Assessing maximum potential water withdrawal for food production under climate change: an application in Spain
D. González-Zeas, L. Garrote and A. Iglesias

ABSTRACT
This paper provides and tests a methodology to compute surface water (SW) availability for irrigation on regulated systems at large scale, considering different alternatives of streamflow monthly time series derived from regional climate models. SW availability for consumptive use for a river basin is estimated through the concept of maximum potential water withdrawal (MPWW). MPWW is defined as the maximum demand that can be supplied at a given point in the river network under certain conditions: management restrictions (such as ecological flows), demand priorities, monthly distribution of demand and required reliability. Calculation was applied in 567 basins that cover the entirety of mainland Spain to evaluate adaptation needs for agriculture by comparing MPWW for irrigation in the current situation and under climate change projections. The results show that streamflow monthly time series obtained from the regional climate model simulations and bias corrected by University of New Hampshire/Global Runoff Data Centre (UNH/GRDC) dataset and Schreiber’s formula provide MPWW values similar to those obtained with the observed data under current situations. Under climate change projections, the capability to satisfy water requirements for agricultural production is significantly reduced and adaptation measures are necessary to mitigate the expected long-term impact.

Key words | adaptation needs, climate change, irrigation, regulation, water availability

INTRODUCTION
Global food production depends on water from precipitation (green water) and from regulated water (blue water) that supplies irrigation. In fact, irrigated land, which represents only 18% of global agricultural land, produces on average between two to three times more than that dependent on precipitation (FAO 2011). In many regions, agriculture and water are closely linked and are responsible for the socio-economic development of many rural areas (Fischer et al. 2005). Climate change is expected to directly affect water resources, and thus agriculture, through the reduction of water availability for irrigation (Iglesias et al. 2011a). Additionally, population and economic growth will likely affect water requirements for irrigation in different regions (Rosenzweig et al. 2004; Iglesias et al. 2012).

The impact of climate change on water resources in natural regimes has been addressed globally in many studies (Vörösmarty et al. 2000; Alcamo et al. 2003; Arnell 2004). Most studies result in a projected reduction of water availability in many regions. However, defining water availability is complex since it is determined by: (1) the variability of the natural resources, (2) infrastructure, regulation and policy, (3) technology and (4) the evolution of the demand sectors (such as population and land use). Many studies have addressed some components of this complexity at the local level (Batalla et al. 2004; López-Moreno et al. 2007; Sluiter & De Jong 2007; Vicente-Serrano & Cuadrat-Prats 2007) and the challenges to provide projections under climate change (Hotchkiss et al. 2000; Fowler et al. 2007). At the global level, Vörösmarty et al. (2004) and Milly et al. (2005) provide indicators of water availability and other measures of water for people and ecosystems. Nevertheless, the results of these important studies may not provide all the information needed for developing adaptation policy.
Accounting for water storage and the role of hydraulic infrastructures is a challenge in water resources studies due to the lack of detailed and available information to address the complex analysis related to water supply systems (Zoltay et al. 2007). The natural characteristics of water resources have been modified through the construction of hydraulic infrastructure such as reservoirs to satisfy demand. Reservoirs play a critical role in making water available to users by overcoming temporal and spatial irregularities of the natural regimes (Vogel et al. 1999; López-Moreno et al. 2009). In addition, climate change threatens to alter the temporal variability of the climate variables and consequently alters the hydrological cycle by modifying the balance of systems and affecting their regulation capacity (Garrote et al. 2010).

Studies that incorporate the effect of the regulation of artificial reservoirs in the assessment of climate change impact have used water resources management models which allow evaluation of complex systems, taking into account elements of regulation and storage (both surface water (SW) and groundwater) of water uptake, transportation, use and/or consumption, and artificial recharge devices (Hingray et al. 2007; Anderson et al. 2008; Medellín-Azuara et al. 2008; Purkey et al. 2008). Similarly, water resources simulation and optimization models have been highly effective in designing and managing water resources systems (Andreu et al. 1996; Sieber et al. 2002). However, their applicability when evaluating the impact of climate change in the long term is limited, considering that they require detailed information related to hydraulic infrastructure and that they include a representation of system demands which may change over time as a result of adaptation measures. In contrast, analysis of the water resources systems and their effect on agriculture at a regional or continental scale is often difficult and unfeasible, since detailed information of the study area or the monthly streamflow series representative of the real data is unavailable. These limitations result in difficulties to perform large-scale simulations under climate change scenarios to obtain the restrictions that water availability imposes on demands.

