Article

Effort and performance of the management of water for agriculture under climate change in Southern Europe

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Abstract: We evaluate alternatives for the management of water for agriculture under climate change in six representative basins of Southern Europe: Duero-Douro, Ebro, Guadalquivir, Po, Maritsa-Evros and Struma. Management objective is maximizing water availability, understood as the maximum demand that can be satisfied with a given reliability. We focus on water availability for agriculture. For simplification we are assuming only two types of demands: urban and irrigation. Water is first allocated to urban demands following the established priority and the remaining resources are allocated to agriculture. If water availability is not enough to satisfy all irrigation demands, management measures are applied with the goal of achieving a balance between resources and demands. We present an analysis of three possible management measures to face water scarcity in the long term scenario: increasing reservoir storage, improving efficiency of urban water use and modifying water allocation to environmental flows. These management measures are globally evaluated for the selected basins in three representative climate scenarios, comparing their possible range and effectiveness. While in some basins, like Ebro or Struma, measures can significantly increase water availability and compensate for a fraction of water scarcity due to climate change, in other basins, like Guadalquivir, water availability cannot be enhanced with management measures and irrigation water use will have to be reduced.

Keywords: water management; water availability; climate change; Southern Europe; agriculture; WAAPA model

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1. Introduction

We present the analysis of alternatives for management of water for irrigation under climate change in six representative basins of Southern Europe: Duero-Douro, Ebro, Guadalquivir, Po, Maritsa-Evros and Struma (Fig. 1). Our analysis illustrates the complexities of water allocation for irrigation and other uses in areas of water scarcity and provides guidance to decision makers on adaptation choices from a quantitative perspective.

The focus of our analysis is water availability for agriculture; particularly water management options to deal with water scarcity for agriculture under climate change. Water availability is the maximum demand that can be supplied at a specific point of a river network satisfying pre-specified reliability conditions. We estimate water availability for agriculture in each basin for a control scenario and under a climate projection. We use a simplified model of the water resources system of the basin, accounting for streamflow, reservoir storage and environmental flows. We consider two types of demands: urban supply and irrigation. We assume that urban demand has priority over irrigation. Water is allocated to urban demands first and the remaining resources are allocated to irrigation, but both demands must satisfy the reliability requirements specified for them.

In our model we consider that water scarcity arises if water availability in the climate scenario is less than water availability in the control scenario. If water scarcity is projected for a certain basin, management measures should be applied until a balance is reached between resources and demands. The obvious measure is to reduce water allocation for agriculture. We explore the possibility of other additional measures that might mitigate the need to reduce water allocation for irrigation. We focus on three kinds of measures: increasing reservoir storage, changing the allocation to environmental flows and improving the efficiency of urban water use. We evaluate the effect of these correlative measures on the need to reduce water allocation for irrigation. We compare the effect of these measures in the six basins under analysis under the climate scenarios projected by three different models.

2. Results

2.1. Water availability for irrigation

We first present the results of our analysis of water scarcity for irrigation in the six basins under study, which are shown in Figure 1. We present results for the models CRNM (top), KNMI (center) and ETHZ (bottom). Blue lines correspond to the historical period (1960-1990) and red lines correspond to the long-term time horizon (2070-2100) under emission scenario A1B. Lighter colors correspond to urban demand and darker colors to irrigation demand. Water availability in each scenario is represented by a vertical line of the corresponding color.

