Assessing the capacity of water resources to meet current and future water demands over the Ebro catchment (Spain)

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Abstract Since the late 1970s, a negative trend in river discharge has been observed at the outlet of the Ebro catchment (Spain). This can be attributed to a decrease in mean precipitation, a rise in mean temperature, and a water consumption increase. Moreover, over 230 storage-dams were built to regulate river discharge in the basin. An integrated water resource modelling framework was developed to assess whether future water demands could be satisfied under both climatic and anthropogenic changes. This approach confronts water supplies, generated by a conceptual hydrological model and by a storage-dam module, and water demands and environmental flow requirements. Water demands are evaluated for the most water-demanding sectors, i.e. the agricultural and domestic sectors. The capacity of water resources to meet demands is assessed through a water allocation index. Results show growing competition among users, especially during the summer season. They also highlight the interest of integrated modelling with regard to providing complete analysis of water resources' capacity to meet water demands under complex evolution scenarios in order to support decision-making.

Key words Ebro catchment; water supply; water demands; water allocation; storage-dam modelling; integrated modelling

INTRODUCTION

Worldwide studies have shown that the Mediterranean region is one of the areas most vulnerable to water crisis. It is characterised by limited and unequally distributed water resources and highly increasing water demands. By 2050, climate change will most likely contribute to the depletion of freshwater resources in already arid to semi-arid catchments. Furthermore, if domestic and agricultural water demands follow past trends, Mediterranean catchments in Spain and in the Maghreb would have to deal with high to severe water stress (Milano *et al.*, 2012). The Ebro catchment, the third largest Mediterranean basin, is very representative of this context. Since the late 19th century, water resources have been subject to increasing pressures due to expanding irrigated areas and growing population. Many storage-dams have been built to respond to these new water demands, thus regulating streamflows and water allocation (Batalla *et al.*, 2004; López-Moreno *et al.*, 2004). Moreover, significant changes in precipitation and temperature patterns have been observed over the past 50 years (López-Moreno *et al.*, 2010; Milano, 2012). In this context, the question arises whether future water demands can be satisfied over the Ebro catchment if climatic and anthropogenic changes follow these past trends. In this paper, an integrated water resources modelling framework is developed in order to describe the Ebro hydrosystem and evaluate water resources' capacity to meet current and future water demands.

STUDY AREA

The Ebro catchment is the largest basin in Spain: it extends over 85 000 km^2 in the northeast of the country. It is characterised by a Mediterranean valley, which forms a triangular morphological unit, surrounded by mountains including the Pyrenees and Cantabrian range to the north, the Iberian massif to the south, and the coastal Catalan chain to the east. The river system is concentrated around the Ebro, a 910 km-long river flowing from the Cantabrian Mountains to the Mediterranean Sea (Fig. 1(a)). The heterogeneous topography of the catchment as well as the climatic influence of both the Atlantic Ocean and the Mediterranean Sea generate a complex spatial distribution of climate variables (Vicente-Serrano & López-Moreno, 2006). Mean annual precipitation and temperatures vary with altitude, ranging from 1800 mm and 8°C in the Pyrenees to 320 mm and 18°C in the Ebro valley, respectively, on average, over the 1957–2002 period. In various gauging stations, a 20–40% decrease in mean annual discharge has been observed between 1957–1979 and 1980–2002. This can be attributed to a general 12% decrease in mean annual precipitation, a rise of 0.7°C in mean annual temperature, and a water consumption increase. This area is a key element in the Spanish agricultural production with 30% and 60% of the meat and fruit production of the country, respectively. Moreover, population has increased by 20% over the catchment since 1970. Finally, over 230 storage-dams have been built over the Ebro River for hydropower production and irrigation water supply purposes.

MATERIALS AND METHODS

Water allocation assessment

In order to assess the capacity of water resources to meet current and future water demands over the Ebro catchment, a water allocation index (WAI) was computed. It is based on the ratio of seasonal water availability to water demand (Fig. 1(b)). A high index value indicates that water supply is likely to meet demands, whereas lower values indicate poor satisfaction of water demands and likely water stress.