To address these limitations, large-scale methodologies have been developed, such as that proposed by González-Zeas et al. (2012) that allows bias-corrected monthly runoff time series to be obtained from the simulation of regional climate models (RCMs) that minimize bias with respect to observed values. Furthermore, Garrote et al. (2011) have implemented a water availability and adaptation policy assessment (WAAPA) model. The WAAPA model was used by other authors (Quiroga et al. 2011a; Iglesias et al. 2011b) to evaluate agricultural decisions linked to irrigation potential. The applications of the WAAPA model emphasize the concept of water availability as the maximum potential water withdrawal (MPWW): the maximum demand that potentially could be supplied at a certain point of the river network and under given reliability criteria. A clear understanding of the possible consequences of climate change in future water availability for irrigation is essential when establishing adaptation measures based on the identified impacts (Quiroga et al. 2011a). The focus on MPWW allows global analyses of water resources under climate change scenarios on regulated systems without the need for a detailed description of the future configuration of the hydraulic system in terms of water distribution infrastructure and demands. Adaptation policy needs to use science-based information about adaptation needs for irrigated agriculture. This study provides an assessment of the impact of climate change on water availability for irrigated agriculture in regulated systems, using a methodology that can be applied to large-scale studies (regional and global) in order to identify adaptation needs. The analysis is carried out in 567 basins that cover the whole of mainland Spain, using the time series of hydrological observations and the output of regional climate models from the PRUDENCE project (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) (Christensen et al. 2007). The specific objectives are: (1) to assess to what extent the bias corrected monthly time series from the RCM simulations can be used for water availability studies by comparing them with the observed water availability; (2) evaluate MPWW as an indicator of water availability under climate change projections; and (3) identify adaptation needs and priorities at the regional scale.

**METHODS**

**Approach**

Considering that properly calibrated hydrological models may not be available for large-scale areas, bias-corrected
runoff outputs from the RCM simulations are tested in reproducing the observed water availability. Due to the bias of the climate change scenarios, climate change projections are constructed by taking into account the ‘observed streamflow series’ and series based on the alternatives that best reproduce the observed water availability in the current situation. The correction of the current streamflow series is made by modifying the key statistics (relative change in mean and coefficient of variation) obtained from the RCM simulations and also by using a climate formula. Gross MPWW for consumptive use (urban and agricultural demand) is determined using a methodology for calculating water availability on regulated systems. Net water availability for irrigation is calculated by subtracting urban demand (UD) from the gross MPWW. Finally, the adaptation needs are identified by comparing irrigation demand (ID) (supplied solely by (SW) availability) and net water availability, as summarized in Figure 1. It should be noted that the study does not seek to evaluate the impact of climate change on water demand for agriculture, although it does allow adaptation needs to be established according to the identified impacts on SW availability for agriculture in the long term and considering that water will be a limiting factor for future food production in irrigated land. The methodology entails the following three main components: (1) evaluation of MPWW (accounting for storage and reservoirs systems) under a control scenario using different alternatives of streamflow monthly time series obtained from the simulations of the RCMs, in order to assess the capability of the alternatives to reproduce the observed water availability; (2) assessment of MPWW under climate change projections; and (3) determination of adaptation needs for agriculture by comparing current water demand with water availability for irrigation in the current situation and under climate change projections.

Data used in this study

Study area

Spain is a country with a long-standing culture of water management that has resulted in large areas of irrigation agriculture. The high hydropower potential and the need for managing drought and flood extremes has conditioned the construction of a large number of reservoirs that provide water in the highly demanding summer months where natural runoff is extremely low. Reservoirs in a semi-arid climate serve also as buffers to provide ecosystem services during dry periods (Richter & Thomas 2007). The temporal and spatial heterogeneity and variability of water resources in Spain has been met with a remarkable organizational structure that includes public participation since the seventeenth century (Rahaman & Varis 2005). The study considers 567 basins that cover the mainland. The 338 elemental sub-basins are defined from points in the river network relevant to management of water resources, with the remainder of the basins being obtained by accumulating all the elemental sub-basins located upstream from the point under consideration. They are defined by the topology of the river network, from the small one at the headwater basin to the largest one draining into the sea. Figure 2 shows the 338 elemental sub-basins and the accumulated basins and classifies them into river basin districts (RBDs).

Observed data

The natural regime monthly runoff time series estimated by the SIMPA model (Estrela & Quintas 1996) are available in Spain. This model has been calibrated over 100 control points throughout the country, using stations where streamflow is measured in natural regimes (Álvarez et al. 2004).
These series are representative of hydrological behaviour in Spain and the information is used as a reference for the observed data for the period 1961–1990.

Regional climate models

The climate change scenarios used in this study are provided by the PRUDENCE project (Christensen et al. 2007). The PRUDENCE project provides outputs of meteorological variables under A2 and B2 emission scenarios that reflect different socio-economic pathways and therefore different levels of greenhouse gas (GHG) forcing for the climate models. Since the analysis in this work is centred on physical aspects, the study has focused on one emission socio-economic emission scenario (A2) and a full range of climate models that consider the projections made by eight RCMs nested in a single global model, referred to as HadAM3H. The new IPCC report (2013) evaluates the level of GHG emissions comparable to those of the A2 scenario as a plausible future. However, it is important to note that the A2 emissions are in the upper range of emissions considered and therefore could be considered a scenario with little mitigation policy. Given that the DMI model has three different simulations, in total the study draws on data generated by 10 climate simulations from the PRUDENCE project (Table 1). The simulations of RCMs provide information relative to a large number of variables (temperature, precipitation, runoff, solar radiation, among others) with daily, monthly and seasonal resolution for the control scenario (period 1961–1990) and for the climate change scenario (period 2071–2100) under the A2 emission scenario.

