Quantitative Assessment of Climate Change Vulnerability of Irrigation Demands in Mediterranean Europe

Luis GARROTE*, Ana IGLESIAS**, Luis MEDIERO*, Francisco MARTIN-CARRASCO*
* *Department of Hydraulic and Energy Engineering, Technical University of Madrid, Spain.*
** *Department of Economy and Agrarian Social Sciences, Technical University of Madrid, Spain*

Abstract: This paper presents an analysis of water resources management under climate change in Southern European River Basin Districts. The analysis is based on the Water Availability and Adaptation Policy Analysis (WAAPA) model, which focuses on the quantitative evaluation of maximum potential water withdrawal for different types of demands. WAAPA performs the simulation of water resources systems at the monthly time scale and allows the estimation of the demand-reliability curve in every subbasin of the river network. Over sixty River Basin Districts of Southern Europe have been analyzed, taking basic information from publicly available databases: basin topology from the Hydro1K database, average runoff from the University of New Hampshire GRDC composite runoff field, population from the Global Rural-Urban Mapping Project (GRUMP) and irrigation area from the Global Map of Irrigated Area dataset. Streamflow monthly time series were obtained from the results of the ENSEMBLES project in four climate scenarios for time horizon 2070-2100. Climate change vulnerability of irrigation demands is estimated from changes in maximum potential water withdrawals for irrigation in current and future scenarios. Maximum potential water withdrawal for irrigation was computed as the largest value of irrigation demand that could be supplied with a given reliability requirement once the existing urban demand is adequately satisfied. The results show significant regional disparities in vulnerability to climate change in the irrigation sector across Europe. The greatest vulnerabilities have been obtained for Southwest Europe (Iberian Peninsula) and some basins in Italy and Greece.

Key words: Water resources management, climate change adaptation, water availability

1. INTRODUCTION

In the water sector, institutions, users, technology and economy cooperate to achieve equilibrium between water supply and demand in water resource systems. This equilibrium could be achieved if conditions persisted during a sufficiently long span of time. However, changing climatic conditions and socioeconomic dynamics of the population act as external forcing that separates systems from equilibrium. Water policy is designed to correct deviations and to recover equilibrium as a response to climatic and socioeconomic forcing. The socioeconomic dynamics usually translate into a change (usually an increase) of population water needs for different purposes, which are supplied by means of the construction of hydraulic infrastructure or the definition of new management or operating rules (Iglesias et al., 2007). The possibility of climatic change is only a new external forcing that should be considered in this continuously adaptive process.

A quantitative methodology to identify and evaluate climate change adaptation policies in the Southern European region is presented in this paper. The methodology is based on the development of a GIS-based model, called “Water Availability and Adaptation Policy Assessment (WAAPA)” (Garrote et al., 2011), which computes net water availability for consumptive use for a river basin taking into account the regulation capacity of its water supply system and a set of management standards defined through water policy. WAAPA model provides a simple way to account for the influence of socioeconomic factors (hydraulic infrastructure and water policy) on climate change impacts on water resources in the Mediterranean region.

2. BASIC DATA

The region under analysis includes the major river basins from Europe draining to the Mediterranean Sea. The area under study is divided in 396 subbasins which are shown in Figure 1. The subbasins were taken from the HYDRO1k Elevation Derivative Database developed by the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS). The total area under analysis is approximately 1,750,000 km^2 with an average basin size of 4,440 km^2. The subbasins are related through the "drain-to" relationship, and the analysis is recursively applied to all possible basins, from the small headwater subbasins to the largest basins draining to the sea. For the purposes of results presentation, relevant regions coincident with major River Basin Districts of Europe have been selected.

Naturalized streamflow was obtained from the results of the regional climate models of the ENSEMBLES project (Hewitt and Griggs, 2004). Several transient model runs are available for the time period from 1960 to 2100. Two time slices were selected for analysis: the control period (1960-1990) and the climate change period (2070-2100). Since runoff obtained from regional climate models usually presents significant bias, average values for the control period were corrected for bias using the UNH/GRDC composite runoff field (Fekete et al., 2004), which combines observed river discharges with a water balance model. Runoff for the future period was also affected by the correction factor identified for the control period.