Water resources availability was simulated over long-term climate periods under current (1971–1990) and future (2041–2060; 2050 horizon) conditions. Seasonal water demands were evaluated for the most water-demanding sectors, i.e. the agricultural (8497 Hm^3/year; CHE, 2011) and domestic (358 Hm^3/year) sectors. Environmental flow requirements at each gauging station were also estimated.

In order to account for the different hydro-climatic processes within the catchment, as well as for the main irrigated agricultural sites and river discharge regulations by storage-dams, the Ebro basin was divided into nine sub-catchments to which 11 water demand sites were attributed. The three main dams regulating flows for the most productive agricultural areas were taken into account (Fig. 1(a)).

Water supply priorities and possible supply areas were attributed to each demand site. Environmental flow requirements were defined as having priority of supply over other water use sectors followed by domestic water demands and agricultural water demands. Each demand site is supplied by upstream flows. Finally, 20% and 80% of water withdrawn for agricultural and domestic needs, respectively, were considered to return to the environment.

Freshwater resources modelling

A conceptual hydrological model based on a modified version of the GR2M model (Makhlouf & Michel, 1994) was applied to simulate water availability, defined as the seasonal renewable water resources, or discharge, within each sub-catchment. The model requires monthly precipitation (P) and potential evapotranspiration (PE) input data. It relies on a soil reservoir and a gravity reservoir.

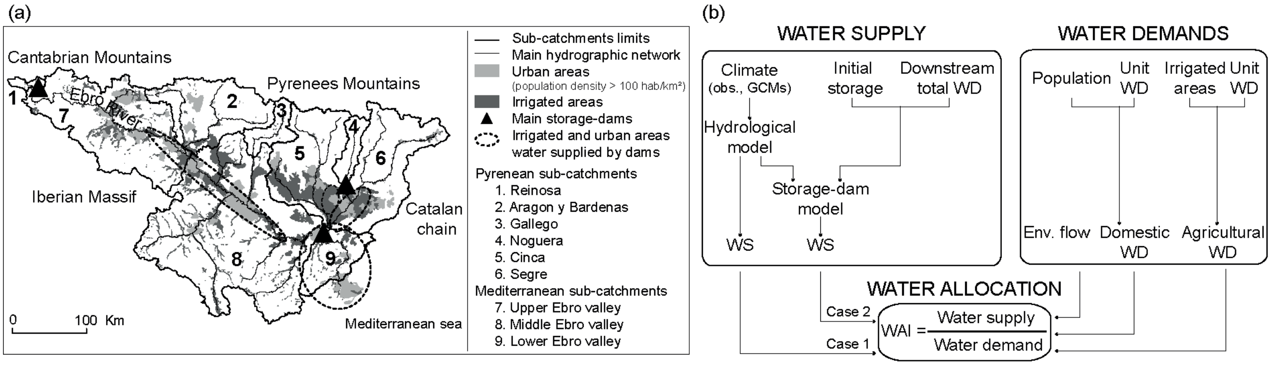


Fig. 1 (a) The Ebro catchment and its main anthropogenic pressures; (b) methodological approach – WD, water demand; WS, water supply; Env., environmental.

It is governed by four parameters. One parameter defines the soil reservoir water holding capacity. The other three regulate P and PE contributions to the change of water level in the soil reservoir and to rapid and delayed runoff. The different runoff sources are summed up to provide estimates of total discharge at the sub-catchment outlet. The model was calibrated and validated against natural discharge data provided by the *Confederación Hidrográfica del Ebro* (CHE; Monreal *et al.,*1999). Simulations were aimed at correctly representing the seasonal dynamics and volume of streamflows. This was done by optimizing two goodness-of-fit criteria: the Nash-Sutcliffe efficiency (NSE; Nash & Sutcliffe, 1970) and the volume error (VE).

Monthly precipitation and temperature series provided by the CHE from 202 and 61 stations, respectively, were interpolated on a 10 km-square grid over the reference period 1971–1990. PE was then computed for each grid cell using a simple formula relying on extraterrestrial radiation and mean temperature (Oudin *et al.*, 2005). Finally, P and PE were spatially aggregated for each sub-catchment. Future climate was based on outputs from two global climate models (GCMs), which were extracted from IPCC's Data Distribution Center: CSIRO-Mk3.0 (CSIRO; Gordon *et al.*, 2002) and CNRM-CM3 (CNRM; Salas-Mélia *et al.*, 2005). These models have often been used over the Mediterranean basin and Milano *et al.* (2013) demonstrated that they simulate similar climate trends and variation rates over this region. Climate scenarios under changing levels of greenhouse gas emissions, specified by the scenarios SRES 20C3M (20th century climate – 350 ppm CO_2) and SRES A2 (2050 horizon climate – CO_2 stabilization at 850 ppm), were generated using the perturbation method (see Ruelland *et al.*, 2012).

