Assessing past and future water demands under climate change and anthropogenic pressures on two Mediterranean basins

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Abstract The Ebro (Spain) and the Hérault (France) are contrasting catchments representative of the Mediterranean context. Simultaneous increases of population, irrigated areas and industrial development observed in the recent past associated with future climate change indicators shows the necessity of considering the capacity of these catchments to satisfy water demand. This evaluation requires knowledge of the spatiotemporal dynamics of water demands and their main drivers. This paper thus presents a conceptual modelling framework to estimate water demand and its evolution. The Ebro basin is dominated by agricultural water demand, which has been increasing, mostly due to the expansion of irrigated areas. In the Hérault basin, domestic demand has greatly increased since the 1970s. Future water demand was assessed by the 2050 horizon under climatic and socio-economic scenarios. Results show that water demand should keep increasing notably for irrigation requirements. This work was a first step to analyse the capacity of each hydro-system to satisfy current and future water demands.

Key words water demand; climate change impacts; anthropogenic pressure; River Ebro; River Hérault

INTRODUCTION

In the future, the increasing consequences of climate change will impact our environment and modify our water use (IPCC, 2007). In the meantime, demographic growth will lead to an increase in anthropogenic pressures such as agriculture, industry, energy and tourism. Under such constraints, the question of water demand evolution becomes crucial. In response to this critical question, it is necessary to develop approaches to assess water demand on hydro-systems at the management scale. Current studies mainly consider separate components of water demand (e.g. Salvador *et al.*, 2011) and limited time periods and/or geographical areas (Kolokytha *et al.*, 2002).

This study aims at associating environmental variables and socio-economic data such as population, crops, industries, with their standardized spatiotemporal variability in order to provide an historical estimation of water demand at the management scale. It presents a conceptualization of the issue through a modelling framework that makes it possible to represent past water demand on two catchments over a 30-year period, and to forecast its possible evolution by the 2050 horizon under the constraints of climatic and anthropogenic scenarios.

STUDY AREA

The Mediterranean region has been identified as highly vulnerable to water crisis (Fig. 1(c), Milano *et al.*, 2013a). In addition to being a hot-spot for climate change, this area should face increasing anthropogenic pressures due to demographic, agricultural and industrial developments. The Ebro (85 000 km^2, Spain) and the Hérault (2500 km^2, France) catchments fit this context, even if they differ with regards to human pressures on water resources. While agriculture accounts for 88% of total water volume used in the Ebro basin (Fig. 1(a)), water demand is now mainly dominated by domestic needs (60%) in the Hérault basin (Fig. 1(b)).

The Ebro catchment is boarded on the North by the Pyrenean and Cantabrian ranges, which contribute to 56% of basin runoff (Lopez-Moreno *et al.*, 2010, Milano *et al.*, 2013b). It has a semi-arid plain rich in irrigated areas (700 000 ha) supplied by a network of canals and storage-dams. Except in a few highly urbanized areas, population density is mostly below 50 inhab/km^2.

The Hérault basin is characterized by a high population density, notably in its downstream parts, which can double in summer as a result of tourism. The Florensac transfer supplies water (22 hm^3/year) to towns located outside the basin, and represents more than 50% of water withdrawn for domestic purposes. Irrigated areas are mostly located in the South due to an agricultural decline in the North since the 1970s. Vineyards cover 54% of the agricultural areas, with a continuingly increasing irrigation rate.

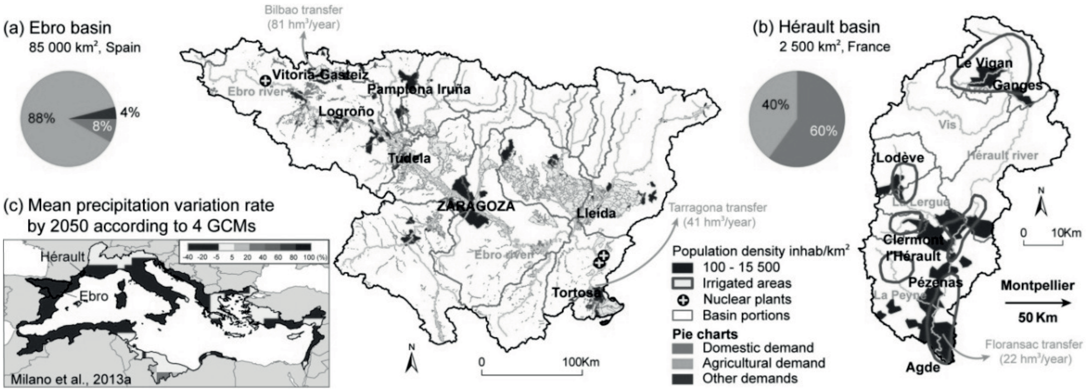

Fig. 1 Main anthropogenic pressures and water demands on the Ebro and Hérault catchments.

