Assessing the impacts of global changes on the water resources of the Mediterranean basin

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Abstract The Mediterranean basin is characterized by limited and unequally distributed water resources, as well as by important development of its anthropogenic activities. The latter has led to continuously increasing water withdrawals. Moreover, the region should be particularly affected by climate change, with rising temperatures and more frequent and intense drought periods affecting water resources availability. This paper assesses the impacts of those changes by investigating the current and future situation of both water availability and water withdrawals. Over the reference period (1971–1990), a conceptual rainfall–runoff gridded model was applied to evaluate freshwater availability, and an overview of agricultural and domestic water use was completed according to national reports. To evaluate the future trends in water availability at short (2025) and mid (2050) terms, climatic scenarios were generated by applying unbias and delta methods to projections from four global climate models. These climatic scenarios were used as inputs to the hydrological model but also to an irrigation management model to evaluate future agricultural water withdrawals. Domestic water use was estimated using demographic scenarios. For both sectors, progress in water-use efficiency was also considered. A water stress index accounting for those various indicators was then computed. The results show that both climate and socio-economic changes will have a significant impact on water resources. The Mediterranean basin might be subjected to a more arid climate and increasing local disparities. Some areas might experience increasing water stress. This study is a first step towards providing indicators combining water resources availability and water use in line with planning decisions at a regional level.

Key words Mediterranean basin; water availability; water withdrawals; water stress index; water balance model; CROPWAT; scenarios

INTRODUCTION

For the past 20 years, climatic and socio-economic changes have been at the heart of the world's science and policy agenda. One fundamental concern is the impacts of these changes on water resources. An increase in temperature of 2°C by the 2050s could modify rainfall distribution over both space and time and could engender a decrease in water resources availability and weaken their exploitability in tropical and Mediterranean areas (IPCC, 2007). To illustrate the evolution of water resources throughout the world, several authors (e.g. Oki *et al.*, 2001; Alcamo *et al.*, 2007; Menzel & Matovelle, 2010) have analysed the impacts of climate change, population growth and water withdrawals on water availability for the 21st century. The results showed that the Mediterranean region is one of the most vulnerable regions in the world. Building on these studies, this paper analyses the evolution of water stress over the Mediterranean basin, using a more detailed approach. It evaluates climate change impacts on both water availability and water demands. It also quantifies the trends in water withdrawals and water-use efficiency for the main water demanding sectors in the basin.

STUDY AREA

The Mediterranean basin is defined by 73 groups of watersheds (Nile excluded) that have their outlets in the Mediterranean Sea. It represents an area of approximately 1 800 000 km^2, in which only 21 catchments exceed 10 000 km^2. Its climate is characterized by mild and wet winters, with mean temperatures ranging from 5 to 15°C and rainfall varying from 50 to 250 mm from south to north. In contrast, the summer season is hot and dry with mean temperatures ranging from 20 to 40°C and rainfall ranging from 10 mm at the southern and eastern rims to 100 mm in the northern watersheds (Bolle, 2002). This unequal distribution over space and time has an impact on water resources availability: 84.2% of the total resources are located in the northern watersheds while only 10% and 5.8% are located in the southern and eastern watersheds, respectively (EUWI-MED, 2007). Another important feature of the Mediterranean basin is the growing demographic pressure. Of the total population, 64.8%, of which 2/3 is urban, lives in the coastal regions (CIESIN, 2004). This urban sprawl in addition to poor farming practices and desertification induce important soil deterioration as well as an increase in water demands. Since the late 1950s, water demands have doubled (Blinda & Thivet, 2009), and the question arises whether future needs in water resources can be satisfied in this region that could be particularly affected by global changes.

MATERIAL AND METHODS

Water resources scarcity assessment

In order to assess the impacts of global changes on the water resources of the Mediterranean basin, a water stress index (WSI; Shiklomanov, 1991) was used. It is based on the ratio of annual water withdrawals to the annual water availability (equation (1)):

$$WSI = \frac{\sum \text{Water Withdrawals}}{\text{Water Availability}} \tag{1}$$

This index expresses the intensity of pressures put on the available water resources by users; the higher the index, the stronger the pressure. This indicator requires data that are usually easily accessible and incorporates long-term effects of changing water use. Adopted by the Mediterranean Strategy for Sustainable Development (MSSD), it has already been applied to the Mediterranean region, but, up to now, without taking into account the impacts of climate change on water use and availability (Plan Bleu, 2005). This index was then computed over the Mediterranean basin to estimate the current state of water stress and its evolution accounting for climate and anthopogenic changes in the short and mid terms (Fig. 1).