A basic input to the model is the storage volume available for regulation in every subbasin. Data were obtained from the ICOLD World Register of Dams (ICOLD, 2003). Required information is reservoir location, storage capacity and flooded area. Evaporation losses from reservoirs were computed using the evaporation output from the regional climate models of the ENSEMBLES project. Environmental flows were computed through hydrologic methods. Monthly minimum required environmental flow was defined as a given quantile in the distribution of naturalized monthly flows. 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 (CIESIN et al., 2000). Per-capita water requirement was obtained from an analysis of continental waters in Mediterranean countries of Europe performed by CEDEX (Estrela et al., 2000). Average return flows from urban demands were estimated as a function of per-capita water requirement. Potential irrigation demands were estimated considering potential irrigation area and per-hectare water requirement. Potential irrigation area was obtained from the Global Map of Irrigation Areas dataset (Siebert et al., 2005). Per-hectare water requirement was obtained from the CEDEX study. Average return flows from irrigation demands were estimated as a function of per-hectare water requirement.

Figure 1. Subbasins considered in this study.

All data were aggregated recursively by subbasins, starting from the HYDRO1k subbasins, which are the elementary computational units. Figure 2 presents a comparison between the values of population and irrigated area inferred from the global datasets and those included in the CEDEX report for the main river basins. The Figure shows good agreement between both data sets.

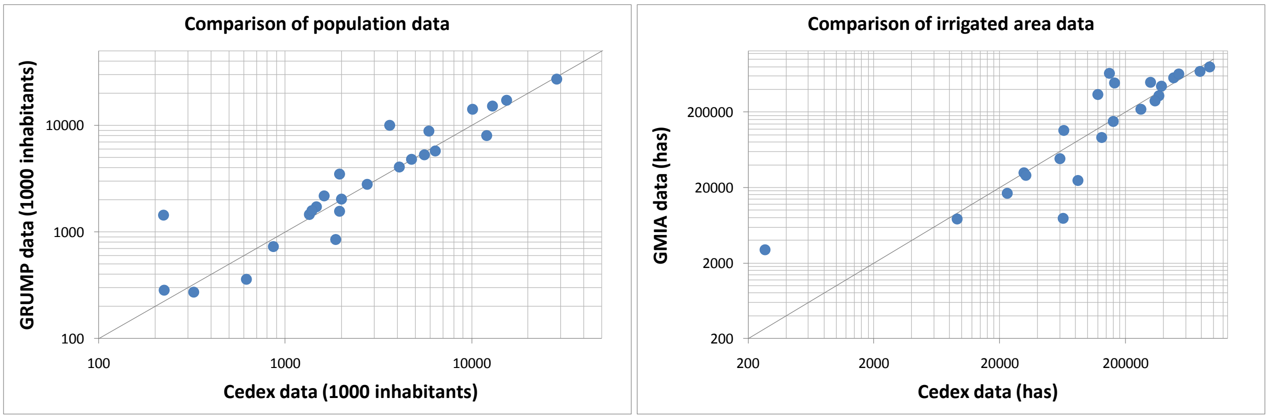

Figure 2. Comparison between population (left) and irrigated area (right) between global data sets and data included in the CEDEX report.

3. METHODS

The WAAPA model (Garrote et al., 2011) was used to provide support for the quantitative analysis of the effect of different water policy options in climate change adaptation. In a climate change context, water policy should focus on long-term time horizons, where there is little information on the specific characteristics of water supply systems. In this context, it is better to have a global overview of the water supply system performance under different policy scenarios using simplified models than carrying out very detailed simulations using conventional models that require very specific information on water demands and infrastructure.

The methodological approach applied in this work is based on the concept of Maximum Potential Water Withdrawal (MPWW), defined as the maximum water demand that could be provided at a given point in the river network with the available water infrastructure. MPWW is associated to a given demand type, which implies a minimum required reliability and certain seasonal variation. WAAPA is well suited for the analysis using its sensitivity analysis feature, which is illustrated in Figure 3.

Figure 3 presents an example of two sensitivity analyses in a system with two demand components (α and β). In this example, demand component α represents urban demand, while demand component β represents irrigation demand. Urban supply has higher priority than irrigation. In the figure on the left, the analysis is performed as a function of a variable value of demand component β (irrigation) with a fixed value of demand component α (urban supply) and of reservoir capacity. Performance values for demand components α (p^{α}_{β}) and β (p^{β}_{β}) are represented as a function of demand value d_{β}. If required performances for urban supply and irrigation are, respectively, p^{α}_{req} and p^{β}_{req}, MPWW values of demand component β would be $d^{\alpha}_{\beta max}$, according to the required performance for demand component α and $d^{\beta}_{\beta}max$, according to the required performance for demand component β. The limiting factor would be demand component α, which has a lower d_{max} value. The figure on the right presents a similar analysis, although the factor that is allowed to change in this case is the reservoir storage, while demand values remain constant. Demand performances for demand components α (p^{α}_{S}) and β (p^{β}_{S}) are represented as a function of reservoir storage S. If a minimum performance is specified, the required reservoir storage would be S^{α}_{min} and S^{β}_{min}. The limiting factor would be demand component α, which has a higher S_{min} value.

