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# Facing climatic and anthropogenic changes in the Mediterranean basin: What will be the medium-term impact on water stress?

## *Face aux changements climatiques et anthropiques dans le bassin Méditerranéen, quelle évolution du stress hydrique à moyen terme ?*

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A B S T R A C T

The Mediterranean basin has been identified as one of the world's most vulnerable regions to climatic and anthropogenic changes. A methodology accounting for the basin specific conditions is developed to assess the current and future water stress state of this region. The medium-term evolution of water stress is investigated using climatic scenarios and a water-use scenario based on efficiency improvements following the recommendations of the Mediterranean Strategy for Sustainable Development. Currently, the southern and eastern rims are experiencing high to severe water stress. By the 2050 horizon, a 30–50% decline in freshwater resources is simulated over most of the Mediterranean basin. While total water withdrawals would stabilize, or even decrease (10–40%), in several northern catchments, they would double in southern and eastern catchments. These changes should significantly increase water stress over the Mediterranean basin and exacerbate the disparities between rims.



R É S U M É

Cet article propose une méthodologie intégrant les spécificités locales du bassin Méditerranéen, afin d'évaluer l'état actuel et futur du stress hydrique de cette région identifiée comme l'une des plus vulnérables aux changements climatiques et anthropiques. L'évolution à moyen terme a été analysée sous contrainte de scénarios climatiques et d'un scénario d'usages de l'eau intégrant les recommandations de la Stratégie méditerranéenne pour le développement durable en matière d'efficience hydraulique. Les rives sud et est subissent déjà un stress hydrique élevé voire sévère. À l'horizon 2050, une diminution de 30–50 % des ressources en eau est simulée sur la majorité du bassin. Tandis que les prélèvements totaux en eau pourraient se maintenir, voire diminuer (10–40 %) sur la rive nord, ils devraient doubler sur les rives sud et est. Face à ces évolutions, le stress hydrique devrait donc s'amplifier et exacerber les disparités entre les différentes rives du bassin Méditerranéen.



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## 1. Introduction

The recent literature includes a number of global overviews of the impacts of climate change, population growth and increasing water withdrawals on water availability for the 21st century (Alcamo et al., 2007; Arnell, 2004; Vörösmarty et al., 2000). Under business-as-usual scenarios – i.e. scenarios that follow past trends and under which no adaptation strategies are undertaken – these studies have identified the Mediterranean basin as one of the regions most vulnerable to climatic and anthropogenic changes.

The Mediterranean basin is characterized by limited and unevenly distributed water resources. It currently accounts for 1.2% of the world's renewable water resources, defined as freshwater resources stored in rivers and groundwater reservoirs whose flows are maintained by the water cycle. These resources amount to approximately 550 $km^3$/year, 75% of which are located in catchments in Italy, France, Greece and Turkey (according to extractions from the Aquastat database; FAO, 2010). Catchments on the southern and eastern rims produce respectively only 4 and 2% of Mediterranean water resources. Since the late 1970s, mean annual temperatures have tended to increase by 0.1 °C/decade and precipitation to decrease by 25 mm/decade (Xoplaki et al., 2004). According to global and regional climate change simulations, temperatures should rise by 2–3 °C and annual precipitation should decrease on average by 30% by the 2050 horizon (Giorgi and Lionello, 2008; IPCC, 2007). Warming and drying should be greatest during the winter and summer seasons (García-Ruiz et al., 2011; Giorgi and Lionello, 2008). A 15% decrease in winter precipitation and a 1.8 to 2.6 °C increase in temperature could severely alter snow accumulation and spring melting processes in mountainous areas (Stewart, 2009). Combined with the projected decrease of 30% in summer precipitation, this would exacerbate summer low-flows (Frederick, 1997; Giorgi and Lionello, 2008). These seasonal changes should lead to more frequent and more intense winter floods and drought periods, owing to snow-free soils and reduced soil moisture (Arnell, 1999; Planton et al., 2005). Another important feature of the Mediterranean basin is the growing anthropogenic pressure. In 2001, 187 million people lived along the Mediterranean coastline, and of this total, 79% lived on the southern and eastern rims (UNPD, 2001). The total population of the Mediterranean basin is projected to reach 269.7 million by the year 2050. Mediterranean valleys and coastal areas should therefore face strong urban expansion (Abis, 2006; Bellot et al., 2007). Irrigated land should also expand. In water-scarce valleys, reservoirs and canals would support water supply and in turn sustain productivity and allow a progressive shift in crops (García-Garizábal and Causapé, 2010; Seguin, 2003). According to García-Ruiz et al. (2011), crops in new irrigated land (mainly maize and alfalfa) will have higher water requirements than traditional Mediterranean crops (cereal crops, olives, grapes). Such a shift has already been observed in the Ebro catchment in Spain, for example (Pinilla, 2006). Therefore, climate change combined with constantly rising water demand raise the question of whether future water needs can be satisfied in this region, which should be particularly affected by these changes.