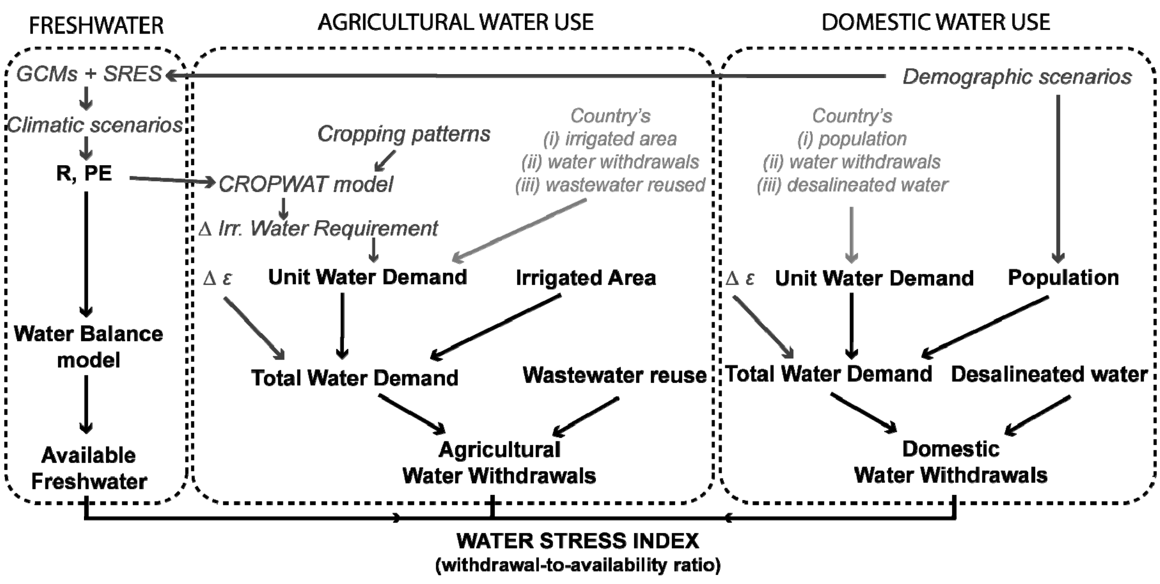

Fig. 1 Methodological approach – in black: methodology core; in light grey: additional data for current situation estimation; in dark grey: additional data for future situation estimation. (R: Rainfall; PE: potential evapotranspiration; ε: efficiency).

Current and future water availability were represented by a long-term mean annual value over the reference climate period (1971–1990) and over the future climate periods 2016–2035 (2025 horizon) and 2041–2060 (2050 horizon). Water withdrawals of the current most water-demanding sectors were considered, i.e. the agricultural (181 km^3/year) and domestic (37.9 km^3/year) sectors (Margat, 2004). Current and future withdrawals, respectively, have been considered according to the recent period 2001–2009 and the years 2025 and 2050.

Freshwater resources modelling

The conceptual rainfall–runoff water balance model (Yates, 1997) was performed to evaluate water availability. Water availability was considered as the annual renewable water resources, or discharge, within a given watershed. The model relies on a one-dimensional reservoir that represents both the root and upper soil layers. It uses continuous functions to describe water movement into and out of a conceptualized watershed, at a monthly time step. Water enters the soil moisture zone and is retrieved according to three parameters either by evapotranspiration, surface outflow or sub-surface outflow (Yates, 1997). No calibration is required to define the value of the parameters, which are determined by an aggregated 13-class diagram. This diagram links vegetation to three climate variables (biotemperature, rainfall and evapotranspiration), thus assuming that vegetation and soil are in equilibrium with climate (Holdridge, 1947). Even though the delineation of the biome regions is quite rough, Leemans (1990) showed that the life zones were particularly reliable in tropical, Mediterranean and boreal regions.

The model requires monthly rainfall (R) and potential evapotranspiration (PE) input data on a 0.5° grid. Over the reference period, R and temperature data were obtained from the CRU TS 2.1 World database (Mitchell & Jones, 2005). As for future estimation, outputs from four global climatic models (GCMs; Table 1) were extracted from the IPCC's Data Distribution Centre. Climate scenarios under changing levels of greenhouse gas emissions, as specified by the scenarios 20C3M (20th century climate – 350 ppm CO_2) and A2 (2025 and 2050 horizons climate – CO_2 stabilization at 850 ppm), were generated using the unbias and delta methods (see e.g. Etchevers *et al.*, 2002; Prudhomme *et al.*, 2002; Shabalova *et al.*, 2003). PE was then computed using a simple formula relying on extraterrestrial radiation and mean temperature (Oudin *et al.*, 2005).