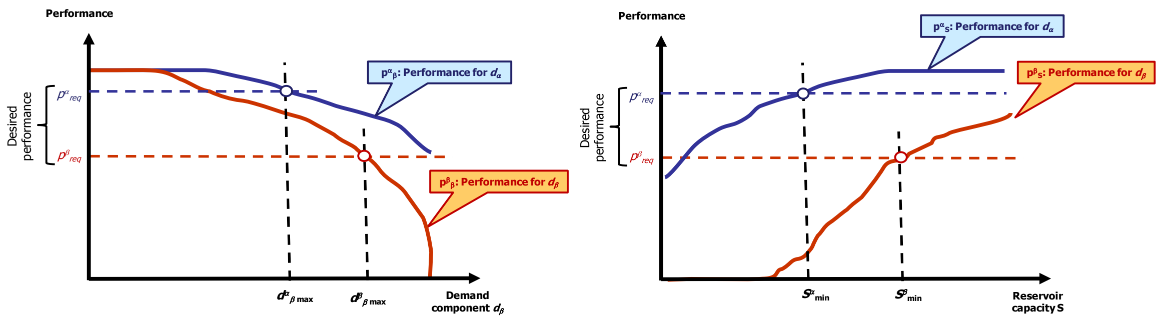

Figure 3. Example of sensitivity analyses performed with WAAPA for fixed storage and variable demand (left) and for fixed demand and variable storage (right).

The demand performance analysis was applied to estimate the exposure of the basins to climate change. The methodology of analysis is presented in Figure 4, also under the hypothesis that the system supplies an urban water supply demand (□) and an irrigation demand (□). An additional assumption is that urban demand is fixed, because it is linked to population, which in the region under analysis is not expected to change significantly in the future. In Figure 4, the analysis presented in Figure 3 is applied in two different scenarios: the control period (blue) and the climate change period (red). The comparison between the MPWW 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. In water scarcity regions, like the Mediterranean, water resources are developed to satisfy existing demands. If we make the assumption that in the control period irrigation demand is similar to MPWW for irrigation, irrigation demand would have to be reduced in the future to adapt it to water availability. The larger the difference between current and future water availabilities for irrigation, the greater the effort required to compensate for climate change though adaptation.

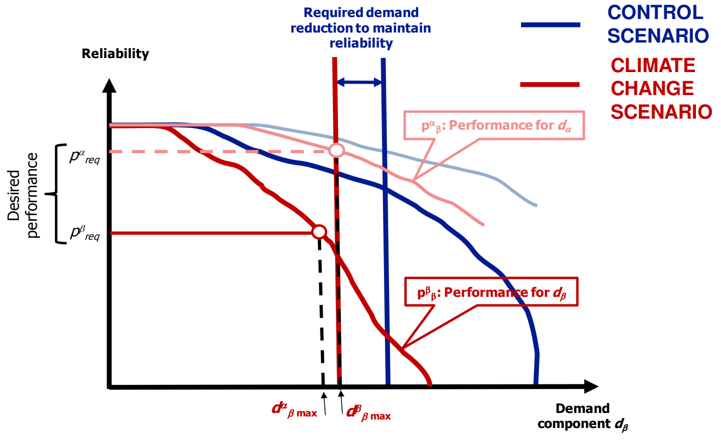

Figure 4. Example of demand performance analysis to estimate the exposure to climate change.

The main reference for the climate change adaptation policy is the reduction in irrigation demand that would be required in the climate change scenario in order to restore the same level of performance that is observed in the control scenario. This value is equal to the difference in MPWW in the control and climate change scenarios. 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 trade-offs between some of these policy measures and irrigation demand management are analysed in this study. The procedure is illustrated in Figure 5. If demand management is applied in combination with another policy, the resulting reliability values for every demand present in the system can be plotted against both adaptation efforts. The line that corresponds to the minimum required reliability for every demand type enables us to identify the required efforts when both measures are applied in combination.