No regional-scale investigation of current and future water stress and its spatial variations has yet been conducted for the Mediterranean basin. This article focuses on 73 groups of catchments that have their outlets in the Mediterranean Sea, thus covering an area of approximately 1.5 million $km^2$ and working at a spatial scale lying between continental and catchment-based scenario studies. The Nile river basin was excluded, primarily because of its tropical hydrologic regime. A homogeneous method for these catchments was developed to fit the Mediterranean context and Mediterranean water issues. It takes into account:

- the impacts of climate change on water availability and agricultural water demands;
- water-use projections from national reports;
- and a sustainable development strategy ratified by the 21 Mediterranean rim countries.

In applying this method, the article pursues three main objectives: to evaluate the possible future conditions of water availability and water withdrawals; to grasp the relative influence of climatic and anthropogenic changes on water stress occurrence; and to evaluate the impacts of all these changes on water resources variability and the capacity of water-use efficiency improvements to reduce the pressure on water resources.

## 2. A regional modeling approach

### *2.1. Interaction between climate, freshwater availability and water withdrawals*

A methodology adapted to the Mediterranean context and adaptation strategies to climate change were set up (Fig. 1). This method was applied over the current period in order to define the current state of pressure on the Mediterranean water resources. It was also applied by the 2050 horizon in order to address the impacts of climatic and anthropogenic changes on water resources variability.

Freshwater availability was estimated as a long-term mean annual value over the reference climate period 1971–1990 and over the future climate period 2041–2060 (2050 horizon). The reference period was chosen for its representativeness of the Mediterranean climate, covering dry and wet periods. Projections of climatic changes were based on the A2 greenhouse gas emission scenario (IPCC, 2007), which corresponds to the largest increase in greenhouse gas emissions, and thus to very substantial changes in climate.

Current water withdrawals were estimated over the recent period 2001–2009, because homogeneous data were not available for all 73 catchments over the 1971–1990 period. Estimates of future withdrawals at the 2050 horizon consider improvements in the efficiency of transport and distribution networks and of irrigated plots. In 2005, the 21 Mediterranean countries adopted the Mediterranean Strategy for Sustainable Development (MSSD), in order to support a dynamic regional process

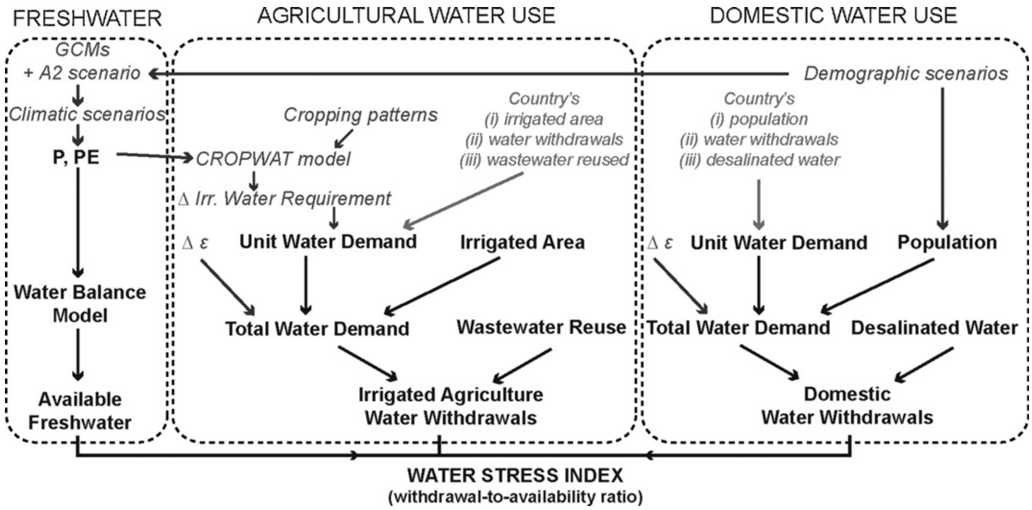



**Fig. 1.** Methodological approach. In black: methodology core; in light grey: additional data for current state assessment; in dark grey: additional data for future state assessment. P: precipitation; PE: potential evapotranspiration; ε: efficiency; Irr.: irrigation.

**Fig. 1.** Approche méthodologique – en noir : données et étapes clef ; en gris clair : données supplémentaires requises pour l'évaluation du stress hydrique sur la période récente ; en gris foncé : données supplémentaires requises pour l'évaluation future du stress hydrique. P : precipitation ; PE : évapotranspiration potentielle ; ε : efficience ; Irr. : irrigation.

to include environmental concerns in the economic development of these countries. Under this framework, they gave commitments to reduce agricultural and domestic networks water losses and to increase irrigation efficiency at the plot level (UNEP-MAP, 2006). This water-use scenario was explored over the medium term.