A dam management model was created to simulate regulations of river flows. River flow regulations are difficult to represent since dam management guidelines are complex and not always clearly expressed by water managers. The model set up in this study aimed at answering two competing objectives: maintaining a safety water stock in the reservoir while satisfying downstream water demands (Fig. 2). In addition to a physical description of the dam (minimum and maximum exploitation level), the model requires monthly inflows (V_{IN}) and downstream water demands (WD) input data. For each month, the ratio between these two variables is used to drive outflows. If V_{IN} is greater than WDs, a first parameter, $\Delta_{storage}$, is used to evaluate how much more water could be stored in the reservoir with the constraint to meet downstream WDs. If V_{IN} cannot meet downstream WDs, a second parameter, $\Delta_{exploit}$, is mobilized to evaluate how much water can be withdrawn from the reservoir to satisfy WDs maintaining a safety water stock in the reservoir (Fig. 2). Mean monthly values were calculated for each parameter according to the dam management rules observed over the 1971–1990 period. This period represents both dry and wet hydro-climatic conditions. The same general rules were applied to run the model under future climatic and water demand scenarios.

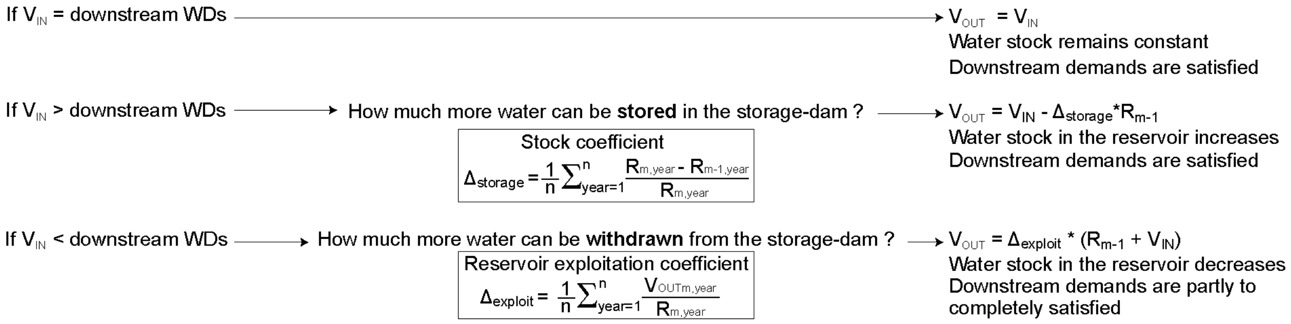


Fig. 2 Conceptual diagram of the storage-dam model – V_{IN}, monthly inflows; WD, water demands; $\Delta_{storage}$, stock coefficient; $\Delta_{exploit}$, reservoir exploitation coefficient; R, water stock in the reservoir; n, number of years; m, considered month; V_{out}, storage-dam outflows.

Current and future water demands evaluation

Water demands were considered as water withdrawn from rivers for domestic purposes and as water needs for irrigated agriculture. Monthly domestic and agricultural water demands were evaluated for each sub-catchment based on an evaluation inquiry done by the CHE in 2007 (CHE, 2011). This inquiry relied on measured domestic water consumption and water losses in each city thus integrating any existing restrictions on water withdrawals. Therefore, our approach will not identify current domestic water stress but will enable highlighting any deterioration in future domestic water allocation. Regarding agricultural water demands, the CHE inquiry was based on an estimation of crops' water needs over large agricultural domains with different geographical location, different water supply sources, and different irrigation techniques. In its prospective study to be published in the next "Ebro Hydrographical Plan report" (PHE; CHE, 2011), the CHE assumed that WDs should only be influenced by population growth and irrigated areas expansion by the year 2027. Unit WD, i.e. water withdrawals per inhabitant or per irrigated hectare, should remain unchanged.