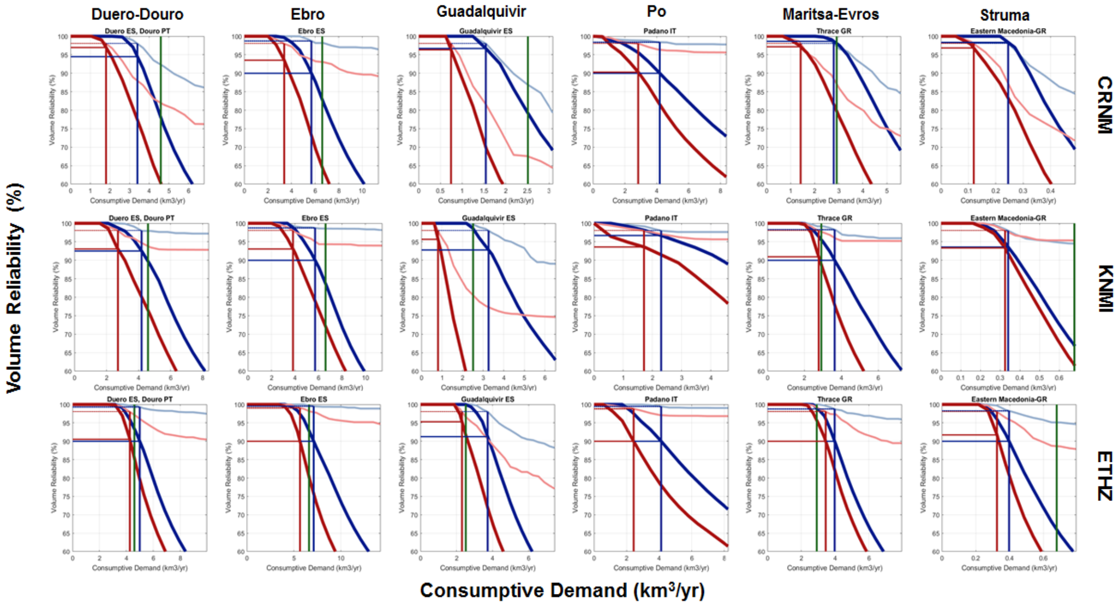

Figure 1. Demand-performance analysis in the basins under study.

2.2. Analysis of policy meaures

Next we present the analysis of the effects of different policies on irrigation water availability in the six basins. The correlative policy measures analyzed in this study are the following: (1) Increase in reservoir storage, (2) Modification of environmental flow requirements and (3) Increase in the efficiency of urban supply.

The results for the climate model CRNM are presented in Figure 2. The figure shows water availability for irrigation for the limiting reliability of urban supply (dashed lines) and irrigation (solid lines) as a function of the corresponding variables: percentage of reservoir storage in the basin (top), percentile of the monthly distribution for environmental flows (center) and per-capita consumption for urban demand (bottom). Blue lines correspond to the historical period (1960-1990) and red lines correspond to the long-term time horizon (2070-2100) under emission scenario A1B for climate model CRNM

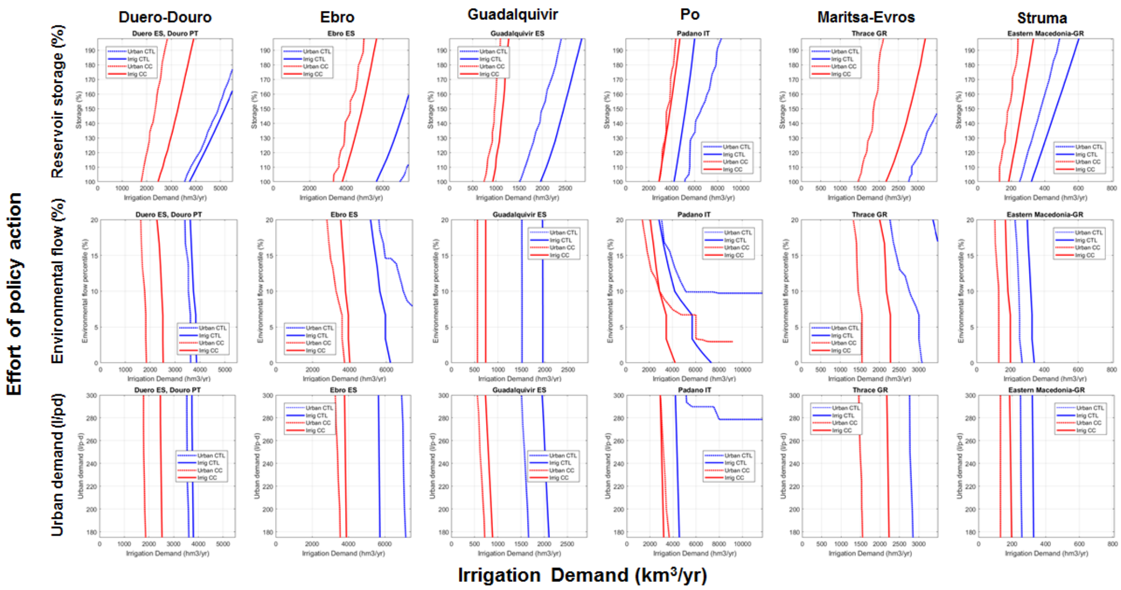

Figure 2. Water availability for irrigation as a function of the three policy efforts.