### 2.2. Modeling freshwater resources

To assess the impacts of global changes on water resources, it was necessary to first evaluate freshwater availability, defined as the annual renewable water resources, or discharge, within a given catchment.

The conceptual rainfall-runoff Water Balance Model (WBM; Yates, 1997) was used to evaluate it. The model relies on a one-dimensional reservoir that represents both the root and upper soil layers. The dynamics of groundwater resources are considered in terms of drainage from soil moisture. The model uses continuous functions of relative storage to compute the water balance of each 0.5° grid cell at a monthly time-step. Contributions of the grid cells of each catchment are summed to give estimates of total discharge. Theoretically, the hydrological model requires no calibration, since its parameters are predetermined by a bioclimatic diagram (Holdridge, 1947; Yates, 1997). Nonetheless, a sensitivity analysis was carried out for ten large Mediterranean catchments ($>$ 10 000 km$^2$). Systematic runs were conducted and aimed at minimizing the difference between simulated and observed runoff volumes using datasets that covered as many consecutive years as possible of the reference period. Since modifying the parameter values provided better agreement between the simulated and observed runoff volumes for all catchment, the new set of parameters was retained. The hydrological model, thus adjusted against historical data, was run over the future period using these optimized parameter values. It was assumed that the bias in the freshwater simulations over the reference period was reproduced in the simulations of future conditions and thus that the error related to freshwater resources modeling on water vulnerability assessment was the same over the reference and future periods.

The model requires monthly precipitation (P) and potential evapotranspiration (PE) input data on a 0.5° grid. Over the reference period, P and temperature data were obtained from the CRU TS 3.0 World database (Mitchell and Jones, 2005). Although this database relies on spatial interpolation of observed data in areas where data are scarce or incomplete, it is currently recognized as one of the most reliable databases for large-scale investigations. For future estimation, outputs from the CSIRO-Mk3.0 (Gordon et al., 2002), HadCM3 (Pope et al., 2000), ECHAM5 (Jungclaus et al., 2005), and CNRM-CM3 (Salas-Mélia et al., 2005) global climatic models (GCMs) were extracted from the IPCC's Data Distribution Centre. These models were selected because:

- they are approved by the IPCC for its fourth and fifth assessment reports;
- they have available data over the periods of time covered in this study;
- they have a low resolution ($< 3^\circ \times 3^\circ$) in comparison to other GCMs;
- and they have often been used in Mediterranean case studies.

Climate scenarios under changing levels of greenhouse gas emissions, as specified by the 20C3 M scenario (20th century climate–350 ppm $CO_2$) and A2 scenario (2050 horizon climate–$CO_2$ stabilization at 850 ppm) were generated using the perturbation method (Ruelland et al., 2012). PE was then computed using a simple

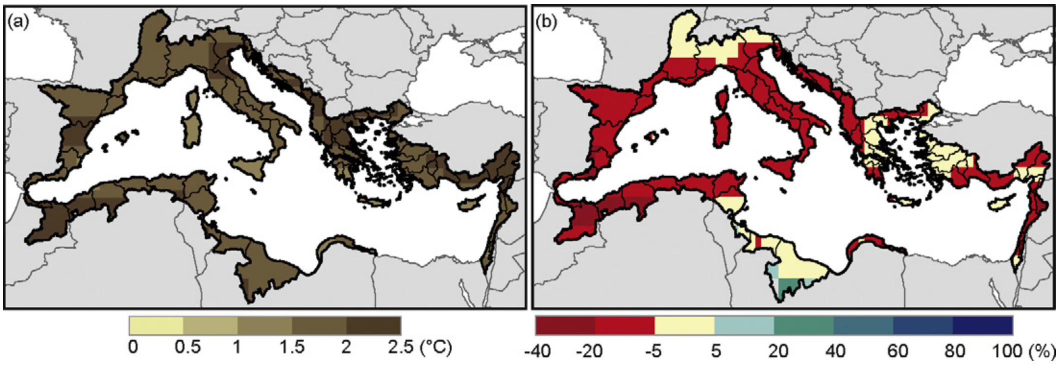



**Fig. 2.** Average trends in climate variables by the 2050 horizon in comparison to the 1971–1990 period: increase in temperatures (a) and variation in precipitation (b).

**Fig. 2.** Évolution moyenne des forçages climatiques à l'horizon 2050, en comparaison avec la période de référence 1971–1990 : hausse des températures (a) et taux de variation des précipitations (b).

formula based on extraterrestrial radiation and mean temperature (Oudin et al., 2005).

