Assessing the long-term evolution of water supply capacity: comparison of two Mediterranean catchments

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Abstract This study aims at defining the main stakes in the development of a generic, multidisciplinary approach to evaluate water supply capacity and its spatial and temporal variability over long time periods. A common modelling framework was applied over two Mediterranean basins with different physical and anthropogenic characteristics: the Ebro (85 000 km^2, Spain) and the Hérault (2500 km^2, France) catchments. Runoff and river flow regulations were simulated using conceptual hydrological models and reservoir management models, respectively. Water demand was estimated from population and unit water consumption data for the domestic sector, and from irrigated area, crop, soil and climatic data for the agricultural sector. A ratio comparing water resource availability to water demand was computed on each catchment. Working on two catchments with different geographical scales and water management issues underlines the challenges in the development of a reliable and generic water allocation assessment method.

Key words integrated modelling; River Ebro; River Hérault; water supply; water demand; water demand satisfaction

INTRODUCTION

In a context of climate change and socio-economic development, water demand has increased. Water supply capacity is essential in the Mediterranean region, which has been identified as one of the most vulnerable regions to water crisis (Alcamo *et al.*, 2007). As a result of climate change, water resources could decrease by 30 to 50% by the 2050 horizon. Combined with increasing water demand, this could lead Mediterranean catchments of Spain and of the southern and eastern rims to face severe water stress (Milano *et al.*, 2012, 2013a). These water supply stakes call for water sharing and efficient allocation between different users, while maintaining sufficient water flows for aquatic and humid environments. Furthermore, projections of hydro-climatic changes encourage water planning with a medium-to-long-term perspective in order to anticipate possible water stress.

Multidisciplinary approaches that simulate water resource developments and demand growth under long-term socio-economic and climatic scenarios are essential to water planning and adaptation to climate change. These approaches can also support decision-making by providing indicators representing water demand satisfaction and its spatial and temporal variability. In order to build realistic scenarios and indicators in line with water policy concerns, it is necessary to link research work on these questions with local management agencies.

This paper investigates these issues by comparing two studies that attempted a representation of water demand satisfaction over long time periods on contrasting Mediterranean catchments: the Ebro (Spain) and the Hérault (France). The aim is to compare the methods and results on both catchments in order to draw prospects for the development of a generic method able to represent the spatial and temporal variability of water demand satisfaction, in areas with varied water management issues.

STUDY AREAS

The Ebro (85 000 km^2, Spain) and the Hérault (2500 km^2, France) catchments differ by their geographical and anthropogenic characteristics. Climatic conditions on the Ebro basin are complex due to the contrasting influences of the Atlantic Ocean and the Mediterranean Sea, and of the various mountain ranges, particularly the Pyrenees. Consequently, hydrological regimes vary from nival (snowmelt) to Mediterranean. The Hérault catchment is characterized by a Mediterranean climate influenced by the Cévennes Mountains.

The Ebro is a large, complex and highly regulated hydro-system with a total of 234 dams, amounting to a storage capacity of 60% of total runoff, whereas five dams with a total storage capacity of 8% of total runoff can be accounted for in the Hérault basin. While water is mostly used for irrigation on the Ebro basin, water demand on the Hérault basin has evolved from mostly agricultural in the 1960s to mostly domestic since the 1990s. Finally, a decrease in runoff has been observed at the outlet of both basins: a statistical break was detected in 1979 on the Ebro (Milano *et al.*, 2013b) and in 1980 on the Hérault (Collet *et al.*, 2013b).

METHOD

A common integrated modelling framework

Both studies relied on information provided by local water management agencies: the *Confederación Hidrográfica del Ebro* (CHE) and the *Syndicat Mixte du Bassin du Fleuve Hérault* (SMBVH). In order to correctly determine the vulnerability of each study area to water shortage, a representation of the spatial distribution of resource *vs* demand was set up. Each basin was divided into portions defining water supply nodes, transporting water to one or more demand nodes. The Ebro and Hérault were divided into nine and six portions, respectively. The division took into account the main geographical and hydro-climatic heterogeneities with the constraint of data availability, while isolating the catchments which contribute most to runoff at the outlet. The main irrigated areas and water demand heterogeneities, as well as the main storage dams (three on the Ebro, one on the Hérault) were also considered (Collet *et al.*, 2013a; Milano *et al.,* 2013b).