Bias-corrected monthly runoff time series

Monthly runoff time series in natural regimes are required in order to assess water availability in a water resources system in the control scenario. Many authors use a rainfall–runoff model forced with climatic variables for this purpose. However, when working with large-scale areas, for which no reliable calibration of a distributed hydrological model is available, the use of the runoff simulated by the RCMs is an alternative to be considered. Taking into consideration that the bias is one of the factors that limits the use of the runoff simulated by the RCM, we have applied bias-correction techniques in order to obtain monthly runoff time series representative of the observed data. According to the results obtained by

Figure 2 | Elemental basins of study. The methods used in this study were applied to the accumulated basins, being a total of 567 basins. The river basin district code is defined in Table 2.
González-Zeas et al. (2012), the University of New Hampshire/Global Runoff Data Centre (UNH/GRDC) dataset (Fekete et al. 2002) and Schreiber’s formula (Schreiber 1904) were the alternatives that provide runoff values nearest to the observed data. The UNH/GRDC provides high-resolution annual and monthly mean runoff outputs from a water balance model that preserves the accuracy of measurements of observed flows at the main hydrologic stations around the world (Fekete et al. 2013). Similarly, Schriber’s formula based on aridity index (Arora 2002) defined as the ratio between the potential evapotranspiration and precipitation, allows annual time series that minimise the bias with respect to observed data to be obtained. A simple bias-correction methodology is used, based on the determination of annual correction factors which are obtained using the UNH/GRDC and Schreiber’s formula alternatives. These multiplying factors are used to correct the monthly runoff time series simulated by the RCMs. In order to assess the capability of these alternatives for use in water availability studies, 31 streamflow simulations at basin scale are considered: one corresponding to the observed data, 10 to the direct runoff of the RCMs, 10 to the direct runoff bias corrected by the UNH/GRDC dataset and 10 to the direct runoff bias corrected by Schreiber’s formula (one for each RCM simulation). The goodness of fit between MPWW obtained by the observed data and the different alternatives considered is evaluated through statistical indicators.

**Statistical indicators of adjustment**

Statistical indicators are used to determine agreement between the MPWW observed in a current situation and MPWW obtained by the different alternatives considered. To compute the goodness of fit, the bias and the index of agreement are evaluated.

The bias reveals the tendency of the model to overestimate or underestimate one variable and quantifies the systematic error of the model (Janssen & Heuberger 1998). The bias can be determined from the mean error, which is normalized by the mean of the values observed for the group of 567 accumulated basins and for the different alternatives analysed, as follows:

$$\text{Bias} = \frac{S - O}{O}$$  \hspace{1cm} (1)

where $S$ and $O$ represent, respectively, the mean annual simulated water availability and observed water availability for the group of basins studied.

The index of agreement is a measure of the mean relative error obtained by normalizing the mean quadratic error with respect to the potential error, which represents the largest value that the squared difference of each pair can attain. As a dimensionless measure that can be used to compare models, and one that is broadly discussed by Willmott (1981, 1982), the index of agreement is expressed...
in the following manner

\[ d = 1 - \frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \]  

(2)

where \( S_i \) represents the simulated water availability in basin \( i \), \( O_i \) is the observed water availability in the basin \( i \), \( \bar{O} \) is the mean observed water availability, \( n \) is the number of basins studied and \( d \) is the index of agreement (which varies between 0 (not a good fit) and 1 (perfect fit)).

**Climate change projections**

The use of RCMs is an important tool for evaluating water management under future climate change scenarios (Varis et al. 2004). Nonetheless, it is well known that the output of the RCMs cannot be used directly if there is no procedure that eliminates the existing bias (Sharma et al. 2007). For this reason, in order to analyse the effect of climate change on water availability for irrigation in a regulated system, the authors propose generation of climate change projections based on the bias-corrected runoff alternatives. These alternatives are tested by a comparison with the results obtained with the climate change projections based on the observed and bias corrected by Schreiber's formula. The corresponding climate change projections of monthly runoff are obtained as follows:

where \( n \) is the total number of years, \( j \) ranges from 1 to 12 and represents the 12 months of the year, \( x \) represents each year of the study period, and \( Y^{xj}_{control} \) is the distribution of the annual value in the months as a percentage of each month with respect to the annual series, with \( x \) \( j \) being the number of months in the period of analysis.

In the second case, Schreiber's formula is applied in order to obtain annual series of runoff, via the precipitation and temperature simulated by the RCMs for the period 2071–2100. A detailed description of Schreiber's formula can be found in Arora (2002). Through use of the mean of the annual series as a representative statistical parameter, constant multiplying factors are determined and used to correct the current runoff time series bias corrected by Schreiber's formula.
water availability, $R_{CC}$ is the mean annual runoff under climate change scenario calculated by Schreiber’s formula for each of the 10 RCMs and $R_{control}$ the mean annual runoff under control scenario calculated by Schreiber’s formula for each of the 10 RCM simulations.