### *2.3. Water withdrawals assessment*

Water withdrawals were evaluated for irrigated agriculture, currently the most water-demanding sector (65.9 $km^3$/year), and for the domestic sector (19.5 $km^3$/year). The latter includes urban and rural water, drinking water supplies and touristic activities which draw on municipal water networks, and are often given priority for water supply. Water withdrawals for industries that are not connected to the municipal water networks and for energy production were not taken into account because they represent less than 2 $km^3$/year within each Mediterranean catchment, except for those in Spain, France and Italy where they amount, respectively, to 4.2 $km^3$/year, 13.2 $km^3$/year and 14 $km^3$/year (Margat, 2004). Water withdrawals were therefore defined as the annual volume of water withdrawn from rivers and groundwater reservoirs that is directly available for irrigated agriculture or domestic purposes.

Due to the limited availability of data on water withdrawals at the catchment scale for the current period, unit water demand (UWD) was evaluated at the country level for each sector. UWD was defined as the ratio of the water withdrawn from the water system plus the unconventional water resources used, to the irrigated surface area in the case of agricultural water use or to national population in the case of domestic water use. Two assumptions were made: (i) the UWD computed at the country scale was applied to each catchment of the country considered; and (ii) for unconventional water resources, reused wastewater was assumed to be dedicated to irrigated agriculture, while desalinated water was considered to be for domestic use. For the 2050 horizon, current agricultural UWD was adjusted according to variations in irrigation water requirements as computed by the irrigation management tool CROPWAT (Allen et al., 1998). Within this model, the various irrigated crops and the expansion of irrigated area – i.e. new agricultural areas or currently non-irrigated areas that are subsequently irrigated – were considered. The proportion of irrigated crops in the current irrigated fields was assumed to remain unchanged by the 2050 horizon. The expansion of irrigated area was taken from national reports (Plan Bleu, 2011) produced between 2005 and 2009 by scientists and policymakers from the 21 Mediterranean countries for the

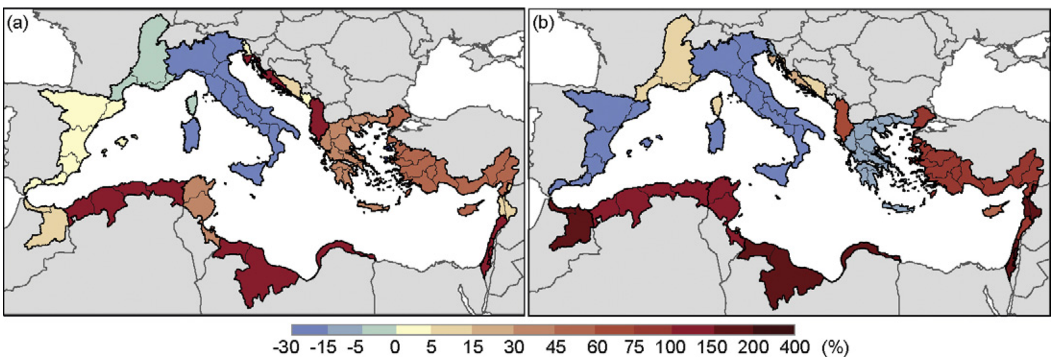
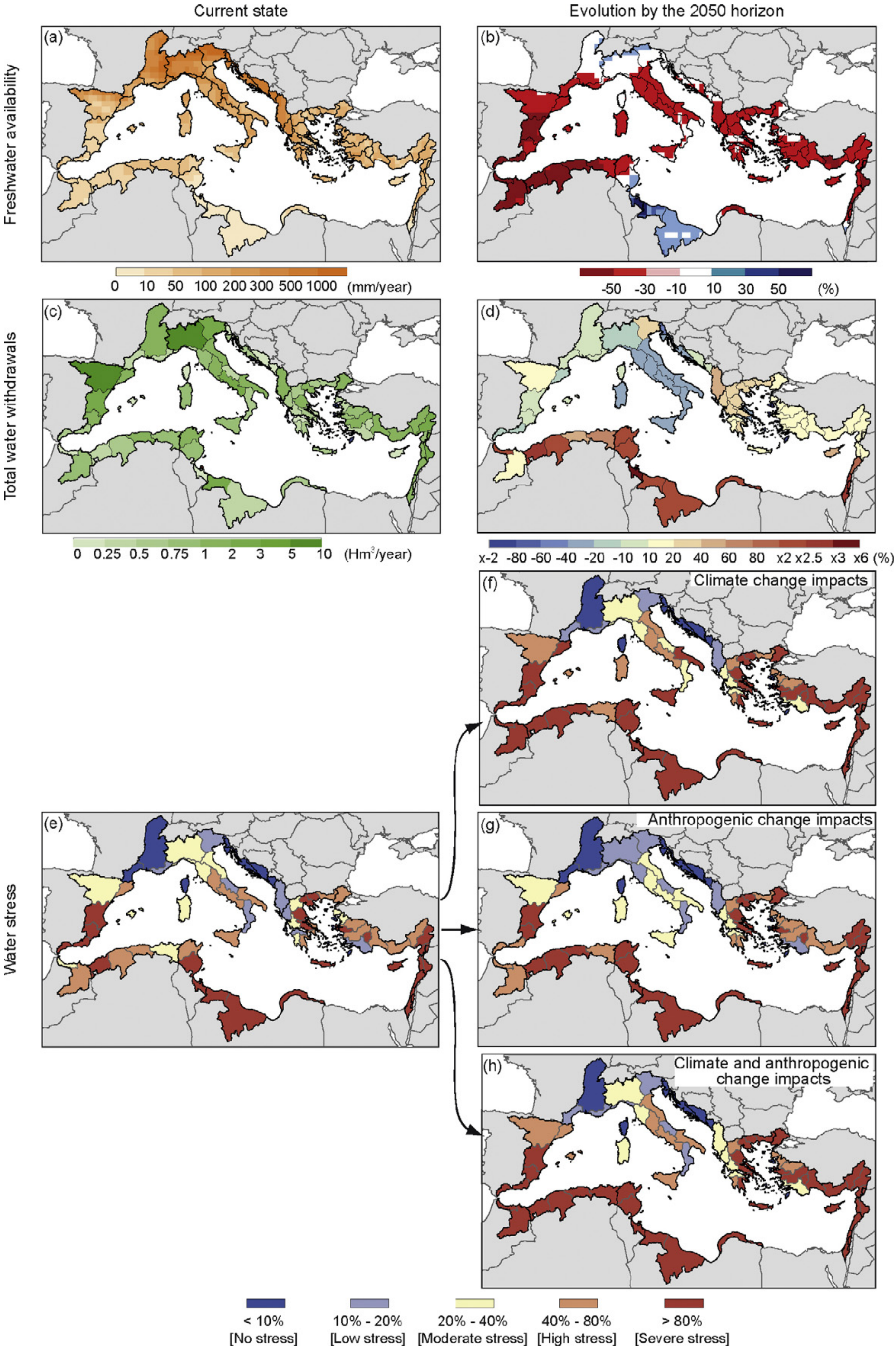