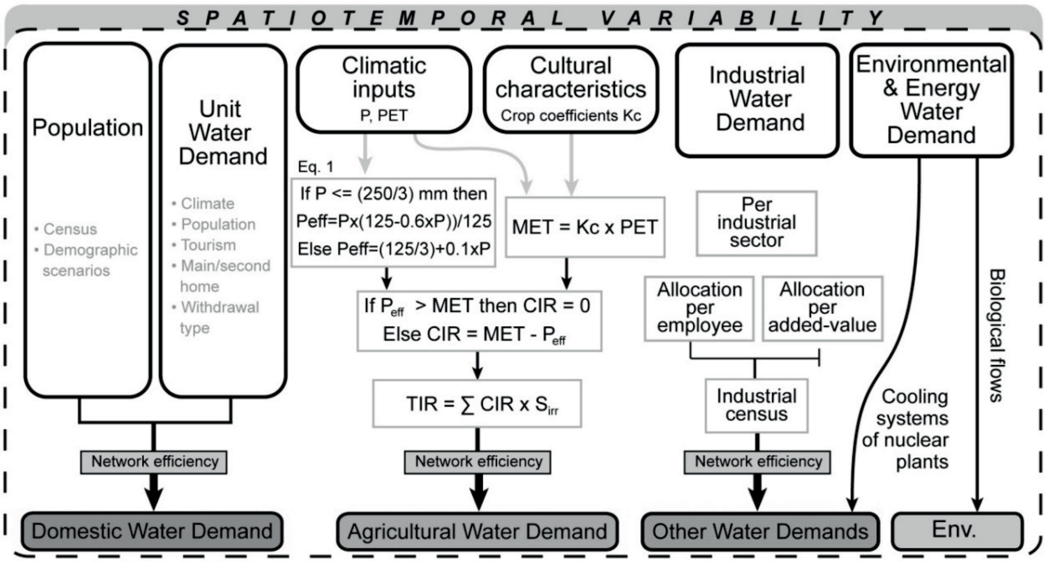

Fig. 2 Methodology for assessing water demands. P: precipitation, PET: potential evapotranspiration, P_{eff}: effective precipitation, MET: maximum crop evapotranspiration, CIR: crop irrigation requirement, TIR: total irrigation requirement, S_{irr}: irrigated areas, Env.: Environmental demand.

WATER DEMAND ASSESSMENT METHOD

Water demand can be divided into three main components: Domestic Water Demand (DWD), Agricultural Water Demand (AWD) and Other Water Demand (OWD), including industrial and energy demands. Environmental demand corresponds to the minimum flow necessary to maintain functioning ecosystems and must be compared to river flows. The evolution of each component was evaluated from key-variables in a conceptual modelling framework that aimed at representing their spatiotemporal dynamics over 30-year periods (1969–1998 and 2036–2065) on both catchments (Fig. 2). The future evolution of each component of water demand was assessed according to demographic, water use and farm practice scenarios by the 2050 horizon. The impact of possible climate change was considered on agricultural demand only. To take into account the spatial variability of water demands, the Ebro and Hérault catchments were divided into 16 and 6 portions, respectively, according to hydrological and management criteria.

Domestic water demand

The evolution of domestic water demand was assessed by multiplying population by unit water demand (UWD, in m^3/inhab/year) at the scale of each municipality, and considering the domestic network efficiency. Population dynamics were evaluated by extrapolations of data from national population census and projections (INE in Spain and INSEE in France).

On the Ebro basin, an average UWD of 106 m^3/inhab/year with an increase rate of 0.14% per year was used on the reference period. This UWD was estimated by the *Confederación Hidrográfica del Ebro* (CHE) using past water withdrawals and population data. A linear interpolation of the INE population projections provided a 27% mean increase between the reference period and 2050; furthermore, the CHE projections plan a 16% increase of UWD by 2050. Also, Bilbao and Tarragona transfers extracted 122 hm^3/year on average over the reference period (Fig. 1(a)); this volume should increase by 10%. Network efficiency for domestic water was considered on each basin portion with a mean value of 80% on past and future periods.