**Calculation of MPWW**

To compute water availability for irrigation under control scenario and under climate change projections, this study follows the basic methodology presented by Garrote et al. (2011). The main rationale of the analysis is to estimate the regulation capacity of reservoirs under climate change scenarios. Climate change scenarios contemplate projections several decades into the future. In this time horizon, it is very likely that water supply systems will experience significant changes with respect to their current configuration, making it difficult to perform detailed water resources management simulations. Nevertheless, in well-developed areas like the case study, the available reservoir storage is a very relevant feature that is not likely to change much in the future. The future offer of water resources available to potential demands will be the result of the regulation capacity of reservoirs acting on future hydrologic scenarios, subject to the constraints imposed by water management. A computational model has been developed to analyze these aspects in large-scale regions. The aim is determining MPWW: the maximum demand that could potentially be supplied in every study basin under certain conditions (demand seasonal distribution, water supply system management and reliability criteria).

Basic inputs to evaluate MPWW are the sub-basin and river network topology, the streamflow series in natural regimes entering different points of the river network, the reservoir characteristics (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates), the main characteristics of water demands, both urban and agricultural (monthly distribution, return flow and required reliability) and management restrictions (ecological flows, demand priorities and reservoir operation criteria).

The input data for the study presented here are based on a large database that was compiled for the White Paper on Water in Spain (MMA 2000). The database consists of naturalized flows, demands and infrastructure for all water resource systems in the Spanish mainland. Model construction was based on the hydrographical network. The model topology included all rivers with current mean annual flow greater than 50 hm$^3$/yr and rivers that currently sustain significant demands. All together, rivers explicitly included in model topology represent over 86% of the mean annual flow generated on the Spanish mainland. The model included the regulation infrastructure available in every sub-basin, considering all reservoirs with storage capacity of 200 hm$^3$ or greater, and those with storage capacity between 10 and 200 hm$^3$ with a ratio of storage volume to mean annual flow equal or greater than 0.3. All together, reservoirs included in the model represent more than 89% of total storage volume in the area under study. Data regarding reservoir storage volume versus surface area and monthly potential evaporation were collected for all reservoirs. An available storage of 95% of active capacity was considered in the model, to take into account reservoir storage allocated for flood control. The model thus built consists of 568 nodes, 567 stream arcs and 202 reservoir nodes, and provides a reasonably detailed representation of water resources systems in mainland Spain.

To compute MPWW, it was considered that potential demands were distributed over all model nodes. A demand node was defined in the upstream end of every river reach in the model, assigning return flows to the downstream end of the corresponding river reach. A mixed monthly distribution of the demand was considered, given by a constant UD (20%) and by a seasonally variable ID (80%), which corresponds to the average distribution in Spain. The monthly distribution of the agricultural demand was obtained from MMA (2000) and calculated as a percentage of the mean annual streamflow. An average return flow of 20% of supply was considered in every demand node.

The maximum demand values that satisfy the reliability criterion on every model node were computed applying an algorithm based on the repetition of simulations with a simple reservoir operation model, modifying demand values until reliability criteria are met. The reservoir operation model performs the following operations in every monthly time step: (1) compute evaporated volume and subtract it from available storage, consequently; (2) subtract prescribed ecological flow from monthly inflow or storage; (3) increase
storage with the remaining monthly inflow, if any; (4) satisfy demand if there is available storage; and (5) compute uncontrolled spills, if storage is larger than capacity. As a result, a set of time series of monthly spills, ecological flows and monthly volumes supplied to the demand is obtained.

The time series of monthly volumes supplied to the demand is used to evaluate supply reliability. Reliability criteria were established according to the water master plans of Spain, which consider for ID 100% time reliability, with the following failure criteria: maximum annual deficit higher than 50% of annual demand, maximum biannual deficit higher than 75% of the annual demand and maximum decennial deficit greater than 100% of annual demand (MMA 2000).

The algorithm to estimate MPWW applies the bisection method. It starts searching an interval that includes the solution, such as, for instance, annual demand between zero and mean annual flow. In every step, the reservoir model is applied to obtain the reliability of the tentative annual demand, which is defined as the midpoint of the previous interval. The method selects the new subinterval depending on whether the required reliability is met. In this way, the interval that contains the solution is reduced in width by 50% at each step until the remaining interval is within the required precision.

The algorithm to estimate MPWW is applied recursively in every node, starting from upstream nodes. Every reservoir is managed to meet the requirements of only local demand, which implies the simplification that there are neither system interconnections nor large-scale water distribution infrastructure. Downstream nodes may only use uncontrolled spillage from upstream reservoirs and return flows from upstream demands, in addition to streamflow generated locally in the sub-basin. A set of local MPWW values is obtained for every node. The final value assigned to every node is the sum of all the local MPWW of upstream nodes.

The results obtained under the simplification that there are neither system interconnections nor large-scale water distribution infrastructure provide a lower bound for the MPWW. If an extensive water distribution network is available, the values of theoretical MPWW are higher because any demand can be supplied from any source available in the network, and therefore all reservoirs could be managed in a coordinated way to supply all demands in the basin. This can lead to an increase in MPWW ranging from 20% to 50%, depending on hydrologic conditions and reservoir configuration and location. However, this management is not applied in practice in very large basins. RBDs are usually divided in subsystems that are managed independently. For instance, in Spain, the 13 RBDs that are analysed in this study are divided into 127 subsystems and therefore the simplification adopted is a good approximation to the actual management of the systems.