**Fig. 3.** Drivers of pressure on water withdrawals: changes in: irrigated area (a) and population (b) between the reference period and the 2050 horizon.

**Fig. 3.** Facteurs d'évolution des prélèvements en eau : évolution des surfaces irriguées (a) et tendances démographiques (b) entre la période de référence et l'horizon 2050.



Current state
Evolution by the 2050 horizon
Freshwater availability
(a)
(b)
0 10 50 100 200 300 500 1000 (mm/year)
-50 -30 -10 10 30 50 (%)
Total water withdrawals
(c)
(d)
0 0.25 0.5 0.75 1 2 3 5 10 (Hm³/year)
x-2 -80 -60 -40 -20 -10 10 20 40 60 80 x2 x2.5 x3 x6 (%)
Water stress
(e)
(f) Climate change impacts
(g) Anthropogenic change impacts
(h) Climate and anthropogenic change impacts
< 10% [No stress]
10% - 20% [Low stress]
20% - 40% [Moderate stress]
40% - 80% [High stress]
> 80% [Severe stress]

regional activity center Plan Bleu (Plan Bleu, 2006). Future domestic UWD was also obtained from these reports, which considered an increase in population and in touristic activities (Plan Bleu, 2011).

The UWD of each sector was then multiplied by the catchments population and irrigated area and corrected by an efficiency rate in order to obtain the total water demand (TWD). The efficiency rate was defined as the ratio of current efficiency (obtained from the national reports) to the efficiency objectives set by the MSSD. The latter aimed at reducing agricultural and domestic networks water losses and improving irrigation techniques for a larger consumption of distributed water, thus rising water-use efficiency to 72% for agriculture and 80% for domestic use. However, these objectives have been modified in some countries (e.g. Italy, Croatia) in accordance with the national reports assessment of their feasibility. Finally, unconventional water resources were subtracted from TWD in order to obtain the water withdrawals of each sector at the catchment scale.

For the current period: water withdrawals; unconventional water production; and irrigated area and crop data were collected, respectively, from the Aquastat (FAO, 2010), FAOStat (2010), and MIRCA 2000 (Portmann et al., 2010) databases. Population data at the national and catchment levels were drawn from the most recent census. For the 2050 horizon, trends in irrigated area and efficiency were taken from the national reports. The climatic data (P and PE) used as inputs to CROPWAT were the same as for the hydrological model. Finally, in order to be consistent with the assumptions of the A2 greenhouse gases emission scenario used for the climatic scenario, the A2 demographic scenario published by the United Nations (UNPD, 2001) was used for future population estimates.