Regarding environmental flow requirements, objectives of the CHE were applied: if the mean inter-annual natural flow at the considered gauging station is greater than 80 m^3/s, then observed runoff must be equal to 5% of the mean inter-annual natural flow whereas if it is lower than 80 m^3/s then observed runoff must be equal to 10% of the mean inter-annual natural flow.

RESULTS

Reliability of the hydrological and storage-dam models

Analysis of the hydrological model efficiency is summarized in Table 1. The dynamics and volumes of simulated runoff in the Pyrenean sub-catchment Aragón y Bardenas and in the Ebro valley are rather accurately represented. NSE values are above 0.73 while VE values never exceed 16.2%, for both calibration and validation phases. Simulations are moderately satisfactory in the Pyrenean sub-catchments of Gallego, Cinca and Segre. They are insufficient in the Reinosa and Noguera sub-catchments with regards to the reproduction of runoff dynamics and volume. In these areas, analysis of seasonal hydrographs shows notably that spring flows are underestimated (not presented here) while autumn and winter flows are overestimated.

With regards to the storage-dam model, the dynamics and volumes of outflows from the Mequinenza dam are very well reproduced (Table 2). In contrast, outflows from the Ebro and Santa Ana dams are poorly simulated with NSE values of 0.49 and 0.35 and VE values of 10.3% and 1.2%, respectively. Outflow volumes are overestimated during autumn and spring and underestimated during winter and summer (not shown). The Santa Ana dam is probably the dam for which water management regulations are the most complex. It regulates flow for three different irrigated areas through different irrigation canals starting at different heights in the reservoir. It is

Table 1 Hydrological model performances in the various sub-catchments.

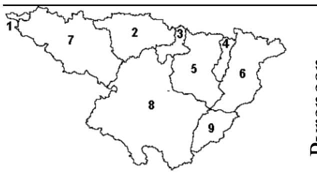
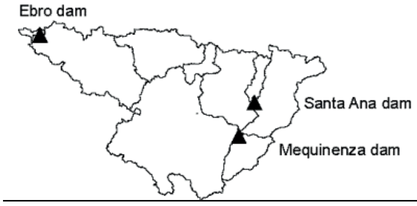
Sub-catchments			Surface area (km^2)	CALIBRATION 1971–1980		VALIDATION 1981–1990	
				NSE	VE (%)	NSE	VE (%)
	Pyrenean	1. Reinosa	466	0.37	17.2	0.48	13.1
		2. Aragón y Bardenas	8470	0.78	–7.2	0.80	2.2
		3. Gallego	2050	0.71	1.4	0.74	3.3
		4. Noguera	1770	0.42	0.3	0.14	7.5
		5. Cinca	9700	0.64	1.3	0.60	12.2
		6. Segre	11270	0.58	0.2	0.52	–1.8
	Medit.	7. Upper Ebro valley	16055	0.92	0.85	0.92	–5.0
		8. Middle Ebro valley	30695	0.88	0.16	0.77	–1.8
		9. Lower Ebro valley	4235	0.90	–1.5	0.73	16.2

Table 2 Storage-dam model performances.

Storage-dams and their geographical position		1971–1990	
		NSE	VE (%)
	Ebro	0.49	10.3
	Mequinenza	0.89	0.8
	Santa Ana	0.35	1.2

also only a few kilometres downstream from the second largest dam of the Ebro catchment that regulates flow for hydroelectric power generation.

Evolution in freshwater availability

According to the analysis of the two selected GCMs' outputs, temperatures are expected to rise by 3°C during summer and by 1.5°C throughout the rest of the year, by the 2050 time horizon. Precipitation should remain at current levels during autumn, winter and summer. Only the precipitation peak in spring should decrease by 15–25%. The combination of increasing temperatures and decreasing precipitation should induce a net decrease in freshwater availability.

In the Pyrenean sub-catchments, water resources should remain near their current level during the autumn and winter seasons. During spring, water resources could decrease by 15–20%. Regarding summer flows, they could decrease by 25–35% according to projections based on CNRM, or increase by 10–15% according to projections by CSIRO.