**Policy assessment: adaptation needs under climate change projections**

The relationship among natural water resources, regulation and water demands is essential when evaluating the effectiveness of possible management alternatives in ensuring an adequate water supply (Iglesias et al. 2007); by which the objectives of the adaptation policies for agriculture may be defined through the comparison between water requirements for agriculture in the current situation and water availability for irrigation under current and future conditions. This comparison allows the establishment of adaptation needs by identifying the most vulnerable areas to climate change and those which should be addressed with greater urgency. In order to reduce the disparities between water supply and demand, it is important to take into account changes in the water supply reliability when addressing water resources management studies (Quiroga et al. 2011). Thus, water policies may help to recover the balance between supply and demand, according to the identified priorities (Bates et al. 2008). In this regard, two possible management alternatives may be applied under climate change scenarios: (1) maintenance of current water allocation for agriculture, though with the probability of reducing supply reliability, and (2) reduction of water allocation for agriculture to obtain satisfactory water supply reliability.

**RESULTS**

**Water availability analysis under different alternatives of current streamflow**

The water availability analysis is done under the simplification of assuming that there are only urban and IDs in the
system. This assumption is reasonable, since UDs are a minor fraction of total demands in Spain and are generally supplied with very high reliability. Therefore, gross MPWW, available to satisfy jointly agricultural and UD, is calculated under current conditions (period 1961–1990), using both the observed data series and 30 alternative series of monthly natural runoff. The reliability criterion adopted is based on the analysis of maximum deficits over periods of different length. Supply to a given demand satisfies the reliability criterion if: (1) maximum deficit in 1 year is not larger than 50% of annual demand; (2) maximum deficit in any period of 2 consecutive years is not larger than 75% of annual demand; and (3) maximum deficit in any period of 10 consecutive years is not larger than 100% of annual demand.

The alternative that provided the closest approximation to the water availability computed with observed data series was evaluated through use of goodness-of-fit statistics. Figure 3 shows the results from the bias and the index of agreement for the MPWW calculated by using direct runoff, runoff corrected by the UNH/GRDC dataset and that corrected by Schreiber’s formula, in each case for the 10 simulations of the RCMs. The results reveal that those adjusted through Schreiber’s formula are the most satisfactory for the observed availability for all the RCMs, followed by MPWW calculated through use of the series corrected by the UNH/GRDC dataset and that corrected by Schreiber’s formula, in each case for the 10 simulations of the RCMs. The best fit is obtained with the GKSS model with a bias value of −1.3% and index of agreement of 0.991; in the second, the GKSS and MPI models show bias values of −9.8% and −6%, and indices of agreement of 0.988 and 0.990, respectively. The direct runoff of the RCMs shows the least favourable values.

Therefore, the alternatives that best represent MPWW in control scenarios (and those later used to generate climate change projections for the period 2071–2100) are the bias-corrected series of monthly runoff performed with the UNH/GRDC dataset, and the bias-corrected series performed through Schreiber’s formula, with the seasonal distribution of the GKSS model being used in each case. The hydrological data used to compute SW availability for irrigation by RBDs of Spain are shown in Table 2.

Table 3 shows the agricultural and UD supplied from SW, obtained from MMA (2000), of the RBDs in Spain. Given the interest in evaluation of net water availability for irrigation, the UD is subtracted from gross MPWW obtained with the model. Table 3 shows water availability for irrigation by RBD, acquired from observed data and from the two alternatives previously selected, with UD being excluded. The total water availability for irrigation in Spain, obtained from the UNH/GRDC dataset and from Schreiber’s formula, differs from the water availability calculated from the observed data by 10% and 5%, respectively.

Figures 4(a)–4(c) show contrasts in the behaviour at each RBD in levels of current demand for irrigation and net water availability obtained from observed data, series bias corrected by the UNH/GRDC dataset and bias corrected by Schreiber’s formula. The results illustrate equilibrium between current demand and water availability for irrigation at the majority of the RBDs, although some (such as South and Segura) reveal a
Table 2 | Hydrological data used in the model for observed data, corrected by UNH/GRDC dataset and corrected by Schreiber’s formula (GKSS model in both cases)

<table>
<thead>
<tr>
<th>River basin district</th>
<th>Code</th>
<th>Area (km²)</th>
<th>Mean annual flow (hm³/year)</th>
<th>Fraction (%)</th>
<th>Total UD and ID (hm³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed UNH/GRDC Schreiber Storage volume (hm³)</td>
<td>UD</td>
<td>SW</td>
<td>GW</td>
</tr>
<tr>
<td>North I</td>
<td>NorI</td>
<td>16,321</td>
<td>12,509 12,170 9,853</td>
<td>2,502</td>
<td>77 71 29</td>
</tr>
<tr>
<td>North II</td>
<td>NorII</td>
<td>13,889</td>
<td>11,540 10,344 10,972</td>
<td>380</td>
<td>214 89 11</td>
</tr>
<tr>
<td>North III</td>
<td>NorIII</td>
<td>4,463</td>
<td>4,009 2,830 2,518</td>
<td>73</td>
<td>269 92 8</td>
</tr>
<tr>
<td>Galicia Coast</td>
<td>Gal</td>
<td>8,599</td>
<td>8,696 8,946 6,576</td>
<td>451</td>
<td>210 89 11</td>
</tr>
<tr>
<td>Duero</td>
<td>Due</td>
<td>75,545</td>
<td>12,344 12,159 14,500</td>
<td>6,739</td>
<td>214 78 22</td>
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<tr>
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<td>Taj</td>
<td>55,758</td>
<td>10,348 8,352 7,861</td>
<td>9,958</td>
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<td>Gna</td>
<td>60,700</td>
<td>3,918 3,688 2,752</td>
<td>7,903</td>
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<td>Guadalquivir</td>
<td>Gqv</td>
<td>60,940</td>
<td>8,077 9,569 2,915</td>
<td>7,967</td>
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<td>Sou</td>
<td>9,973</td>
<td>1,446 525 488</td>
<td>1,223</td>
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<tr>
<td>Segura</td>
<td>Seg</td>
<td>15,752</td>
<td>760 212 548</td>
<td>739</td>
<td>172 96 4</td>
</tr>
<tr>
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<td>Juc</td>
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<td>16,922 23,636 21,023</td>
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<td>313 74 26</td>
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<td>Catalonia</td>
<td>Cat</td>
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<td>710</td>
<td>682 89 11</td>
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<tr>
<td>Spain</td>
<td></td>
<td>45,526</td>
<td>95,705 95,532 85,771</td>
<td>48,353</td>
<td>4419 80 20</td>
</tr>
</tbody>
</table>