Table 1 Selected GCMs from IPCC's Data Distribution Centre.

GCM	Country	Atmospheric Resolution	Reference
CSIRO-MK3.0	Australia	1.9° × 1.9°	Gordon *et al.*, 2002
HadCM3	U.K.	2.5° × 3.75°	Pope *et al.*, 2000
ECHAM5/MPI-OM	Germany	1.9° × 1.9°	Jungclaus *et al.*, 2005
CNRM-CM3	France	2.8° × 2.8°	Salas-Mélia *et al.*, 2005

Estimate of agricultural and domestic water withdrawals

Water withdrawals were considered as the annual volume of water withdrawn from the environment for agricultural or domestic purposes. Due to the limited availability of these data at the watershed scale, two intermediate key variables were used in order to approach them: per Unit Water Demand (UWD) per sector at the country level, and Total Water Demand (TWD) per sector at the watershed level. In this study, water demand was considered as the sum of the water withdrawn from the environment and the use of non-conventional water resources (Plan Bleu, 2005).

Current and future UWD were calculated at the country scale and attributed to each watershed of the considered country. According to the available data and prospects, current and future UWD were computed following equations (2) and (3), respectively:

$$UWD_{\text{Country, current state}} \frac{\text{WaterWithdrawals}_{\text{Country}} + NCWR_{\text{Country}}}{\text{Unit entity}_{\text{Country}}} \quad (2)$$

with UWD the per unit water demand (i.e. the agricultural water withdrawals per irrigated hectare or the domestic water withdrawals per inhabitant), NCWR the non-conventional water resources (here wastewater re-use was supposed for agricultural use and desalinated water for domestic use), and unit entity the irrigated area (in hectares) in the case of agricultural water use and total population for domestic water use.

$$UWD_{\text{Country, future horizon}} = UWD_{\text{Country, current state}} \times \Delta UWN_{\text{Country}} \times \Delta\varepsilon_{\text{Country}} \quad (3)$$

with ΔUWN the variation in per unit water need (i.e. the agricultural water required for an agronomic optimal crop growth per irrigated hectare or the domestic water use per inhabitant at household level), and Δε, the variation in efficiency.

The irrigation management tool CROPWAT (Allen *et al.*, 1998) was performed to evaluate the impacts of climate change on agricultural UWN. CROPWAT calculates water requirements for crops and irrigation based on monthly R, PE and cropping patterns. It was applied over all the periods considered in order to compute the evolution rate in irrigation water requirements between the reference period and the 2025 and 2050 horizons. With regard to domestic UWN, variations were provided by national reports produced by the Mediterranean countries for the Plan Bleu between 2005 and 2009. These trends were supposed to be independent from climate change. Agricultural and domestic UWN were corrected by an efficiency variation rate to obtain the future UWD. Indeed, by adopting the MSSD in 2005, the Mediterranean countries committed reducing agricultural networks' losses to 10% and maintaining plot efficiency to 80%, and reducing domestic networks' losses to 15% (Plan Bleu, 2005).

Once the UWDs were computed, the watersheds' TWD could be estimated (equation (4)):

$$TWD_{\text{Watershed}} = UWD_{\text{Watershed}} \times \text{Unit entity}_{\text{Watershed}} \quad (4)$$

with $TWD_{\text{Watershed}}$, the water demand for total irrigated land or population within a given watershed.

Finally, non-conventional water resources were retrieved from the TWD in order to obtain the sector's water withdrawals at the watershed scale (equation (5)):

$$\text{Water withdrawals}_{\text{watershed}} = TWD_{\text{Watershed}} - NCWR_{\text{Watershed}} \quad (5)$$

For the current period, (i) water withdrawals, (ii) non-conventional water production and (iii) irrigated area data were collected from the Aquastat (FAO, 2010), FAOStat (2010) and MIRCA (Portmann *et al.*, 2010) databases. Population data were obtained from the last national census. Over the 2025 and 2050 horizons, evolution trends of irrigated area, UWR and efficiency were given by the national reports. Cropping patterns were supposed to remain the same. The climatic data used as inputs of CROPWAT were the same as for the hydrological model. Finally, the A2 demographic scenario published by the United Nations (UN, 1998) was used for future population estimates.