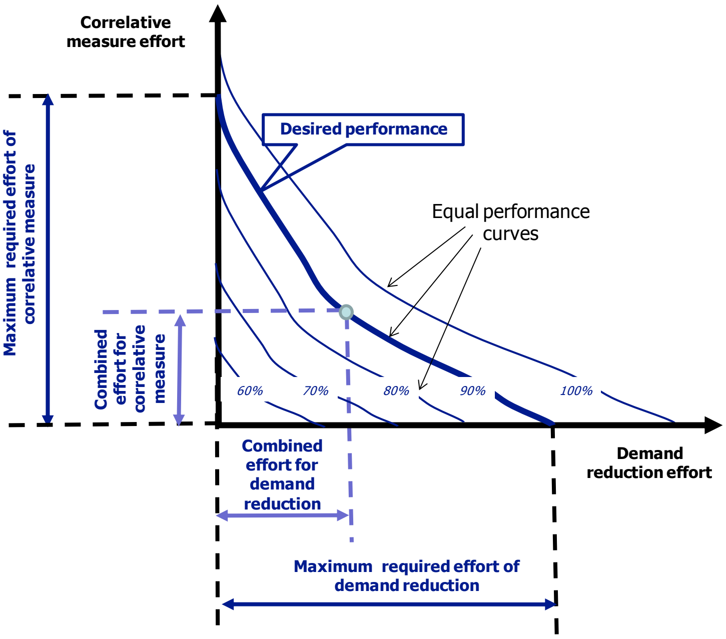

Figure 5. Schematic of trade-off between demand reduction and another correlative policy measure.

As shown in Figure 5, there is always a trade-off between both measures. If an estimate of the cost of each measure is available, the optimum course of action can be easily identified.

4. RESULTS AND DISCUSSION

The above methods were applied to all subasins in Mediterranean Europe. Climate change scenarios were taken from transient model runs in the ENSEMBLES project. Four runs were analysed, three corresponding to the A1B scenario (with models from CNRM, ETHZ and KNMI) and one corresponding to the E1 scenario (with model from CNRM). For every point of analysis we compared mean annual streamflow and MPWW for irrigation in the control and climate change periods. The analysis of MPWW for irrigation was carried out with a fixed urban demand and variable irrigation demand. Demand-performance curves were built by running the WAAPA model with fixed environmental flows (10th percentile of marginal monthly distribution) and urban demand (inferred from population and regional per capita consumption) and variable irrigation demand, ranging from 0 to mean annual streamflow minus urban demand. System performance was evaluated for urban and irrigation demand. For urban demand, required volume reliability was set at 98%. For irrigation demand, a minimum volume reliability of 90% was adopted. The maximum irrigation demand that satisfied the requirements for both urban and irrigation demand was selected as MPWW for irrigation. The results for all subbasins and models are shown in Figure 6.

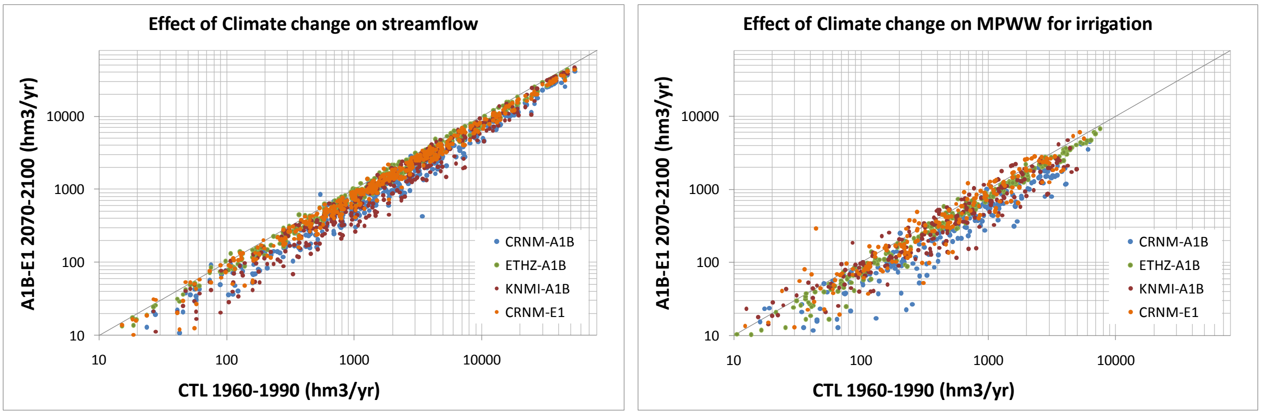

Figure 6. Effect of climate change on mean annual runoff and MPWW for irrigation.