The fraction of the surface water (SW) and ground water (GW) of the total urban demand (UD) and total irrigation demand (ID) is also shown by RBDs of Spain.

Table 3 | Current urban and agricultural demand (hm³/year) supplied from SW, and net water availability for irrigation (hm³/year) for observed data, corrected by UNH/GRDC dataset and corrected by Schreiber’s formula (GKSS model in both cases) by RBDs in Spain

<table>
<thead>
<tr>
<th>River basin district</th>
<th>Code</th>
<th>UD</th>
<th>SW</th>
<th>Agricultural demand</th>
<th>Observed water availability</th>
<th>Corrected by UNH/GRDC water availability</th>
<th>Corrected by Schreiber water availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>North I</td>
<td>NorI</td>
<td>55</td>
<td>475</td>
<td>3,649</td>
<td>3,198</td>
<td>3,375</td>
<td>3,198</td>
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<tr>
<td>North II</td>
<td>NorII</td>
<td>192</td>
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<td>1,744</td>
<td>1,903</td>
<td>2,041</td>
<td>1,903</td>
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deficit in levels of satisfaction of ID and, therefore, are characterized as those which encounter water scarcity problems. Conversely, in the wetter basins (such as North I, II and III) water availability for irrigation exceeds current demand. The results obtained by the two earlier mentioned alternatives (from the UNH/GRDC dataset and Schreiber’s formula) resemble those obtained with observed data, which would justify the use of such alternatives for large-scale studies of water availability. However, it should be noted that these alternatives do show a deficit of current water availability at the Guadalquivir and Jucar RBDs.

Water availability under climate change projections

Figures 5(a) and 5(b) show the variation (the difference between climate change scenario A2 and the control scenario, per unit) of the annual mean streamflow and of the coefficient of variation obtained through the 10 simulations of the RCMs at the RBD. The results show a decrease in the annual mean streamflow, with values ranging from 26% to 56% and an upward trend in variability (particularly in the basins located in the north) with values that reach 58%.

Water availability for irrigation was evaluated under climate change projections using the same approach as in the current situation. Current UD supplied from SWs was subtracted from MPWW obtained with the model. This implies the hypothesis that UD will remain approximately constant during the period under study. The variation of water availability obtained through the observed data, that corrected by the UNH/GRDC dataset and Schreiber’s formula, is shown in Figure 6(a)–6(c) for each of the 10 simulations of RCMs at the RBDs. The results draw attention to the influence of the changes in basic statistical data (mean and variability) of the natural streamflow which have a significant influence on the decrease in water availability for irrigation under climate change scenarios. The impact will be of a greater or lesser intensity depending on the hydrological characteristics of the RBDs and the
respective capacity of regulation. In the case of the observed data (Figure 6(a)), water availability for irrigation is reduced in all the RBDs and RCMs, which leads to decreases that range from 23% to 72%. The basins with most significant decreases are the RBDs of Catalonia, Guadalquivir, Jucar, North III, Segura and South which show values greater than 50%. The results obtained with climate projections generated from datasets bias corrected by the UNH/GRDC
dataset significantly resemble those obtained with observed data and show agreement that the impact of water availability for irrigation affects all the RBDs. Those results acquired with climate projections bias corrected by Schreiber’s formula show more pronounced decreases than those obtained with observed data and projections based on the UNG/GRDC. This could be a consequence of the use of a climate formula and an inability to capture the impact of torrential rainfall events in arid or semi-arid regions, such as those located in the south (the Guadalquivir, Segura and South RBDs). However, the variation of water availability obtained, both with observed data and the two alternatives analysed, shows agreement in that water will remain an important limiting factor for irrigated agriculture as a consequence of climate change.