The compared effect of the three policies analyzed is presented in Figure 3, which shows the range and effectiveness of the three measures in the same units for the six basins. The figure shows the required reduction of irrigation demand in hm³/yr as a function of the correlative policy adopted. The effort of policy action represents the storage increment in hm³ (blue line), the reduction or increment of water allocation to environmental flows in hm³/yr (green line) and the reduction of urban water consumption in hm³/yr (red line). Results are shown for the CRNM (top), KNMI (center) and ETHZ (bottom) models in the long-term time horizon (2070-2100) under emission scenario A1B.

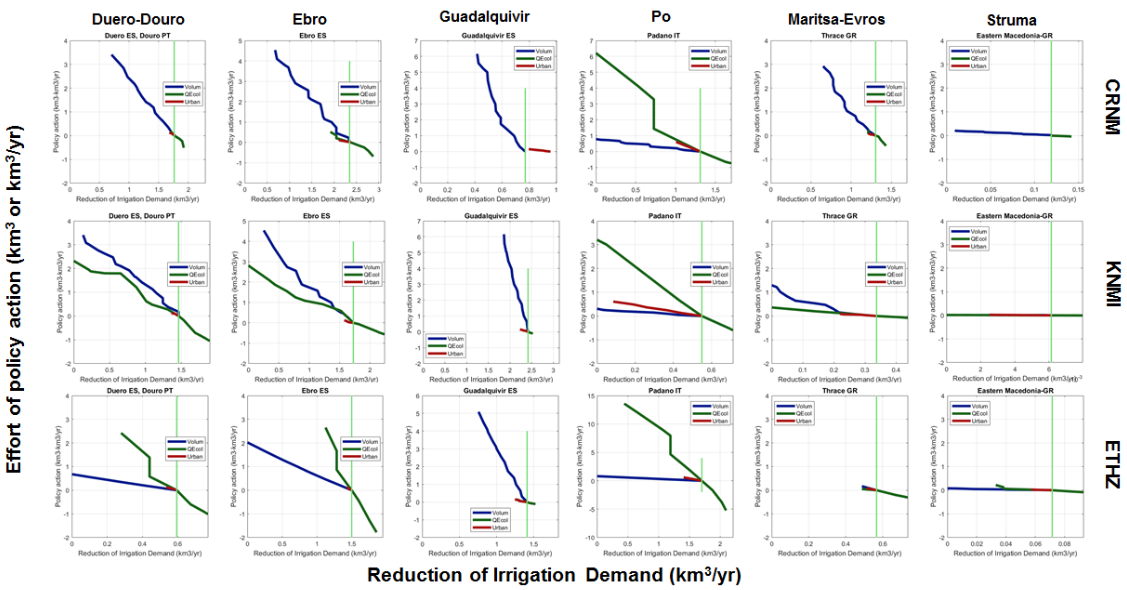

Figure 3. Compared effectiveness of the three policies analyzed.

3. Discussion

The analysis of water availability showed significant reductions of water availability in the climate scenario while compared with the current scenario. These reductions are consistent across the six basins for all three models analyzed. According to the analysis performed, the effect of growing irrigation demand on the reliability of urban demand is apparent in all cases. Water availability for irrigation in current conditions would be limited by the reliability of supply to urban demands in Duero-Douro, Guadalquivir, Po and Struma basins. Only in the case of Ebro and Maritsa-Evros the limiting condition is the reliability of irrigation demand. In the future scenarios the limiting factor is the reliability of urban demands in all cases, suggesting that irrigation will have to face strong competition for scarce resources in the future.