In the Ebro valley, both models project a decrease in monthly river discharge throughout the year. Projections based on CNRM model are more pessimistic. During the autumn season, both models agree on a decrease of 25–30%. During winter and spring, a 15–20% decrease is projected with CSIRO, while a 30–40% decrease is projected with CNRM. Both models identify the highest decrease in the lower Ebro valley, by 30% according to CSIRO and by 75% according to CNRM. During the summer season, the model CNRM projects a decrease of 40% in the upper valley, 51% in the middle valley and 65% in the lower valley, whereas CSIRO projects, respectively, a 12%, 10% and 22% decrease.

Evolution in water demands

The total WD over the Ebro catchment is close to 9240 Hm^3/year (evaluated in 2007 by the CHE; CHE, 2011). Agricultural water demands (AWD) represent 92% of this amount. The largest AWDs are located in the middle and lower Ebro valley (1660 Hm^3/year and 2750 Hm^3/year, respectively) and in the Pyrenean sub-catchments Cinca, Segre and Aragón y Bardenas (900–1400 Hm^3/year). Domestic WDs represent only 3.8% of the total WD. The highest domestic WDs are in the Ebro valley where population is mostly concentrated (Fig. 1(a)) whereas the lowest are in the Pyrenean sub-catchments, characterized by the lowest population densities.

By the 2050 time horizon, areas with the most important total WD should be the middle and lower Ebro valley (2400 Hm^3/year on average) as well as the Pyrenean sub-catchments Cinca, Segre and Aragón y Bardenas (1400–1800 Hm^3/year). This should be associated with a 30–40% expansion of irrigated areas in these catchments causing an increase of AWD by 25% in the Ebro valley and by 50–60% in the Pyreneans. The Ebro valley should also face a 25–30% increase of its population, proportionally increasing the domestic WD.

Capacity of water resources to meet current and future water demands

Currently, water resources are able to fully meet agricultural and domestic WDs as well as environment flow requirements at each gauging station considered from October to June (Fig. 3).

During the summer season, environmental flows and domestic WDs are met at a very high level, whereas AWDs are highly met. The Cinca sub-catchment is the only one for which AWDs are satisfied only up to 30%. In the medium-term (2050 horizon), domestic WDs and environmental flow requirements could still be met at a very high level all year round. Only AWDs could face some water shortage during the summer season. Considering changes in WDs as estimated by the CHE and hydrological trends projected with CNRM, AWDs in the Pyrenean sub-catchments of Segre and Aragón y Bardenas could be poorly-to-moderately met, while water allocation could be very low in the Cinca sub-catchment (Fig. 3). In the middle and lower Ebro valley, AWDs could be met at a moderate level. In other sub-catchments, water resources should be able to meet AWDs at high to very high levels. Considering hydrological trends as projected with the CSIRO GCM in the largest Pyrenean agricultural areas, water resources could moderately meet AWDs except in the Cinca sub-catchment where the water allocation could be low. In contrast, water resources should highly meet AWDs of the middle and lower Ebro valley and other sub-catchments.