RESULTS

Present and future water stress

The Mediterranean basin is currently under high water stress (Fig. 2(a)). "Hot spots" include the southern and eastern watersheds, as well as southern Spain. The watersheds in Italy and Greece are under moderate water stress, while the watersheds in France and the Balkans are not suffering from any stress. During the 21st century, the socio-economic context and climate could evolve and influence water availability and water withdrawal patterns, and thus affect the water stress situation.

Watersheds currently under moderate or no stress, such as the Ebro, the French coastal watersheds and the western Greek watersheds, should be under high water stress by the 2050s

(Fig. 2(c)). This evolution can be explained by decreasing water availability associated with higher agricultural water withdrawals. Watersheds currently under high water stress should remain so, despite an improvement in water use efficiency. This can be linked to a decrease in water availability combined with an increase in water withdrawals. Pressures on water resources are projected to decrease only for the Po watershed at the 2025 horizon (Fig. 2(b)). This watershed should move from moderate to low water stress due to stable freshwater availability and a 10–30% decrease in water withdrawals. However, at the 2050 horizon, it could evolve back to moderate water stress, mainly because of a decrease in freshwater availability (Fig. 2(c)). The Rhone and the Balkans' watersheds are the only basins that should stay under no stress conditions thanks to projected upheld freshwater abundance.

In order to better understand the cause of the high water stress conditions projected for the Mediterranean basin, it is necessary to analyse the evolution of the two main factors affecting it.

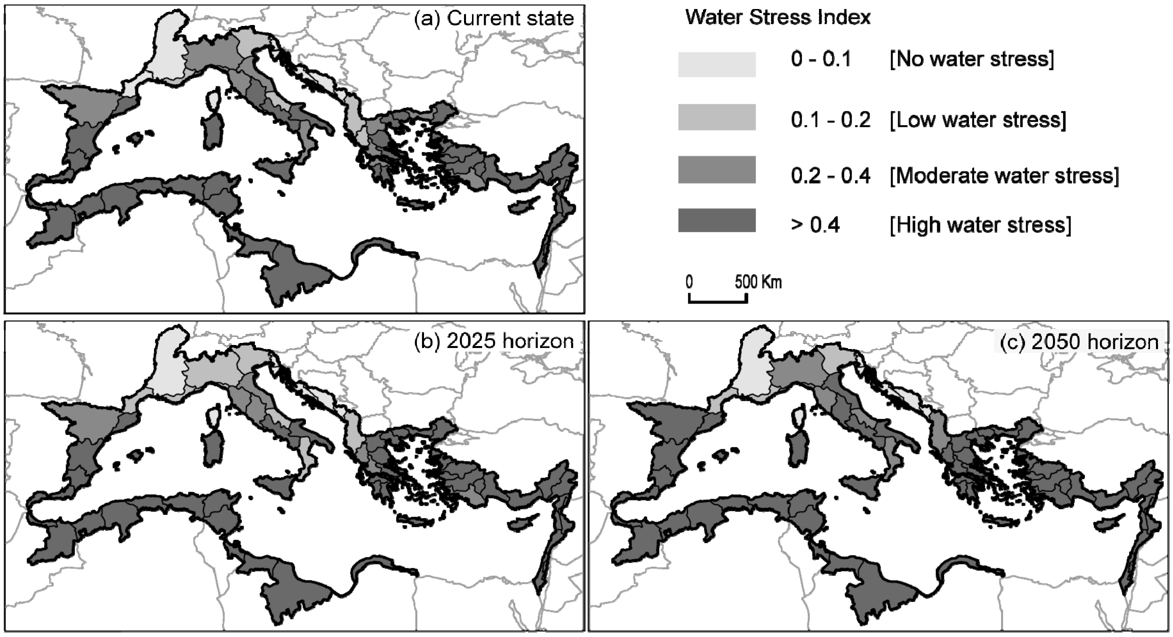

Fig. 2 Water stress index over the Mediterranean basin, expressed as water withdrawals-to-availability ratio: (a) current state; (b) 2025 horizon; (c) 2050 horizon – mean value of the 4 GCMs is expressed.

Changes in freshwater availability

According to the analysis of the GCM outputs, temperatures are expected to rise by 0.5 to 1.5°C in the Mediterranean basin by 2025 and by an extra 1°C by 2050. This rise in temperatures is likely to reduce relative air humidity and increase the atmosphere's capacitive moisture load, hence increasing PE. At the 2025 horizon, annual rainfall should decrease by 10% on average over the Mediterranean basin except in Libya and in the Mashriq where it should increase by 10%. At the 2050 horizon, rainfall should be reduced by 10–30% in the whole region. The combination of increasing PE and decreasing R should induce a net decrease in freshwater availability.