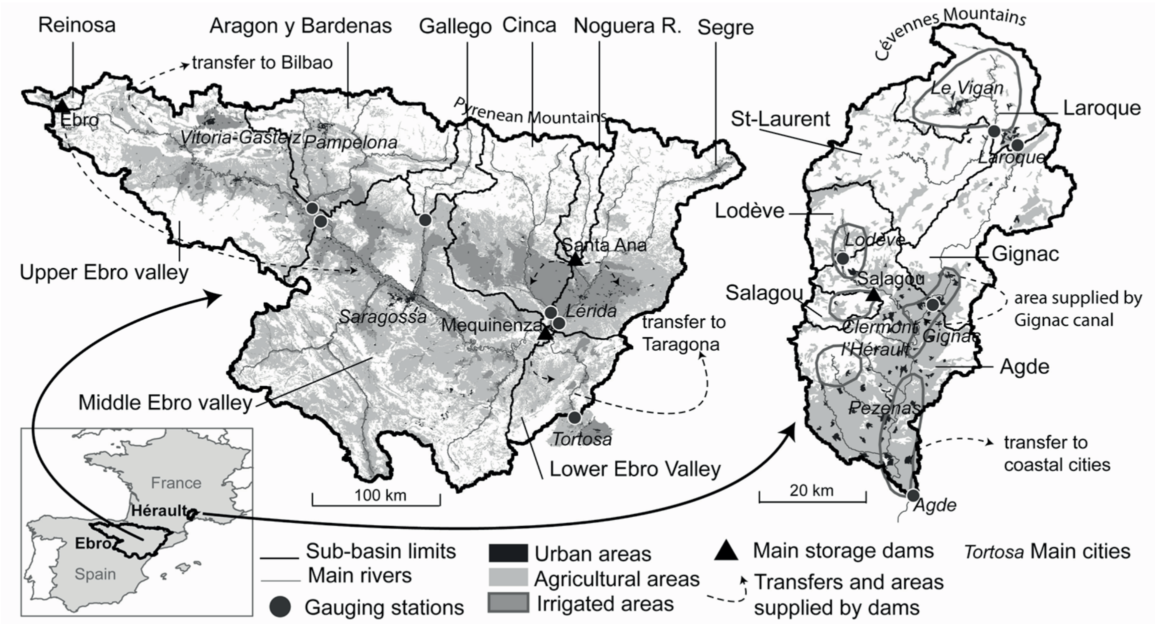

Fig. 1 The Ebro and the Hérault catchments: location of the main human pressures (urban and agricultural areas, main storage dams and water transfers) on water resources.

A common modelling framework relying on the comparison of water resource availability to water demand was applied to both areas. Water resource availability was defined by river flows at the outlet of each studied area, taking into account regulations by storage dams. Water demand was evaluated separately for the domestic and agricultural sectors. A water demand satisfaction rate (WDSR) based on a ratio of water availability to water demand was then computed as an indicator of the potential ability of each portion to satisfy the main water demands. Water supply priority was attributed to domestic demand over agricultural demand on both basins. In order to test the ability of the modelling chain to evaluate spatial and temporal variability of the basins' water supply capacity over the long term, the models were run over 20 years (1971–1990) on the Ebro basin and 50 years (1961–2010) on the Hérault basin. On the Ebro catchment portions WDSR was calculated at a monthly time step and averaged over the 1971–1990 period. Seasonal values were then calculated and results were analysed over the summer. WDSR was calculated at a

10-day time step from 1961 to 2010 on the Hérault catchment portions and analysed as a frequency of years presenting at least one unsatisfactory 10-day period.

Runoff simulation

Two conceptual hydrological models were used to simulate runoff. The GR2M model (Makhlouf & Michel, 1994), which runs at a monthly time step, was adapted to be applied on the Ebro basin (Milano *et al.*, 2013b). On the Hérault basin, the GR4j model (Perrin *et al.*, 2003) was run at a daily time step and calibrated over 10-day periods. Both models were calibrated using multi-objective functions aggregating different goodness-of-fit criteria, including the Nash-Sutcliffe efficiency index (NSE) and the cumulative volume error (VE). The hydrological models rely on precipitation (P) and potential evapotranspiration (PE) inputs. On the Ebro basin, daily temperature and precipitation measurements from 61 and 208 stations, respectively, were interpolated on a 10 × 10 km grid using the inverse distance weighted method. PE was then calculated for each grid cell using a simple formula based on mean temperature and extra-terrestrial radiation (Oudin *et al.*, 2005). Over the Hérault, daily climate forcings were extracted from an 8 × 8 km grid from the Météo France meteorological analysis system, SAFRAN (Quintana Segui *et al.*, 2008). PE was calculated based on the FAO Penman-Monteith formula (Allen *et al.*, 1998). Calibration over the Ebro was based on estimated natural river flows provided by the CHE, whereas observed runoff was used to calibrate the model GR4J over the Hérault catchment.