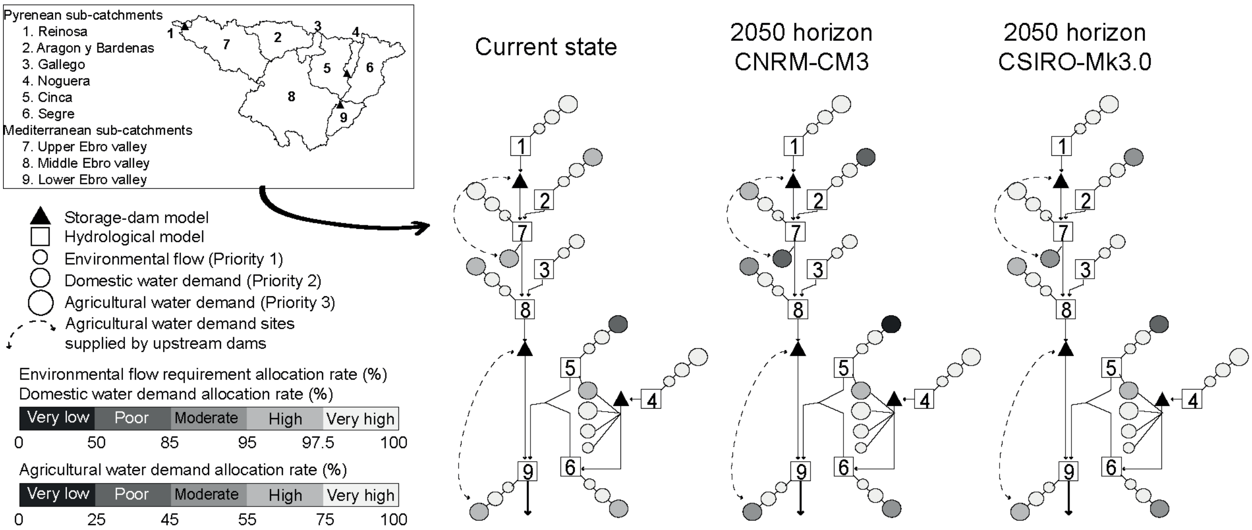


Fig. 3 Water allocation rate over the Ebro catchment during the summer season (June, July and August) over the reference period and by the 2050 horizon, under climatic and anthropogenic changes.

DISCUSSION AND CONCLUSION

In this paper, an original approach combining climatic and water use scenarios and considering water regulations by the main storage-dams was developed. It aimed at presenting a first simplified description of the Ebro's complex hydrosystem and qualifying water resources' capacity to meet current and future water demands under climatic and anthropogenic changes. Results show that current water resources and their regulation management allow water demands to be almost fully satisfied. By the 2050 time horizon, temperatures could increase by 1.5–3°C and precipitation decrease by 15–25% during spring. As a result, water resources could decrease by 10–20% in the Pyrenean sub-catchments and by 25–35% in the Ebro valley. In addition, population is expected to increase (+0.5 million), especially in the Ebro valley, while irrigated areas should expand by 30% mainly in the currently most productive areas. These hydro-climatic and anthropogenic trends could lead to water stress during the summer season. Domestic WDs and environmental flow requirements could still be satisfied but irrigated areas would face water shortages. In the Ebro valley water allocation should be supplied at high level whereas in the Pyrenean the water supply to AWDs will be moderate.

A number of uncertainties influencing the results should however be noted. First, only three dams were taken into account. In the Pyrenees, more than 30 dams have been built to stock snowmelt resources. Water releases are regulated to satisfy AWD during the summer season

(Batalla *et al.*, 2004; López-Moreno *et al.*, 2004). Some of these dams are also connected to irrigation canals flowing down to the Ebro valley irrigation sites. Considering other dams would probably improve water allocation evaluation, notably in the Cinca sub-catchment. Moreover, the storage-dam modelling could be improved. Mean observed rules were applied for water regulation. The associated parameter values could evolve under drier conditions. Hydropower production should also be taken into account to better represent the water stock variations in the reservoirs and thus improve the simulation of outflow volumes. Also, other water use scenarios could be investigated. It was voluntarily chosen in this study to apply the scenario considered by the CHE in its upcoming PHE. However, water use scenarios considering climate change impacts on agricultural water demands could be evaluated, as was already done over the Mediterranean basin (Milano *et al.*, 2012, 2013). This would be a first step towards alternative scenarios exploring crop or irrigation techniques adaptation in order to reduce WDs. Finally, many uncertainties come from future climatic data. Results are influenced by the selected SRES, GCMs and downscaling technique. The SRES-A2 was chosen to study a worst-case scenario. Regarding the GCMs used, Milano *et al.* (2013) showed that they have converging climatic trends over the Mediterranean basin. However, over the Ebro catchment, they seem to have diverging impacts on hydrological regimes during summer months. A range of possible futures is thus presented in this study. Moreover, due to their coarse resolution, GCMs cannot capture fine-sale meteorological processes. The perturbation method was applied to reduce this bias. Ruelland *et al.* (2012) showed that this downscaling method was reliable when estimating seasonal variations or changes in water resources volumes.

The presented framework is a first step towards a more complex description of the Ebro catchment. Despite the possibility to improve it, this method enables us to identify the most vulnerable areas to climatic and/or anthropogenic pressures as well as sectors and periods of time during which water shortages might occur. Moreover, it supports developing adaptation strategies in collaboration with local stakeholders and water managers in order to reduce water tensions and improve water allocation.

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