The Mediterranean basin is currently characterized by a significant, spatial contrast in water availability (Fig. 3(a)). Freshwater availability ranges from low (0–200 mm/year) to high (>500 mm/year) values from the southern and eastern arid watersheds to the northern mountainous areas, with an intermediate zone (200–300 mm/year) in Spain, Italy and Greece. These disparities should increase under climate change.

At the 2025 horizon (Fig. 3(b)), freshwater resources should remain approximately at today's level, except in Spain and in the southern rim where they are expected to decrease by 10–30%. Morocco and Eastern Libya should be particularly affected with a projected reduction of 30–50%.

Only western Libya and southern Tunisia should face a 30–50% increase of their freshwater resources, but note that the absolute values would remain low. At the 2050 horizon (Fig. 3(c)), a strong decrease in freshwater resources is projected over the whole Mediterranean basin (30–50%). The watersheds in Morocco, Algeria, southern Spain, southern Turkey and in the Mashriq should be the most affected with a reduction of over half of their current freshwater resources. Mountainous areas (e.g. Alps, Balkans) should also face a decrease of 10–30%. Only western and central Libya's freshwater resources are supposed to increase (10–30%) compared to the current situation, despite a slight decrease between the 2025 and the 2050 horizons.

Therefore, under the influence of increasing PE and decreasing R, freshwater resources should become less available over the Mediterranean basin, in particular in its already arid to semi-arid watersheds (e.g. Spain, Morocco, Algeria, Mashriq). To evaluate whether projected water resources would meet future water demand, an evaluation of future freshwater withdrawals is required.

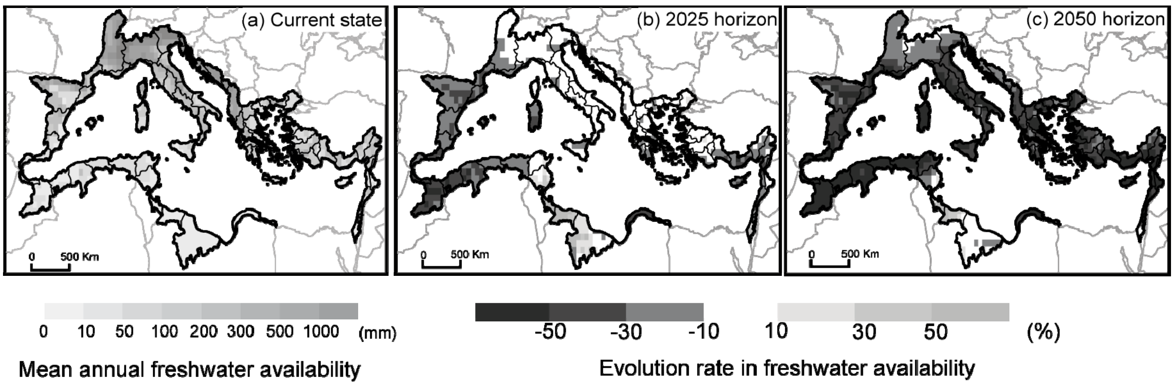

Fig. 3 Freshwater availability and mean evolution according to the reference period 1971–1990.

Changes in agricultural and domestic water withdrawals

In this section, the effects of climate change, irrigated area evolution, growing population and improvements in networks' efficiency on water withdrawals are investigated. To illustrate the causes of increase or decrease in water withdrawals in the Mediterranean basin, the current state and possible future development of water withdrawals are presented for three case studies in Fig. 4. Water withdrawals are subdivided into the individual water use sectors.

At the 2025 (2050) horizon, about 30 (40) watersheds out of the 73 groups of watersheds should face an increase in water withdrawals compared to the current situation. A 10–30% increase in irrigation water requirements should be the main factor for the northern watersheds (Greece, Balkans, Ebro) due to warmer and drier conditions. Current domestic withdrawals should be maintained (see e.g. Ebro watershed, Fig. 4(b)). This can be attributed to increased water use efficiency, current adequate access to water supply, and a slight population decline. In contrast, a 50% increase in water withdrawals should occur in the southern and Mashriq's watersheds (see e.g. the Moulouya watershed, Fig. 4(c)) in line with a high population growth although agricultural water withdrawals should slightly decrease due to an improvement in efficiency.