On the Hérault basin, a stable UWD of 74 m^3/inhab/year was considered on the reference period. This value was evaluated in a local study (Neverre, 2011) using specific drivers (Fig. 2). UWD is projected to decrease by 18% in 2050 as a result of water saving policies. Seasonal population variations due to tourism were taken into account for each portion separately and considering the Florensac transfer. INSEE demographic projections expect a resident/tourist population increase of 75% by 2050. A rise of the transfer should be added due to the new municipalities connected in the 1990–2000s and future population growth. Network efficiency values varied geographically between 51 and 75% over past and future periods.

Agricultural water demand

Agricultural water demand was simulated (Fig. 2) at a 10-day time step considering crop irrigation requirements based on climate forcings (P, PET) and crop characteristics (crop coefficients, phenology, harvesting dates). Maximum crop evapotranspiration (MET) was calculated by multiplying crop coefficient K_C to evapotranspiration PET. Effective precipitation was assessed using equation (1) (Fig. 2), developed by USDA Natural Resources Conservation Service and recommended by the FAO (Allen *et al.*, 1998). MET represents the water necessary for the crop's optimal growth. Additional crop water needs (CIR) were evaluated by subtracting P_{eff} to MET if $P_{eff} < MET$. They were calculated by crop for each municipality. Considering irrigated areas, the theoretical need for irrigation (TIR – Fig. 2) was obtained at the municipality scale and aggregated per basin portion. Water demand per municipality was attributed to the portion providing water supply to the given municipality, considering inter-basin transfers by canals.

On the Ebro basin, wind, humidity, and solar radiation data were unavailable, thus a simple formula relying on extra-terrestrial radiation and mean temperature (Oudin *et al.*, 2005) was used to assess PET. Crop coefficients and calendars were estimated locally by the CHE according to the FAO methodology (Allen *et al.*, 1998). In the absence of more precise information, the basin variation rate of irrigated areas over the reference period and by 2050 (+91%) was applied to each municipality. Irrigation network efficiency was fixed globally at 60%.

On the Hérault basin, a FAO Penman-Monteith PET was calculated (Collet *et al.*, 2013) using climatic data from the Météo France meteorological analysis system SAFRAN. Crop coefficients and calendars came from the FAO (Allen *et al.*, 1998) for Mediterranean climate. Irrigation network efficiency was considered stable on both periods and varied per portion between 40% and 80%. The basin manager expects a 25% increase of irrigated areas by 2050.

In order to consider the impact of possible climate change on agricultural water demand, a mean climatic scenario was computed from four Global Climate Models (CSMK3, HadCM3, CNCM3 and ECHAM5) provided by the IPCC (2007) under a SRES-A2 scenario and using a perturbation method described in Ruelland *et al.* (2012). Future agricultural water demand was assessed on both basins, considering this climate change scenario and evolutions in irrigated areas. In the absence of relevant data, the same crop distribution, agricultural calendar and network efficiency were considered between past and future periods on both basins.

Other water demands

Industrial water demand, ignored on the Hérault basin due to a reduced industrial sector, was estimated on the Ebro basin according to a municipal census from 2007, water allocation per employee and added-value of manufactured products (Fig. 2). An extrapolation of CHE industrial projections between 2007 and 2027 was applied to define a trend on the reference period. Water demand related to hydroelectric plants was ignored on both study areas since the water withdrawn returns entirely to the environment. On the Ebro, water demand from the energy sector is related to the presence of three nuclear plants (Fig. 1(a)) with minimum flows and cumulated evaporation currently around 122 hm^3/year. Linear extrapolations of CHE projections led to an increase of 400% of industrial water demand between the reference period and the 2050 horizon.