### 2.4. Water stress evaluation

Once these main variables were obtained, it was possible to compute the water stress index (WSI) adopted in the MSSD to monitor the impacts of climatic and anthropogenic changes on water resources. The index is based on the ratio of annual water withdrawals to annual renewable water resources (Shiklomanov, 1991; equation (1)).

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

This index expresses the intensity of anthropogenic pressure on available water resources: the higher the index, the stronger the pressure. It indicates the margin between renewable water resources and water demand, and consequently the scope of action available to water managers. It has previously been applied to the Mediterranean region (Plan Bleu, 2005) but without taking into account the impacts of climate change on water use and availability. For our study, this index was computed over the Mediterranean basin to estimate the current state and evolution of water stress. Possible trends in water stress were explored first under climate changes, then under anthropogenic changes, and finally under both climatic and anthropogenic changes.

Normally, the use and presentation of different climatic scenarios is recommended in order to give a range of possible futures and to express uncertainties for water planning (Le Treut et al., 2008; Menzel and Matovelle, 2010). However, as the four selected GCMs simulated very similar climatic trends, individual runs of the method gave very similar results in terms of water stress shifts. Uncertainty linked to the choice of GCM is thus negligible here, and for the sake of concision, the following section presents average trends for water resources and water stress evolution.

## 3. Trends in Mediterranean water resources under climatic and anthropogenic changes

### 3.1. Freshwater availability under climate change

As can be seen from Fig. 4a, the current water resources of the Mediterranean basin are unequally distributed, being particularly scarce on the southern rim. The four selected GCMs agree that annual air temperature should increase by 1.5 to 2.5 °C (Fig. 2a) and annual precipitation should decrease by 5–20% (Fig. 2b) over the Mediterranean basin as a whole by the 2050 horizon. The strongest decreases are projected for southern Spain, Morocco, Algeria and the Middle East (20–40%), while an increase is projected for Libya (40–60%), although this would still leave the latter with low absolute values of precipitation. The combined effects of increasing temperatures and decreasing precipitation should reduce freshwater availability and exacerbate the disparities between rims.

In climate change simulations under the A2 greenhouse gas emission scenario at the 2050 horizon, the hydrological model simulates a significant decrease (30–50%) in freshwater resources over the whole Mediterranean basin (Fig. 4b). Catchments in southern Spain, Morocco, Algeria and the southeastern Mediterranean should be the most affected, with a reduction of over half of their current freshwater resources. The smallest decreases (15%) are projected in catchments in France, northern Italy, and the Balkans, as precipitation is expected to remain constant in the mountainous parts of these catchments. Only Libya and southern Tunisia should experience an increase (10%), maintaining their current level of renewable freshwater resources, between 0 and 15 mm/year (Fig. 4a and b).

**Fig. 4.** Trends in Mediterranean water resources: current freshwater resources availability (a) and their evolution by the 2050 horizon (b); current total water withdrawals (c) and their evolution by the 2050 horizon (d); current water stress (e) and its evolution by the 2050 horizon under climate change (f); anthropogenic changes and water-use efficiency improvements (g), and both climatic and anthropogenic changes (h).

**Fig. 4.** Impacts des changements globaux sur les ressources en eau en Méditerranée : lame d'eau disponible sur la période récente (a) et évolution à l'horizon 2050 (b) ; prélèvements en eau totaux sur la période récente (c) et évolution à l'horizon 2050 (d) ; situation actuelle du stress hydrique (e) et évolution à l'horizon 2050 sous contraintes climatiques (f) ; sous contraintes anthropiques avec amélioration de l'efficience (g) et sous l'effet conjugué des changements climatiques et anthropiques (h).

Climate change should thus have a significant impact on freshwater availability by the 2050 horizon, with the already arid to semi-arid catchments being the most affected. Moreover, the latter should be the most prone to anthropogenic changes.

### 3.2. Possible trends in water withdrawals

According to the national reports, irrigated area should stay at their current level in Spain and Slovenia (+2%); decrease in France (4%), Italy (18%) and Malta (27%); and increase over the rest of the Mediterranean basin (Fig. 3a). The largest increases should be observed in catchments in the Balkans, Algeria, Libya, Israel, and Lebanon, where irrigated area is expected to double (Fig. 3a). Population should stabilize or decline in northern catchments, increase by 85–90% in catchments in Turkey and Lebanon, and at least double in the southeastern Mediterranean and on the southern rim (Fig. 3b). These trends will inevitably lead to changes in water withdrawals. These changes are presented in Fig. 4d.