However, nearly 20 (15) watersheds should undergo a decrease in withdrawals. The watersheds in Italy and Algeria should mostly be concerned (10–30%). This can be explained mainly by an improvement in domestic water use efficiency by 15% and 30% respectively, according to the national reports.

Finally, some watersheds, notably in Turkey (see e.g. the Seyhan watershed, Fig. 4(d)), France and Spain, should tend to maintain their water withdrawals at the current level. Efficiency improvements should temper water withdrawals affected by growing irrigation water requirements and population.

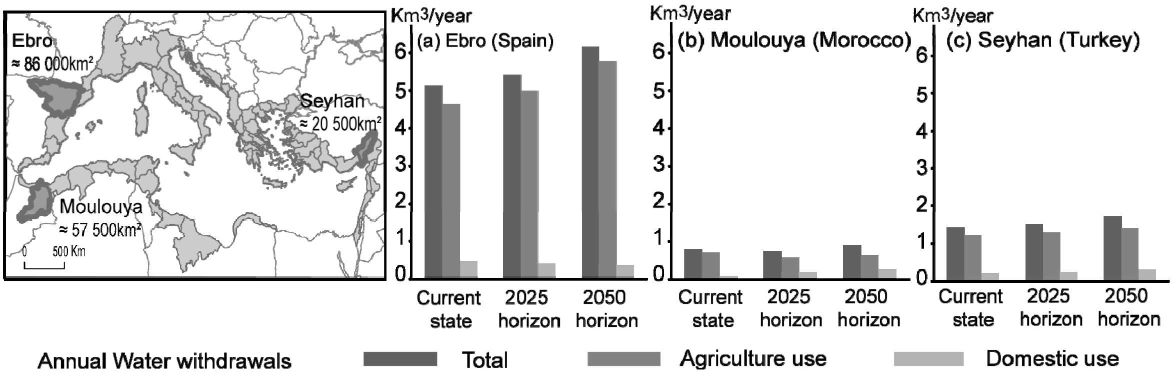

Fig. 4 Evolution in water withdrawals in the short and mid terms for three Mediterranean watersheds.

DISCUSSION AND CONCLUSION

In this paper, a methodology combining different models and key variables was developed in order to analyse the evolution of freshwater availability and water withdrawals over the Mediterranean basin at the 2025 and 2050 horizons. Climatic changes as well as population growth and variations in: (i) per unit water demands, (ii) irrigated area, (iii) non-conventional water production, and (iv) network efficiency were considered. Results show that freshwater availability could be reduced by the 2050 horizon. In contrast, both agricultural and domestic water withdrawals could increase, even if tempered by an improvement in networks' efficiency. These changes should not modify the water stress situation of the Mediterranean basin at the 2025 horizon, but the situation should deteriorate by the 2050 horizon. Other authors (e.g. Oki *et al.*, 2001; Alcamo *et al.*, 2007; Menzel & Matovelle, 2010) have investigated the impacts of climate and socio-economic changes at the world scale. They also found deterioration in the water stress situation over nearly the whole Mediterranean basin. However, note that watersheds in France and in the Balkans should face no stress and that northern Italy should be under moderate water stress.

A number of uncertainties that influence the results should however be noted. Firstly, the hydrological model used does not require any calibration since a bioclimatic diagram predetermines its parameters. Therefore, the choice of the class for each cell is the determinant for water availability computation. The hydrological simulations could be improved if a preliminary calibration was performed *via* for instance a regional parameterization over the whole Mediterranean basin. Another uncertainty comes from the future climatic data. Due to their low resolution, GCMs cannot capture fine-scale meteorological processes that influence rainfall patterns (e.g. local topography, local winds). However, this bias was reduced by applying corrections and by working with outputs from four different GCMs. As far as water withdrawals are concerned, the main uncertainty comes from simplification of the social and economic processes. Per unit water demand was assumed to be constant over an entire country and non-conventional water resources exclusively allocated to specific sectors.

Despite these uncertainties, this study provides a first overview of water resources in the Mediterranean basin. Possible evolution trends have been assessed, which may be useful to identify the number and location of watersheds that are likely to be under pressure. Such a study is a first step towards broader prospective studies implying contrasting scenarios. It can also help setting up regional adaptation strategies to cope with water stress. Yet, in order to be able to support adaptation water management plans, more detailed information should be taken into account (e.g. industrial water use, dams, tourism) with a more local-scale perspective. This is the subject of ongoing research.

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