WATER DEMANDS: PAST AND FUTURE TRENDS

Water demand on the reference period

On the Ebro basin, annual domestic water demand increased at a 0.2% rate since 1969 to reach 451 hm^3 in 1998 (329 hm^3 to internal basin population, 122 hm^3 to external transfers). The distribution of population density over the basin with highly urbanized areas induces a heterogeneity of domestic water demand reaching its highest level in 1998 in the Logroño-Vitoria, Tudela, Zaragoza, Lleida and Tortosa portions (from 35 to 72 hm^3), and no more than 15 hm^3/year in the other ones. Agricultural water demand reached 4665 hm^3 in 1998 on the whole basin, representing 88% of total water demand, with an average of 4088 hm^3/year in the reference period (Table 1). It increased nonlinearly around 2% per year over 1969–1998 due to: (a) a mean decrease of precipitation of 1% per year; (b) a mean increase of PET of 0.2% per year; and (c) the expansion of irrigated areas from 621 000 ha to 700 000 ha, notably on the central plains and some Pyrenean portions (Fig. 3). Other water demands are mainly represented by industrial demand that increased by 3% per year on average to reach 220 hm^3 in 1998. Since the nuclear plants started operating (in 1982), energy demand has represented 122 hm^3/year.

In the Hérault basin, domestic water demand increased at a 5% rate since the 1980s to reach 38 hm^3 in 1998, i.e. 60% of total water demand. Seasonal population, mainly in the downstream parts, doubles the demand in summer, with a peak in June. In 1998, the Florensac transfer (18 hm^3) represented 40% of domestic water demand of the basin. Agricultural water demand has decreased nonlinearly at a mean rate of 1.1% from 22 hm^3/year in 1969 to 14 hm^3/year in 1998, due to agricultural decline generalized over the basin until the 2000s. Water demand is higher in the southern portions.

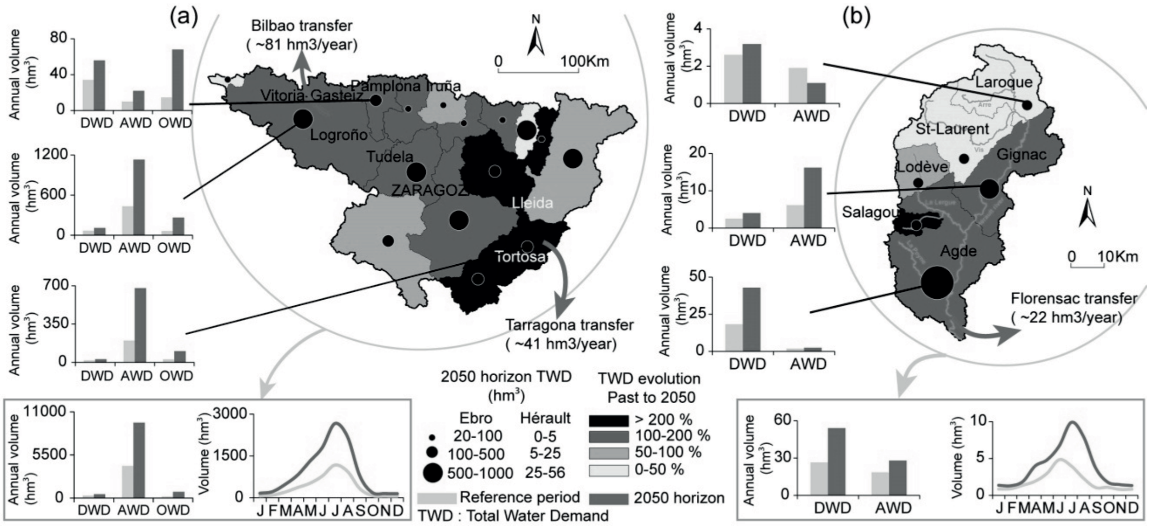

Fig. 3 Water demand evolution by 2050 over (a) the Ebro catchment and (b) the Hérault catchment.

Water demand by the 2050 horizon

At the scale of the whole Ebro basin, water demand should increase on all portions, especially around irrigated areas that are expected to expand in the future (Fig. 3(a)). Evolution of total water demands between past and future periods should vary from +44% to +265% in the 16 portions.

Analysis of the seasonal variations in water demand at a monthly time step shows a seasonal peak in summer according to the same dynamics as in the reference period (Fig. 3(a)). Domestic demand should increase by 41% (Table 1) to reach 624 hm^3/year as a result of population growth (+27%) and UWD evolution (+17%). It should increase from 2 to 84% depending on the portions. In some highly populated portions, such as Pamplona-Iruña (Fig. 3(a)), DWD should double. Agricultural demand is projected to increase by 135% due to irrigated area expansions (+91%), a decrease of mean annual precipitation by 11% and an increase of mean annual PET around 11%. In the Vitoria-Logroño portion (Fig. 3(a)), irrigation needs could increase by 260%, reaching 1100 hm^3/year. In the Tortosa portion, rice farming particularly impacts water demand (18 000 ha in 2004). This crop requires water not only for evapotranspiration, but also to offset losses by percolation in flooded rice fields. By 2050, this demand should triple, reaching 700 hm^3/year. Other water demands, mainly driven by industrial demand, should continue to increase by 357% to reach 791 hm^3/year and overtake domestic water demand.