The green vertical line in Figure 1 corresponds to the estimated water withdrawal for irrigation, inferred from the irrigated area in each basin. The figures obtained for water availability in current conditions compare well with the estimates of water withdrawals for irrigation in each basin. In most basins these figures are actually a bit smaller than the estimated agricultural demand, but we need to account for return flows and water reuse. The distance between water availability in current and future conditions is an indicator of the intensity of climate change impacts on water resources in each basin. While in Struma the effect is relatively small, in the Guadalquivir basin this effect is really dramatic. For example, for KNMI model we obtain a reduction from 3200 hm^3/yr for current conditions to 850 hm^3/yr for the climate change projection.

With the strong reduction of water availability obtained in the analysis for most basins, the obvious adaptation measure is to reduce irrigation demand. The estimated required reduction would be the difference between water availability in the control and future scenario, in order to restore the same level of performance that is observed in the control scenario. However, demand reduction is not the only policy alternative to reach the objective of adequate supply reliability. Other measures that increase water supply or improve water use efficiency in other sectors can be applied in combination with irrigation demand management. The effects of these policy actions are shown in Figure 2. Not all basins respond to the policy actions in the same way. For instance, the basins most sensitive to reservoir storage are Duero, Ebro and Maritsa-Evros. In these basins, increasing reservoir storage can increase water availability for irrigation to a greater extent than in the other three basins. Increasing the efficiency of urban demand is the policy action that shows the least sensitivity, because urban demand is small compared to irrigation demand in all basins. Water allocation to environmental flows does not show strong sensitivity for the model shown in Figure 2 (CRNM), but this is not the case for the two other models, as can be seen in Figure 3.

We now focus on the compared effect of the three correlative policies studied. For the case of the Duero-Douro and Maritsa-Evros basins, the effectiveness of the three policies is very similar, because the three lines are almost superimposed for CRNM and KNMI models. However, the range is very different. The range of urban use efficiency is very small compared to the amount of irrigation demand that has to be reduced. The range of storage increment is also limited; especially if we account for the fact that storage has been doubled in our analysis. The Ebro and Po basins have behaviors similar to those of the Duero-Douro and Maritsa-Evros basins, with larger scope for action in storage although with less effectiveness as shown by the larger slope. The Guadalquivir basin is significantly different because the little scope for action and the very high slope of the lines imply that the only possible adaptation measure among those considered in this study is the reduction of the irrigation demand. Other Spanish basins, like Júcar or Guadiana, show a similar behavior, suggesting that reduction of irrigation demand is unavoidable in these regions if climate change projections are confirmed.

4. Materials and Methods

The methodology of analysis is based on a computation model to estimate water availability provided by a set of reservoirs in a water resources system under different hypotheses. The model, named WAAPA (Water Availability and Adaptation Policy Analysis), is based on a basic module to simulate the behavior of a set of reservoirs that supply water for a set prioritized demands, complying with specified ecological flows and accounting for evaporation losses [1].

WAAPA is a model that simulates reservoir operation in a water resources system. Basic components of WAAPA are reservoirs, inflows and demands. These components are linked to nodes of the river network. WAAPA allows the simulation of reservoir operation and the computation of supply to demands from an individual reservoir or from a system of reservoirs accounting for ecological flows and evaporation losses. From the time series of supply volumes, supply reliability can be computed according to different criteria. Other quantities may be computed using macros that repeat the basic simulation procedure: The demand-reliability curve, the maximum allowable demand corresponding to a given storage or the required storage volume to meet a given demand, all according to different reliability criteria.

The simplified water resources system models of the basins were based on the Hydro1k topographic dataset [2] and on the ICOLD World Register of Dams [3]. We divided each basin in the subbbasins included in the Hydro1k dataset, plus the basins corresponding to all dams in the basins with storage capacity larger than 5 hm^3. Reservoir data were obtained from the ICOLD database. Climate scenarios were obtained from runoff provided by Regional Climate Models (RCMs) in the ENSEMBLES project [4], using several transient model runs available for the time period from 1960 to 2100 produced by three RCMs under emission scenario A1B: CRNM, KNMI and ETHZ. Three time slices were considered: historical (1960-1990), short term (2020-2050) and long term (2070-2100). Urban demands were estimated from population data and per-capita water requirement. Subbasin population was obtained from the Global Rural-Urban Mapping Project (GRUMP), available at the Center for International Earth Science Information Network [5]. Irrigation demands were estimated from the Global Map of Irrigation Areas dataset [6], using an average consumption of 10,000 m^3/ha.yr.