Figure 7 shows the results obtained at the basins examined. It shows the contrast between water availability under the control scenario (period 1961–1990) and that under the emission scenario A2 (period 2071–2100) obtained from observed data (Figure 7(a)), the UNH/GRDC dataset (Figure 7(b)) and Schreiber’s formula (Figure 7(c)). The 567 basins studied are represented by each point; in each of the three cases the results for the 10 simulations of RCMs are shown. In general, a reduction in water availability for irrigation is noted across the RCMs under scenario A2, with the exception of the ICTP model that reveals an upward trend for projections obtained from observed data and the UNH/GRDC dataset. The results obtained from the series bias corrected by Schreiber’s formula show a greater dispersion and greater decrease in water availability.

Adaptation needs under climate change projections

Figure 8 shows a comparison, in terms of absolute values at the RBDs, of water availability for irrigation under current and climate change projections with current ID. In accordance with future scenarios, it is known that climate change will also produce an increase of water ID, owing
to precipitation and an increase in evapotranspiration (in turn due to high temperatures and changes in other meteorological variables), however, this study does not include adjustments of the demand for future scenarios, given that our results emphasize the potential impact that would affect water availability for irrigation. In the case of the climate projections generated from the observed data (Figure 8(a)), the results in the control scenario highlight equilibrium between water availability and current demand for irrigation in the majority of RBDs. Under climate projections the ability to satisfy needs for agriculture is reduced significantly, with application of adaptation measures to recuperate equilibrium between supply and demand being necessary. Given that the RBDs of the Guadalquivir, Guadiana, Jucar, Segura, South, and Tagus are more vulnerable to climate change, they would require a greater degree of attention in facing the long-term potential impact. In Spain, where enough regulation capacity is already available and many non-conventional water resources are already mobilized, a reduction in water availability for agriculture would imply application of measures centred on demand management. The two alternatives analysed (the UNH/GRDC dataset and Schreiber’s formula, and shown in Figures 8(b) and 8(c), respectively) offer results for water availability under climate change projections that resemble those obtained with observed data. These results enable validation of the use of such alternatives when evaluating the impact of climate change on large-scale water availability.

Figure 8 | Water availability–demand performance analysis in the RBDs of Spain. The dotted line represents the water availability in current conditions, the circles show the current agricultural demand and the box plot shows the water availability under climate change projections obtained by the 10 RCM simulations. The lines extend up to 1.5 times the interquartile range to the right and left of the box. The box extends from the 25th to the 75th percentile. The line within the box indicates the median projection, and the crosses outside the box indicate the outliers. Climate change projections based on: (a) observed data, (b) UNH/GRDC dataset and (c) Schreiber’s formula. The river basin district code is defined in Table 2.
DISCUSSION AND CONCLUSIONS

The study provides insights about the future SW limitations to supply current ID. This study proposes a methodology to examine the effect that regulation has on the determination of SW availability for irrigation and illustrates the possibility of using it in large-scale studies where the accessible information is limited on many occasions. The methodology enables direct evaluation of climate change projections without the need of relying on an alteration of historical or observed data. This is achieved by constructing future scenarios of streamflow, based on runoff simulated by the RCMs and bias corrected by Schreiber’s formula and the UNH/GRDC dataset, in turn utilizing in each case seasonal distribution simulated by the GKSS model, which best reproduces the observed water availability. These two alternatives of calculation provide water availability estimates under current and climate change scenarios comparable to those obtained with the observed data. Therefore, the approach is adequate to estimate water availability under climate change projections and the evaluation of adaptation needs. The study characterizes adaptation needs in the water districts of Spain, by comparing the current ID (discounting the percentage of the demand supplied by groundwater) with SW availability for irrigation, through the use of net MPWW as an approximate indicator of the impact on long-term food production.

There are some limitations of our approach and results. First, our description of Spanish water resources system is schematic and does not include groundwater, non-conventional water resources, such as water recycling or desalinization, water transfer facilities or water distribution infrastructure. The use of groundwater for irrigation in arid and semi-arid areas has experienced a large increase in the last 50 years in Spain; groundwater represents around 20% of the total ID in Spain (Hernández-Mora et al. 2007). Groundwater use is adapted to demand allowing an additional source that complements the irregularity of surface runoff (López-Geta 2006). The use of groundwater is significant especially in areas with water shortages. In the same sense, according to López-Geta (2006), the volume of groundwater use also increases in times of scarcity, when SW resources are less available. Our study focuses on SW for irrigation and does not take into account the use of groundwater. However, by focusing on SW, the study provides insight on future needs and priorities for adaptation of regulated irrigation systems. Second, our analysis provides gross SW availability (MPWW) and distributes it only into urban supply and irrigation according to the current situation in Spain. However, other non-consumptive demands are present in the system, such as hydropower, recreation or aquaculture, that may alter the allocation of water to irrigation. Third, our proposed adaptation strategies do not capture the full range of possible climate change policies, particularly since they do not propose additional infrastructure, subsidies, or voluntary market solutions. Additionally, in the context of the water policy model, the factors considered are likely to be only the most salient ones and other important future factors are not considered.

Water availability for irrigation under climate change clearly decreases and is more uncertain. Scenarios project a reduction in runoff and an increase in the corresponding coefficient of variation, resulting in a significant reduction of water availability. Similar results of runoff reduction have been obtained by Rodríguez (2004), Wurbs et al. (2005) and Iglesias et al. (2011b), in which decreases in streamflow are translated into consequent reduction in the resource available. Our results define the changes with greater detail over the entire territory and characterize the combined changes or magnitude and reliability that are necessary to prioritize adaptation strategies in the basin districts.