River flow regulations on the Ebro basin were accounted for through a generic storage-dam management model applied to the three main dams. The model considered reservoir management to be demand-driven. It took into account incoming flows and downstream demands and evaluated outflows depending on the reservoir level and two empirical parameters based on observed management practices over the 1971–1990 period (Milano *et al.*, 2013b). A specific dam management model driven by the reservoir level was set up for the Salagou dam in the Hérault basin (Collet *et al.*, 2013a).

Evaluation of water demands

Domestic water demand (DWD) was considered to depend on population, unit water demand (UWD) and the efficiency of distribution networks. On the Ebro basin it was evaluated at an annual time step for 2007 and distributed at a monthly time step using coefficients provided by the CHE (2011). Monthly DWD calculated for 2007 was applied to the years 1971–1990. On the Hérault, annual variations of population and UWD from 1961 to 2010 were taken into account. As the monthly distribution of DWD was only available for 2007, the same distribution was applied to every year of the period. The monthly DWD series were disaggregated evenly to a 10-day time step.

On both basins, agricultural water demand (AWD) was estimated through water balances based on FAO recommendations (Allen *et al.*, 1998). On the Ebro, an evaluation of crop water needs conducted by the CHE was used to determine unit water needs at each demand node and was multiplied by the irrigated area for 2007. Unit crop water needs were determined by the difference between efficient precipitation and maximum crop evapotranspiration. On the Hérault, an irrigation model based on P, PE, cropping patterns, and soil characteristics was run at a 10-day time step for each portion from 1961 to 2010 (Collet *et al.*, 2013a). On both basins the efficiency of irrigation systems was considered.

RESULTS

Freshwater availability

The performances of both hydrological models are summarized in Table 1. In the Aragón y Bardenas and Ebro valley catchments, runoff dynamics (represented by NSE) and volumes (represented by VE) are correctly reproduced. NSE and VE show acceptable values on the Pyrenean basins of Gallego, Cinca and Segre, and less satisfactory on the two smallest portions, Reinosa and Noguera. In these areas, winter flows tend to be overestimated whereas spring flows

Table1 Hydrological model efficiency and mean annual discharge produced in each catchment portion.

Ebro basin portions (discharge (m^3/s), 1971–1990)	Calibration/Validation NSE	VE (%)	Hérault basin portions (discharge (m^3/s), 1990–2010)	Calibration/Validation NSE	VE (%)
Reinosa (11.6)	0.37/0.48	–17.2/13.1	Saint–Laurent (9.9)	0.89/0.78	0.1/14.8
Upper Ebro Valley (123.3)	0.92/0.92	0.85/–5.0	Laroque (8.7)	0.81/0.71	0.1/–17.2
Aragón y Bardenas (134.3)	0.78/0.80	–7.2/2.2	Gignac (7.6)	0.82/–	0.4/–
Gallego (33)	0.71/0.74	1.4/3.3	Lodève (4.1)	0.84/0.89	0.0/3.3
Middle Ebro valley (37.7)	0.88/0.77	0.16/–1.8	Salagou (1.0)	0.94/–	0.2/–
Noguera (19.2)	0.42/0.14	0.3/7.5	Agde (8.9)	0.37/–	–11.3/–
Cinca (77.2)	0.64/0.60	1.2/12.2			
Segre (92.6)	0.58/0.52	0.2/–1.8			
Lower Ebro valley (7.1)	0.90/0.73	–1.5/–16.2			

are underestimated. On the Hérault, results are very satisfactory for calibration and validation periods, except on the Agde portion, where high flows and low flows are both underestimated.

Concerning the dam management models, dynamics and volumes of outflows from the Mequinenza dam on the Ebro and from the Salagou on the Hérault are well reproduced, with NSE and VE values of 0.89 (0.86) and 0.8% (3%) in Mequinenza (Salagou). The generic model produced less satisfactory results on the Ebro (NSE 0.49, VE 10.3%) and Santa Ana (NSE 0.35, VE 1.2) dams.