We first evaluate water availability for agriculture considering two types of demand: an urban demand corresponding to the projected population in every basin with a reference allotment of 300 liters per capita and day and a variable irrigation demand. The analysis is based on obtaining the demand-reliability curve for the urban and the irrigation demand as the irrigation demand increases, as shown in Figure 4. We adopt a minimum volume reliability of 98% for irrigation demand and 90% for irrigation demand. These minimum reliability values determine water availability, which corresponds to the minimum irrigation demand that makes either demand to fail the required reliability criteria. The comparison between the water availability for irrigation in the control and in the climate change scenario provides a proxy variable to estimate exposure to climate change. If the objective of water policy is to maintain adequate reliability for both urban and irrigation demand, we can estimate the adaptation effort from the difference between water availability for irrigation in the control and in the climate change scenario. The larger the difference between current and future water availabilities for irrigation, the greater the effort required to compensate for climate change though adaptation

The analysis of the effects of management policies is illustrated with the example of the Guadalquivir basin. The correlative policy measures analyzed in this study are the following: (1) Increase in reservoir storage, (2) Modification of environmental flow requirements and (3) Increase in the efficiency of urban supply. Each of these factors is analyzed in combination with a reduction of irrigation demand by computing the reliability for the urban supply and the irrigation demands that result from the joint application of both measures.

The analysis for reservoir storage was performed by increasing the capacity of existing reservoirs in the basin progressively (in 15 stages), from the current value to almost 200% of current value and repeating the analysis of the demand reliability curve for each stage. The analysis of environmental flow modification was performed by considering ecological flows ranging from the 15% percentile of the marginal distribution of monthly flows to 5%, in 7 stages. The reference situation, assumed for the control scenario is 10%, so in this case policy might increase or decrease water availability with respect to current conditions. The analysis for urban demand efficiency was performed by considering diminishing values of the maximum allowable per capita urban demand. The starting value was 300 l/p.d and it was reduced to 175 l/p.d in 6 stages.

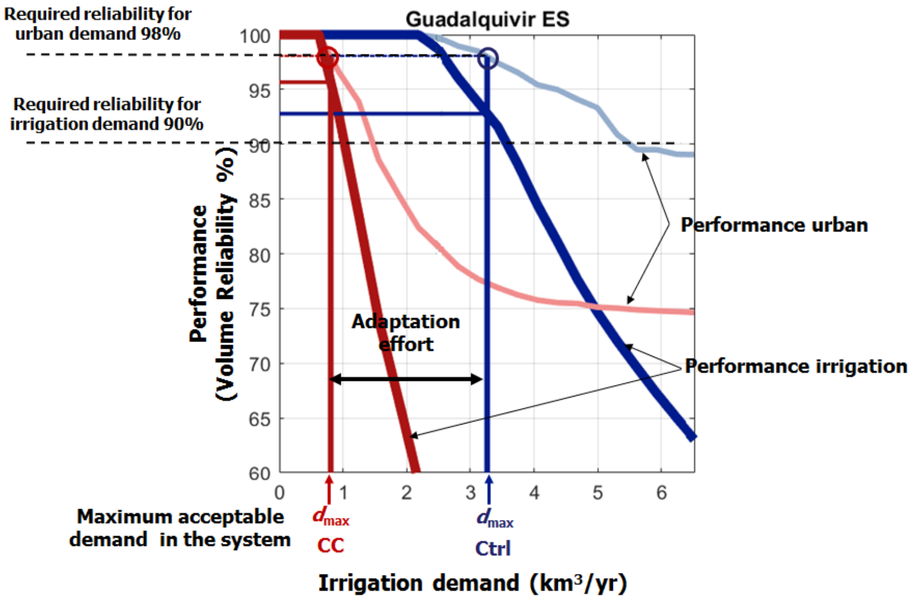

Figure 4. Methodology for the analysis of water availability for irrigation

The four plots of Figure 5 show the results for the combined analysis of demand reduction and reservoir storage in the Guadalquivir river basin. The plots show reliability for urban supply (top) and irrigation (bottom) demands as a function of irrigation demand (horizontal axis) and reservoir storage in the basin (vertical axis) for the control scenario (left) and the climate change scenario (right). Vertical lines correspond to irrigation water availability in each scenario (blue in control and red in climate change period).

