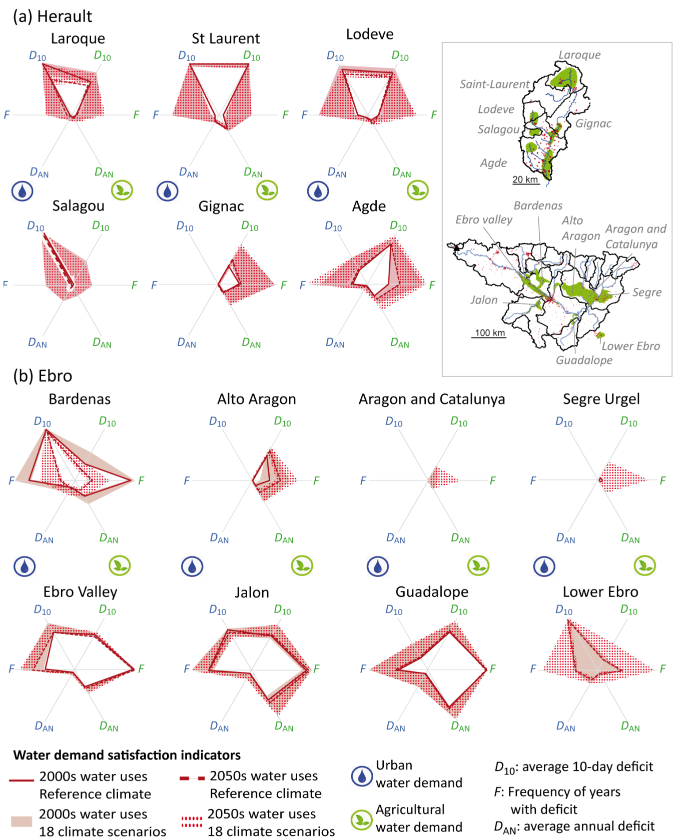

Figure 5. Water demand satisfaction indicators for urban and agricultural water demands in **(a)** the Herault basin and **(b)** the Ebro basin under four combinations of water use and climate scenarios. Each radar chart presents the results for one demand node. For all three indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).

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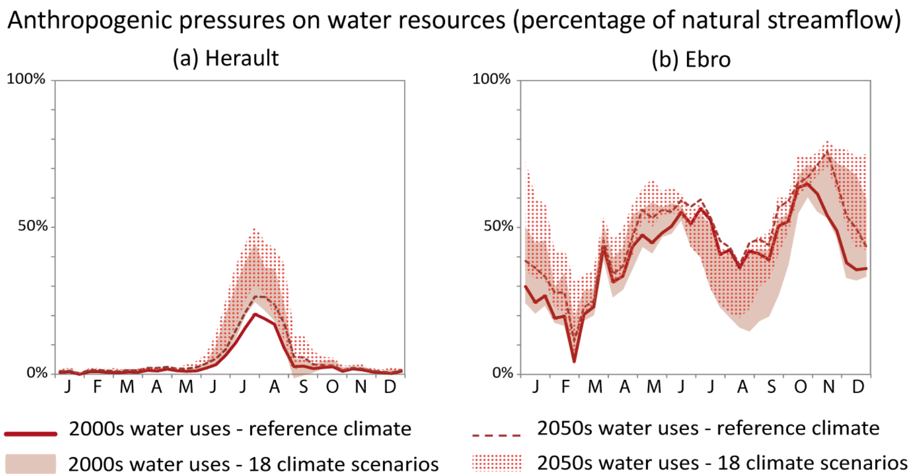

Figure 6. Anthropogenic pressures on water resources under four combinations of climate and water use scenarios in **(a)** the Herault basin and **(b)** the Ebro basin. Anthropogenic pressure is computed through the difference between natural and influenced streamflow at the outlet of each basin, expressed as a percentage of natural streamflow.

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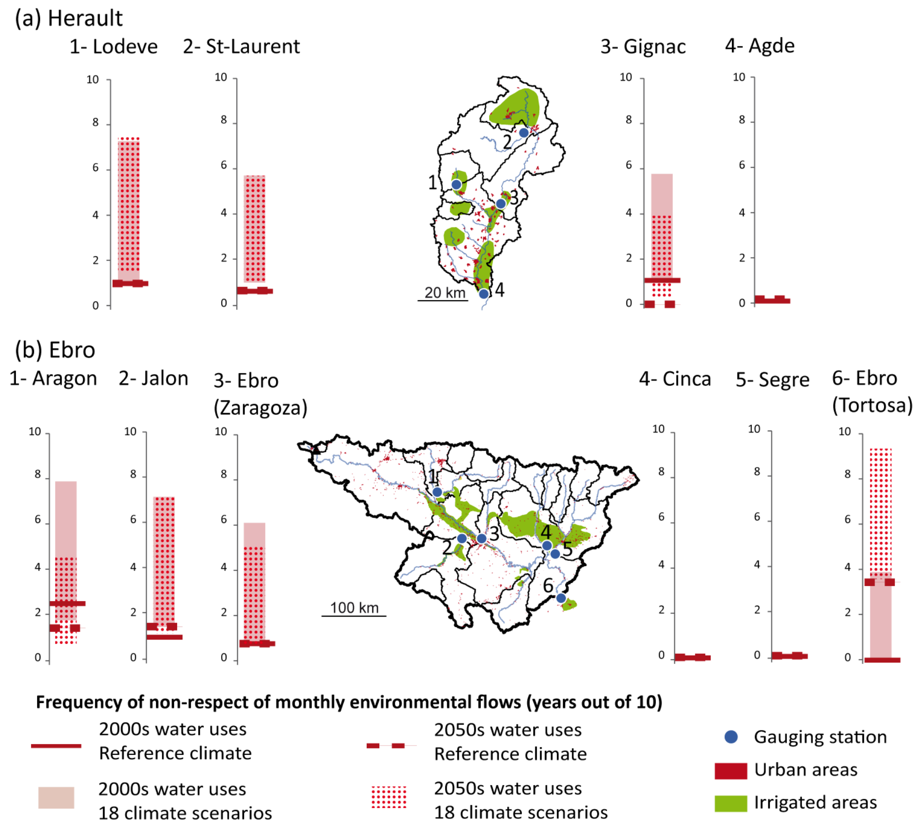

Figure 7. Frequency of years (out of ten) with monthly influenced streamflow inferior to the objective monthly environmental flow Q_{OBJ} in **(a)** the Herault basin and **(b)** the Ebro basin. Frequencies are considered acceptable under two years out of 10.

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