Water demand

On the Ebro catchment total water demand amounted to 8857 hm^3/year. DWD is concentrated mostly in the Ebro valley (cities of Saragossa and Tortosa, Fig. 1) and represents 4% of total water demand with a low seasonal variability. AWD amounts to 96% of total water demand and is highly seasonal, reaching a maximum in July. The highest AWDs are located in the Middle and Lower Ebro valley and in the Pyrenean basins of Aragón y Bardenas, Cinca and Segre (Fig. 1).

Total water demand on the Hérault catchment varied from an average of 60 hm^3/year before 1980 to 80 hm^3/year after 1980. This increase is due to a high population growth coupled with a rise in unit demand from the 1990s to the mid-2000s, which led to an increase in DWD on the portions of Saint-Laurent, Lodève and Agde. DWD on the Hérault presents more seasonal variations than on the Ebro, reaching a peak in summer, when the population can triple due to tourism. As for AWD, it has not varied in the Hérault basin (42 hm^3/year before 1980, 40 hm^3/year after 1980). However, it has decreased in the Saint-Laurent and Laroque portions as a consequence of farmland abandonment and in the Gignac portion due to the modernization of irrigation systems, and increased in the Lodève, Salagou and Agde portions with the expansion of irrigated areas. AWD also peaks in the summer, with the highest values in July and no demand in winter.

Water supply capacity

Water demand satisfaction criteria are different in each local water agency; however, in order to compare results on both catchments, WDSR classes from the Hérault were applied on the Ebro. Results are presented in Fig. 2.

On the Ebro basin, DWD is estimated as satisfied in all catchment portions. Moderate WDSR values are found for AWD in the irrigated areas of Aragón y Bardenas, the Middle Ebro valley, the Segre and areas of the Cinca irrigated by the Santa Ana dam, while AWD satisfaction is low on the Cinca portion (Fig. 2(a)). Figure 2(b) shows results for the Hérault catchment portions of Laroque, Gignac and Agde only, as no unsatisfactory year appeared on the other portions. Contrasting trends can be noted within the area: satisfaction of AWD improved in Laroque and Gignac as a result of the decrease in AWD, while it started to deteriorate in the 2000s in Agde (very low WDSR in August, as shown by Fig. 2(c)) consequent to a decrease in water availability combined with a strong increase in water demand. Agde is also the only portion showing DWD satisfaction problems, with WDSRs reaching low to very low levels in the summer (Fig. 2(c)).