In Figure 6 the values of mean annual flow and MPWW for irrigation in the control period are plotted against the same values for the climate change period for the four models analysed. Both the mean annual flow and the MPWW for irrigation are significantly reduced in most basins. The effect is smaller in the E1 scenario than in the A1B scenario. The spread is larger for MPWW than for mean annual flow, suggesting a possible amplification of the climatic signal. A detailed analysis of the results obtained with the model KNMI for scenario A1B is presented in Figure 7.

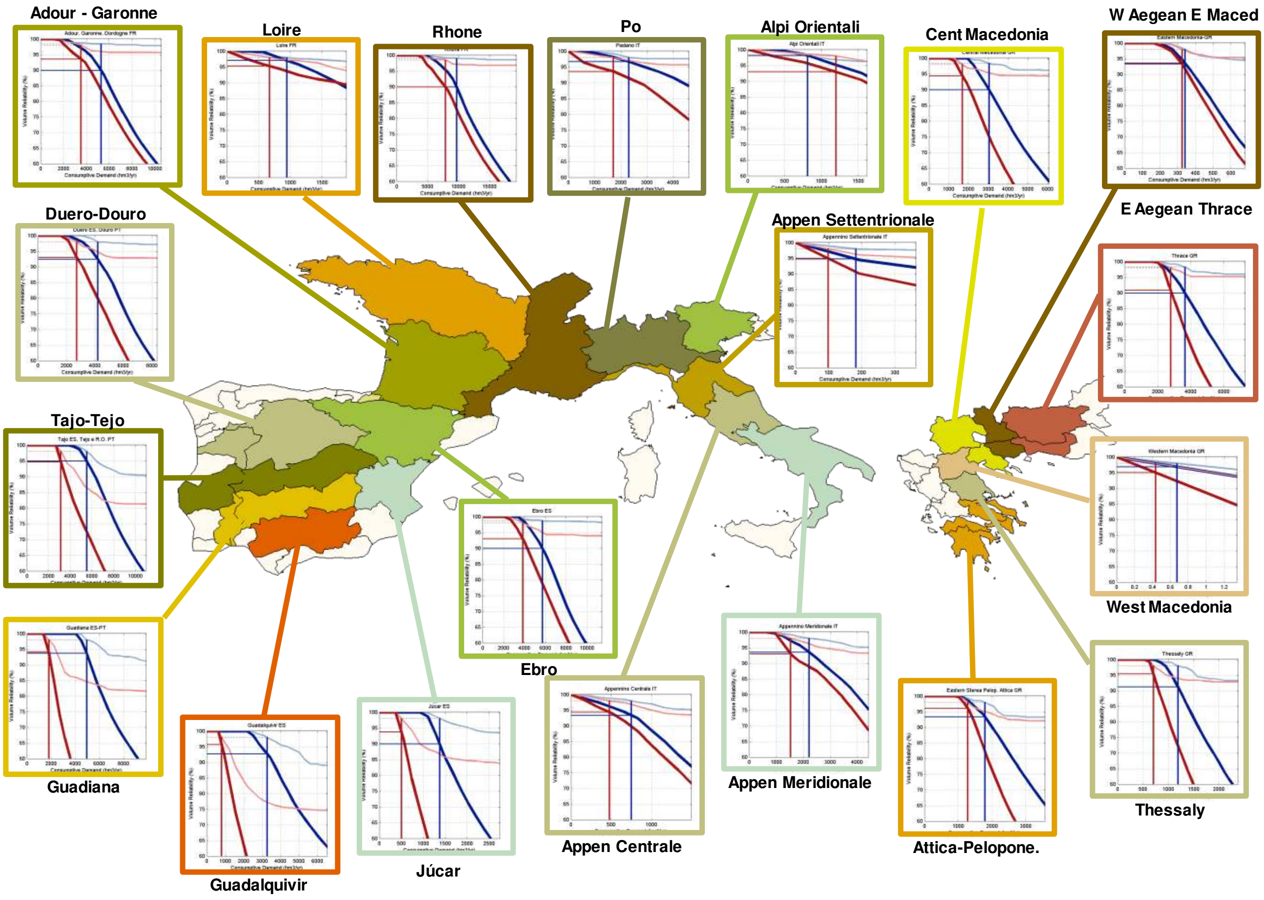

Figure 7. Demand reliability curves obtained with KNMI model for relevant river basins across Mediterranean Europe. The graphs show the reliability of irrigation (dark) and urban water supply (light) for the control (blue) and climate change scenarios (red). The vertical lines represent MPWW in the control (blue) and climate change scenario (red).