Efficiency improvements should hold down water withdrawals over the whole Mediterranean basin. On the northern rim, total water withdrawals should increase only in Greece, Albania, the Veneto region of northern Italy, and the Ebro catchment in Spain (Fig. 4d). This can be attributed to an increase in agricultural water withdrawals (Fig. 3a and b) as a result of the 42% expansion of irrigated lands in Greece and Albania (Fig. 3a) and of warmer and drier conditions in Spain and Italy. Otherwise, total water withdrawals over the northern catchments should remain at their current level or decrease by 10 to 40% at the 2050 horizon, notably in Italy, Slovenia, and Croatia (Fig. 4d). This trend should be due mostly to a decrease in domestic water withdrawals, as access to water supply is already adequate and population is projected to stabilize in these areas (Fig. 3b). In the Balkans, in contrast, this evolution can be attributed to considerable progress in efficiency, which should rise from 50 to 80% on average. In catchments of the Maghreb and the Middle East, total water withdrawals should at least double (Fig. 4d), owing to both the expansion of irrigated land and high population growth (Fig. 3a and b). Total water withdrawals should remain rather close to their current level (+10–20%) only in Turkey, Syria, and the Moulouya catchment in Morocco as a consequence of strong improvements in agricultural efficiency, which should rise from 45 to 72%.

### 3.3. Current and future water stress states

Analysis of Fig. 4e shows that the Mediterranean basin is currently under high water stress. Hot-spots include catchments where renewable water resources are scarce and water demand is high, i.e. in southern Spain, Tunisia, Libya, and the southeastern Mediterranean (Syria, Lebanon, Israel and the Palestinian Territories). Catchments in northern Italy, western Greece and the Ebro in Spain are shown to experience moderate water stress, whereas catchments in France and the Balkans seem not to suffer from any stress. As stated above, however, water withdrawals for industrial use were not taken into account. As such withdrawals amount to around 13.2 $km^3$/year in Mediterranean catchments in France alone (Margat, 2004), human pressure might be higher than illustrated in these catchments. The combined effects of freshwater availability and water withdrawal trends shown above suggest that the Mediterranean water stress state will deteriorate by the 2050 horizon, especially on the southern and eastern rims.

If the medium-term impacts of climate change alone are considered, the reduction in water resources on the northern rim should cause catchments with low to moderate water stress to experience respectively moderate to high stress, and even severe stress in southern Italy (Fig. 4f). Only catchments in France and the Balkans should continue to experience no stress. On the southern and eastern rims and in southern Spain, water tensions could be severe (Fig. 4f).

If water resources are projected to remain at their current volumes and water withdrawals to change, water stress should remain at its current state on the northern rim, except in Italy and Greece. In western Greece, the current low to moderate state of water stress should deteriorate to moderate to high water stress respectively. In Italy, the projected 30 to 35% decrease in water withdrawals should lead catchments currently under moderate to high water stress to experience low to moderate water stress respectively in the medium term (Fig. 4g). On the southern and eastern rims, water stress should certainly increase, remaining close to its current level only in Turkey and in the Moulouya catchment in Morocco (Fig. 4g).

Therefore, in the northern Mediterranean, although moderate to high water stress could occur under climate change conditions alone, the current water stress state should be maintained owing to a projected decrease in population and irrigated areas, and increased efficiency (Fig. 4h). Water stress should worsen only in western Greece and in the Ebro catchment in northern Spain due to the projected increase in total water withdrawals. Catchments in France and the Balkans should be the only ones remaining under no- to low-stress conditions (Fig. 4h). On the southern and eastern rims, the combined effect of decreasing freshwater availability and increasing water withdrawals should lead to severe water stress (Fig. 4h). Moreover, despite the projected progress in efficiency, Turkey, Syria and the Moulouya catchment in Morocco should still experience severe water stress owing to the significant decrease in their freshwater resources (Fig. 4b) and high population growth (Fig. 3b).

## 4. Conclusions and prospects

This article explores the impacts of climatic and anthropogenic changes on Mediterranean basins water stress in the light of a sustainable development strategy adopted by the 21 Mediterranean countries.

By the 2050 horizon, climate change will most likely contribute to the depletion of freshwater resources in the Mediterranean region and more specifically in already arid to semi-arid catchments. Moreover, although improving the efficiency of transport and distribution networks and of irrigated plots would significantly limit total water withdrawals, the latter should still double in the Maghreb and the Middle East. The projected decline in water resources, considered in isolation, would lead to high to severe water stress over the entire Mediterranean basin. However, projected efficiency improvements in water withdrawals could significantly reduce water stress over the northern rim, especially in Italy, and help maintain the current water stress state in Turkey and Morocco. In the other southern and eastern Mediterranean catchments, however, the increase in population and irrigated area would lead to severe water stress despite efforts to improve efficiency. As a result, the combined effect of climate change on freshwater availability and of improved efficiency on water use should cause water stress to remain stable for most northern catchments up to the 2050 horizon but to increase severely over the rest of the Mediterranean basin. On the southern and eastern rims, efficiency improvements alone would not be able to reduce water tension. These trends could lead to greater disparities between the northern, southern, and eastern rims and water shortage might worsen.