On the Hérault basin (Fig. 3(b)), an 82% increase in total water demand is projected by 2050 according to the chosen scenarios. Our estimates reproduce the predominance of domestic water demand, especially in the downstream portion that is strongly influenced by the Florensac transfer (7 hm^3/year on average over the reference period, 26 hm^3/year by 2050). Analysis of the seasonal variations in total water demand (Fig. 3(b)) shows a seasonal peak centred on June for the past period, and mostly centred on summer months by 2050, which can be explained by a 25% decrease of precipitation in July–August by 2050. Despite a significant decrease in UWD (18%), domestic demand is projected to double reaching 54 hm^3/year by 2050 as a result of population growth inside and outside the basin. Outside transfers should then represent 48% of the domestic demand. Agricultural demand should increase by 56% due to expansion of irrigated areas (+1700 ha), a 6% decrease of annual precipitation (average of four GCMs) and a 12% increase of mean annual PET. However, agricultural demand in the upstream portions should decrease by 32% due to the agricultural decline already observed in the Cévennes Mountains near Laroque.

Table 1 Key-variables and water demand over both catchments: average over 1969–1998 and evolution by the 2050 horizon under the constraints of climatic and anthropogenic scenarios.

	Units	Ebro		Hérault	
		Average on 1969–1998	Evolution by 2050	Average on 1969–1998	Evolution by 2050
Population (+ tourism)	hab	2 958 375	+27%	170 972	+75%
Unit water demand	m^3/hab/year	128	+17%	74	–18%
Domestic water demand	hm^3/year	443	+41%	27	+100%
Irrigated areas	ha	666 106	+91%	4191	+41%
Precipitation	mm/year	573	–11%	1077	–8%
Evapotranspiration	mm/year	832	+11%	845	+12%
Agricultural water demand	hm^3/year	4088	+135%	18	+56%
Other water demands	hm^3/year	173	+357%	0	0%
Total water demand	hm^3/year	4 703	+134%	45	+82%

CONCLUSIONS AND PROSPECTS

This study investigated an approach for evaluating the different components of water demand and its spatiotemporal evolution over two Mediterranean basins. First applied over a historical 30-year period (1969–1998), this approach made it possible to forecast the evolution of water demand by 2050 under the constraints of climatic and anthropogenic scenarios. It brings forward the complexity of combining physical and socio-economic variables, which requires many upscaling/downscaling operations to match and communicate. Assessing past water demand over the Ebro and Hérault basins showed the increasing pressure of human activities on water resources. Under a 2050 baseline scenario, considering socio-economic trends and projected climate change from four GCMs, water demand could increase by +134% and +82% on the Ebro and Hérault catchments, respectively, which should significantly increase tensions in water use.

A major difficulty in assessing water demand refers to the lack of observations to validate estimations. If water withdrawal data are now becoming more easily available (e.g. meters increasingly installed) and can provide a helpful approximate for withdrawn volumes, their frequency in space and time is too sparse to rigorously validate the spatiotemporal dynamic of water demand. This type of data also leads to semantic issues. For example, volumes can refer to water consumption, withdrawal or allocation. As a result, estimating the evolution of water demand relies on assumptions and methodological choices (spatial upscaling/downscaling, temporal interpolation, loss rates, volume returned to environment), which generate many uncertainties of unknown magnitude. Moreover, combining climatic and anthropogenic scenarios raises questions about the relative impact of each one on water demand evaluation: what is the specific impact of precipitation decrease and/or temperature rise on future water demand? Is the domestic water demand more sensitive to population or UWD variations?

Answering these questions is essential in order to test adaptation strategies aimed at reducing water demand in the future. However, even if water demand can be limited through alternative scenarios, it will be necessary to compare water supply and demand, including environmental demand. This work constituted a first step for a larger research project that aims at analysing the capacity of each hydro-system to satisfy current and future water needs by using indicators confronting water supply and water demands.

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