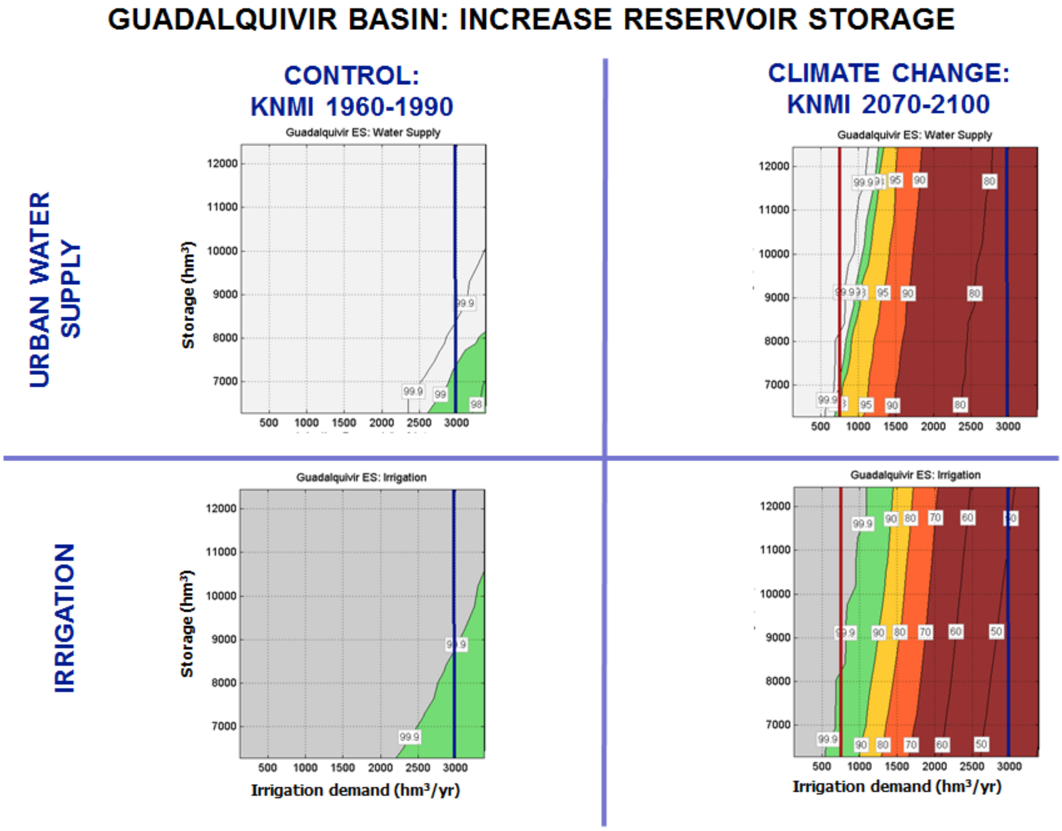

Figure 5. Demand reliability curves for the Guadalquivir river basin as a function of reservoir storage.

The lines corresponding to acceptable reliability (separation between the green and yellow areas in Figure 5) were shown in Figure 2 to determine water availability for irrigation as a function of the three policy efforts. We then took the most limiting case in the climate change scenario to produce Figure 3, where we represented the required reduction of irrigation demand as a function of the correlative measure.

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Author Contributions: Álvaro Sordo proposed the methodology and wrote the first draft of the manuscript. Alfredo Granados conducted the numerical experiments and participated in paper writing; Ana Iglesias and Luis Garrote participated in the analysis and discussion of results and paper writing, contributing to the general idea of the research.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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