These results show the respective and combined impacts of climate change and anthropogenic activities on water stress occurrence in the Mediterranean basin over the medium term. To get to these results, some global scale assumptions were made for climate change scenarios. The water-use scenario, in contrast, was adapted to the regional scale by relying on the Mediterranean Strategy for Sustainable Development and the national reports provided by Plan Bleu. Other evaluations of water stress have been carried out, but only at the global scale and using business-as-usual scenarios (Arnell, 1999; Vörösmarty et al., 2000). These studies have provided an overview of water resources vulnerability and have proven to be useful in identifying hot-spots, but they do not take local specificities into account. They arrive at strongly convergent results, due to their use of similar climatic and demographic projections. To complement these studies, other authors have considered alternative scenarios based on global trends (Alcamo et al., 2007; Menzel and Matovelle, 2010; Shen et al., 2008). Although these authors agree on the major causes for changes in water systems, they make different assumptions and hence arrive at divergent results for water withdrawals trends. In addition, they tend to emphasize water withdrawals and therefore accentuate their impacts on water resources and water stress occurrence. This highlights the importance of relying on expert studies whenever possible and of studying alternative scenarios based on planned progress at the local level.

Nonetheless, a number of limitations in our method should be pointed out. In the assessment of freshwater availability, the main source of uncertainty is that the Water Balance Model used does not include a separate groundwater reservoir. Like other regional-scale models – e.g. MacPDM (Arnell, 1999) and WaterGap (Döll et al., 2003) – the model defines groundwater resources by drainage from soil moisture. Consequently, water stress may have been misevaluated in some catchments that are highly dependent on groundwater resources, notably in Libya and Malta. In Libya, for example, 80% of water supply comes from fossil groundwater resources (Margat, 2004). Moreover, as in other regional-scale studies, it was not possible to evaluate the seasonal match or mismatch between water demand and water availability, because no estimation was made of the monthly dynamics of water withdrawals for all 73 catchments. In addition, the changes in the seasonal distribution of water from earlier snowmelt that is potentially available for withdrawal were not assessed, although they could influence water stress in some mountainous catchments (e.g. Ebro, Rhone, Po, Moulouya).

As far as water withdrawals are concerned, irrigated land expansion as projected by national reports was taken into account, but without considering the possible changes in crop types. Water is certainly one of the main factors explaining why food self-sufficiency is not a realistic political aim in most of the southern and eastern Mediterranean countries (Fernandez, 2008). The respective shares of rainfed and irrigated agriculture and the types of crops to be produced depend not only on water availability but also on factors lying outside the catchment scale and the water sector, such as food security strategies linked for instance to the evolution and volatility of international food prices as well as to geopolitical relations with exporting countries. Indeed, various southern and eastern Mediterranean countries currently depend heavily on cereal imports, as shown by their related virtual water flows and balances (Fernandez, 2008; Fernandez and Thivet, 2008). Nevertheless, this article makes it possible to verify whether these trends are compatible with future water availability and to study whether increased water-use efficiency could make a difference. Further studies could provide more in-depth analysis of the implications of climatic and anthropogenic changes for food production in the Mediterranean region. Another uncertainty is that water withdrawals for industries that are not connected to the municipal water networks and for energy production were not considered. Human pressures on water resources might then be higher than illustrated, especially in the Mediterranean catchments in Spain, France and Italy. Finally, water withdrawals were simulated independently from water resources availability. Limitation of water withdrawals as a response to shortage in freshwater availability is thus not considered. In Libya, Tunisia, Algeria and the Middle East, agricultural water withdrawals are projected to double, while water resources should decrease. However, the use of unconventional water resources for agriculture is expected to increase in these water-scarce countries (Qadir et al., 2007), which means that water stress in these areas may have been overestimated.

Despite these limitations, this paper gives a synoptic view of possible future conditions regarding water availability and water withdrawals as well as the evolution and spatial variations of water stress. It can be useful for formulating other sustainable development strategies and for identifying the catchments that are most likely to be under pressure. It points to the need to focus on these vulnerable areas and to develop interdisciplinary approaches that take account of issues at the sub-regional level such as dam operating systems or seasonal pressures (e.g. crop water demand; snow-melt). Developing such a method in collaboration with local stakeholders would make it possible to grasp specific local issues and thus provide support to water management plans.

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