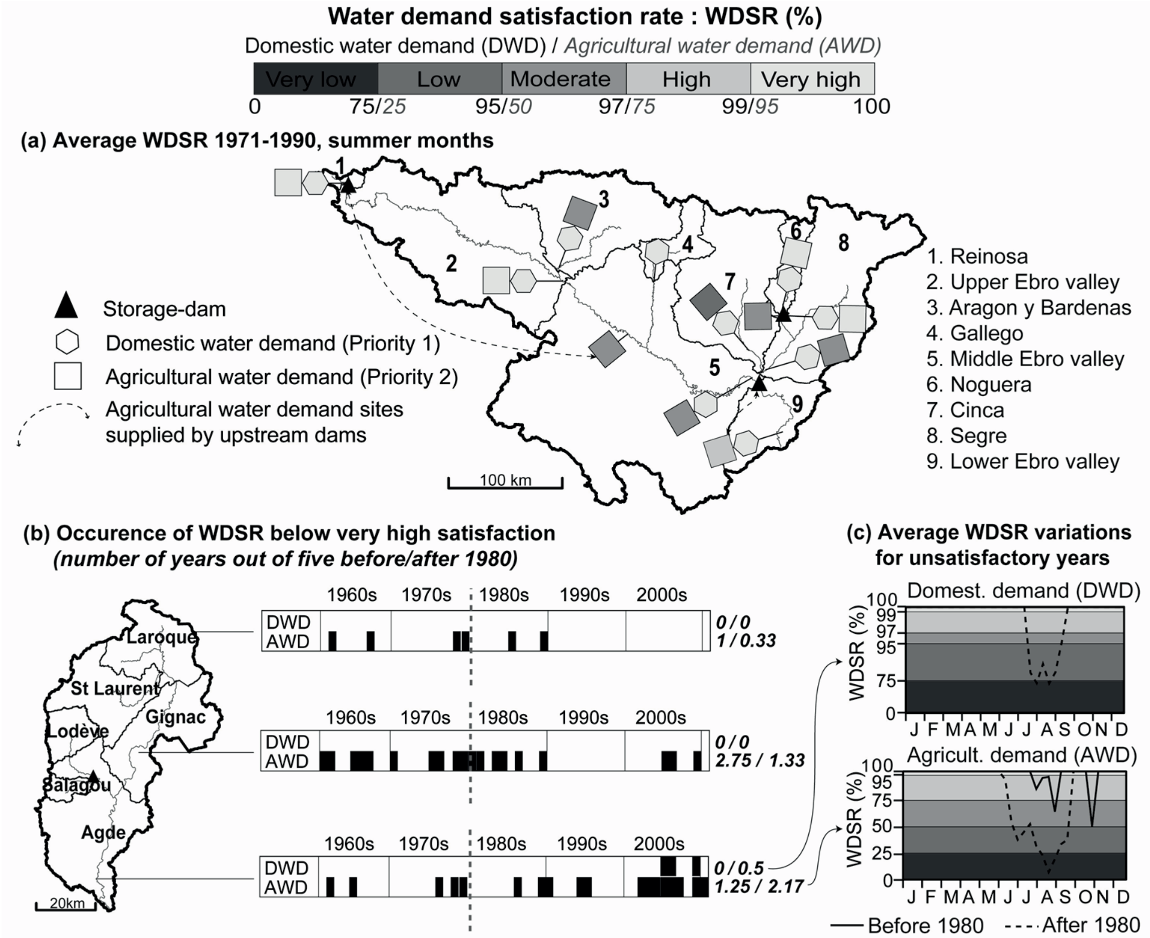

Fig. 2 Water demand satisfaction rates (WDSR) over the Ebro (a) and Hérault (b), (c) basins: (a) mean WDSR for summer months (July, August, September) for 1971–1990; (b) yearly occurrence of WDSR below "very high" for DWD and AWD and frequency of occurrence out of five years, before and after 1980; (c) 10-day WDSR variations, averaged on unsatisfactory years for 1961–1980 and 1981–2010.

CONCLUSIONS AND PROSPECTS

By applying an integrated modelling framework over two Mediterranean basins, their capacity to satisfy the main water demands was evaluated over long time periods. The areas most vulnerable to water stress were found. Schematic views of both basins were presented. Water resources were evaluated by simulating runoff and reservoir levels from climatic variability and dam management rules, and water demand was estimated based on population dynamics and unit consumption for the domestic sector, and on irrigated areas, crop types and climatic variability for agriculture.

Both approaches present limits and should be analysed in view of being sufficiently generic to be applied on various catchments. On the Ebro catchment, the hydrological model's performance was moderately satisfactory in Pyrenean sub-catchments. This is most likely due to the influence of snowmelt on runoff, which could be taken into account by adding a snow reservoir to the hydrological model. Moreover, only the three main dams were considered, limiting the representation of river flow regulations. A division into more portions, taking into account additional dams and hydrological regimes, could come closer to representing the geography of water management on the Ebro basin. Furthermore, inter-annual water demand variations were not evaluated on the Ebro catchment. Finally, a monthly time step does not seem sufficient to grasp resource and demand variability and their evolution under climate change scenarios. A 10-day time step, as applied on the Hérault catchment, seems to be more adapted to highly variable Mediterranean conditions. On the Hérault catchment, the hydrological model performed poorly on the downstream portion of Agde. However, total discharge was correctly simulated, as runoff from upstream portions, contributing to 78% of total discharge, was well evaluated. Another limit in this portion is the lack of evaluation of groundwater contribution to total resource, considering most of the domestic demand is supplied by groundwater.

In view of applying such integrated modelling approaches under climatic and anthropogenic change scenarios, it is essential to test their robustness in varying conditions. The comparison of studies carried out on the Ebro and the Hérault basins opens prospects for the development of a generic approach applicable to different basins. In addition to the limits underlined here above, questions on the method arise: which indicators better translate water supply capacity issues? What is their sensitivity to the different inputs? Can the same methods be applied to basins with different water management stakes and levels of complexity? These questions are the subject of on-going research.

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