The information associated with the differences between current ID and water availability under climate change projection, in addition, enables evaluation of the extent to which irrigation needs could be affected according to the spatial distribution of the water availability. An important, though not surprising, finding is the identification of a few specific geographical areas that need further attention, such as Segura and Guadalquivir basins. In fact, the Segura Basin is one of the most interesting cases of water conflicts in Spain, with problems meeting IDs. In addressing this question, similar studies, such as those carried out by Izaurralde et al. (2003), Rosenberg et al. (2003) and Rosenzweig et al. (2004), have identified the implications of climate
change on water availability at the point of satisfying ID. The spatial disparities in the identified impacts are given by the existing capacity for regulation at the RBDSs and hydrological characteristics. Climate projection emphasizes that the predominant equilibrium between water availability and ID under current conditions will be considerably affected under future scenarios. It can be noted that in Spain, even under current climate conditions, water resources are overused in several regions and that agricultural use requires not only large volumes of water but also at times when the hydrological cycle is unable to provide it (hydraulic infrastructure is hence necessary for such demand to be satisfied). Thus under climate change conditions, the country is highly sensitive to diminishing water resources or an increase in variability. Our analysis may have some limitations due to the uncertainty of climate scenarios and the lack of resolution in the simulation of water resources systems. However, our results indicate that strong policy actions will be needed to address the issue of water availability in the future. The main strength of the results is their quantitative nature to translate the expected alteration of hydrologic time series due to climate change into global figures of future water availability accounting for the storage available for regulation. These findings highlight the importance of accounting for non-stationarity of water resources available for consumption for the development of future water policy.

This clearly shows the need for adaptation measures centred on management that enables the future impact of climate change on agriculture to be faced. Given that water availability is influenced by changes in variability and seasonality of runoff, as well as by modification of the operation of existing water infrastructure or investment in new infrastructure, adaptation policies in principle should be focused on both supply and demand management. The first case is an alternative of limited scope, owing to the abundance of hydraulic infrastructure in Spain, that would make further development inefficient except in local situations. The second case involves both a need to reduce pressure on hydrological systems (to avoid jeopardizing future sustainability) and to adapt to a constant reduction of water availability due to climate change which, in turn, obliges water planning to become increasingly centred on reducing demand. In such a context, management alternatives could either be focused on maintenance of agricultural demand but providing compensations for the reduction of reliability, or be centred on reduction of agricultural demand in order to achieve adequate reliability.

Climate change will affect not only water availability but also demand. However, the demand in Spain is linked to long-term administrative concessions. In accordance with Chávez et al. (2013), in the case of a modification or increase in the amount of water demanded by agriculture in the future, the cultivated area or the agricultural crops should be adapted to the water allocated to the irrigation district in correspondence with the water concession. In this context, our study is focused on evaluating to what extent the decrease of water availability will affect the water allocation for agriculture. In our model, water availability is a fraction of mean annual runoff. The amount depends on several hydrological factors. If we compare the availability for irrigation with our estimation of current ID (Figure 4), it is possible to identify that there are some basins with less availability than demand, which is an indicator of water scarcity. Nonetheless, the model is highly uncertain, thus we assume that current water availability is equal to ID. These results allow establishment of policy measures in order to maintain acceptable reliability in irrigation. The obvious policy action is therefore, to reduce ID down to availability for irrigation under climate change.

Accordingly, access to information associated with the possible effects of climate change on water availability for irrigation can entail a significant impact on the decisions in the agricultural sector. In this context, Quiroga et al. (2011b) analysed the effects of drought management plans in corn production in the Ebro Basin in Spain, with an examination of the willingness of farmers to insure themselves through purchase of a policy to offset potential hydrological risk. This could serve as an option to be considered in the future as a buffer against impact and one that could cover agricultural needs. Similarly, Meza et al. (2008) evaluated the incorporation of double cropping in irrigated Mediterranean regions, as an alternative to adaptation. In conclusion, evaluation of water availability for irrigation under different climate change projections enables identification of those areas that could potentially be affected when satisfying the water demand of agriculture.
This requires the application of adaptation measures in such a way that farmers, water authorities and other interested parties have access to the necessary information that permits them to foresee the extent to which climate change could affect agricultural production and, therefore, enable them to apply those solutions most in line with the priorities identified. The analysis moves forward our knowledge of water availability to support adaptation policy by providing an increased understanding of the variations in reasons water may fail to provide services for agriculture in the future and the geographic variability in a complex country.

ACKNOWLEDGEMENTS

This research has been supported by MAEC – AECID (Ministry of Foreign Affairs and Cooperation – Spanish Agency for International Cooperation) through its scholarships for foreigners to doctoral studies, European Commission CIRCE project (contract No. 036961), ARCO project (20080005084550) of the Spanish Ministry of Environment, Rural and Marin Affairs (MARM) and CYTED Action VIAGUA (410AC0399). Data have been provided through the PRUDENCE data archive, funded by the European Union through contract EVK2-CT2001-00132.

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First received 20 March 2013; accepted in revised form 11 February 2014. Available online 6 May 2014