Figure 7 shows the results of the demand performance analysis presented in Figure 4 for 20 major river basins in Europe. In each individual graph, the demand-reliability curve is presented for the control (blue) and climate change (red) periods. The analysis was performed with constant urban demand and variable irrigation demand. The curves corresponding to the urban demand are presented in light colours and those corresponding to the irrigation demand are presented in dark colours. The values of the MPWW for irrigation demand are marked with vertical lines. To facilitate comparison between basins, the scale of the horizontal (demand) axis has been chosen to place the MPWW for irrigation for the control period in the centre of the graph. Of all results presented, only in the case of Alpi Orientali the MPWW obtained for the climate change scenario is larger than that of the control period. In the rest of basins, the MPWW for irrigation in the climate change period is smaller than in the control period, meaning that irrigation demand management would be required to adapt to climate change. The reduction is larger for the basins on the Iberian Peninsula and Greece, with the Guadalquivir basin presenting the largest reduction. The light coloured horizontal lines mark the required reliabilities, and the dark coloured horizontal lines mark the reliabilities of the irrigation demand for the demand values equal to the MPWW. When these reliabilities are higher than the minimum required reliability for irrigation (90%), the factor limiting the irrigation water availability is its effect on the reliability of urban demand. This means that a correlative action to improve efficiency of urban water use would have a beneficial effect on water availability for irrigation.

Next we present the analysis of the trade-offs between different policies. The correlative policy measures analysed 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 analysed 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. For instance, the four plots on the left of Figure 8 show the results for the Ebro river basin: reliability of urban supply (top) and irrigation (bottom) demands as a function of irrigation demand (horizontal axis) and basin storage (vertical axis) for the control scenario (left) and the climate change scenario (right). Vertical lines correspond to MPWW in each scenario (blue in control and red in climate change period).

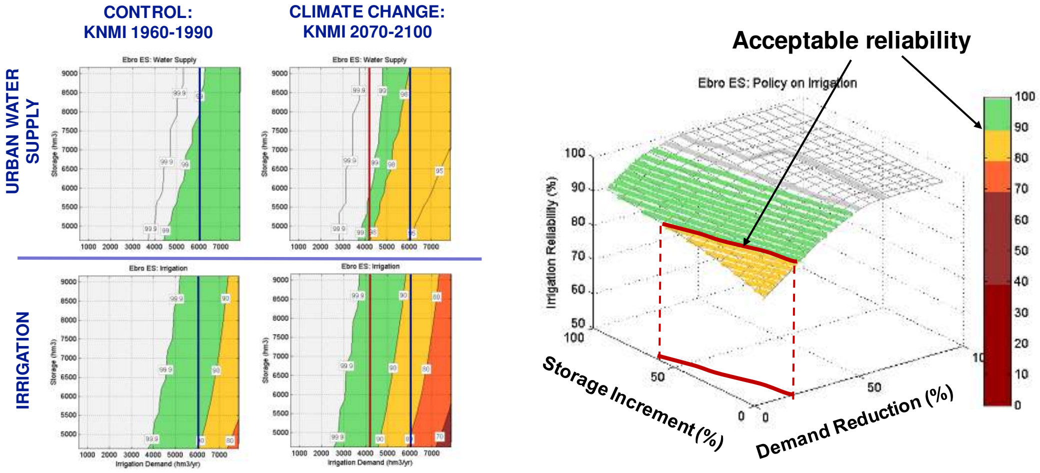

Figure 8. Demand reliability curves for relevant river basins across Mediterranean Europe. The graphics show the reliability of irrigation (dark) and urban water supply (light) for the control (blue) and climate change scenarios (red). The vertical lines represent MPWW in the control (blue) and climate change scenario (red).

The graph on the right of Figure 8 illustrates how the trade-off is analyzed. The highlighted red line that corresponds to the acceptable reliability (separation between yellow and green areas in the graph) marks the objective of management. This objective can be achieved with efforts along the two lines compared: only through demand reduction, only through storage increment or through a combination of both.

The results obtained for the major river basins of Europe in the three policies analyzed are shown in Figure 9.

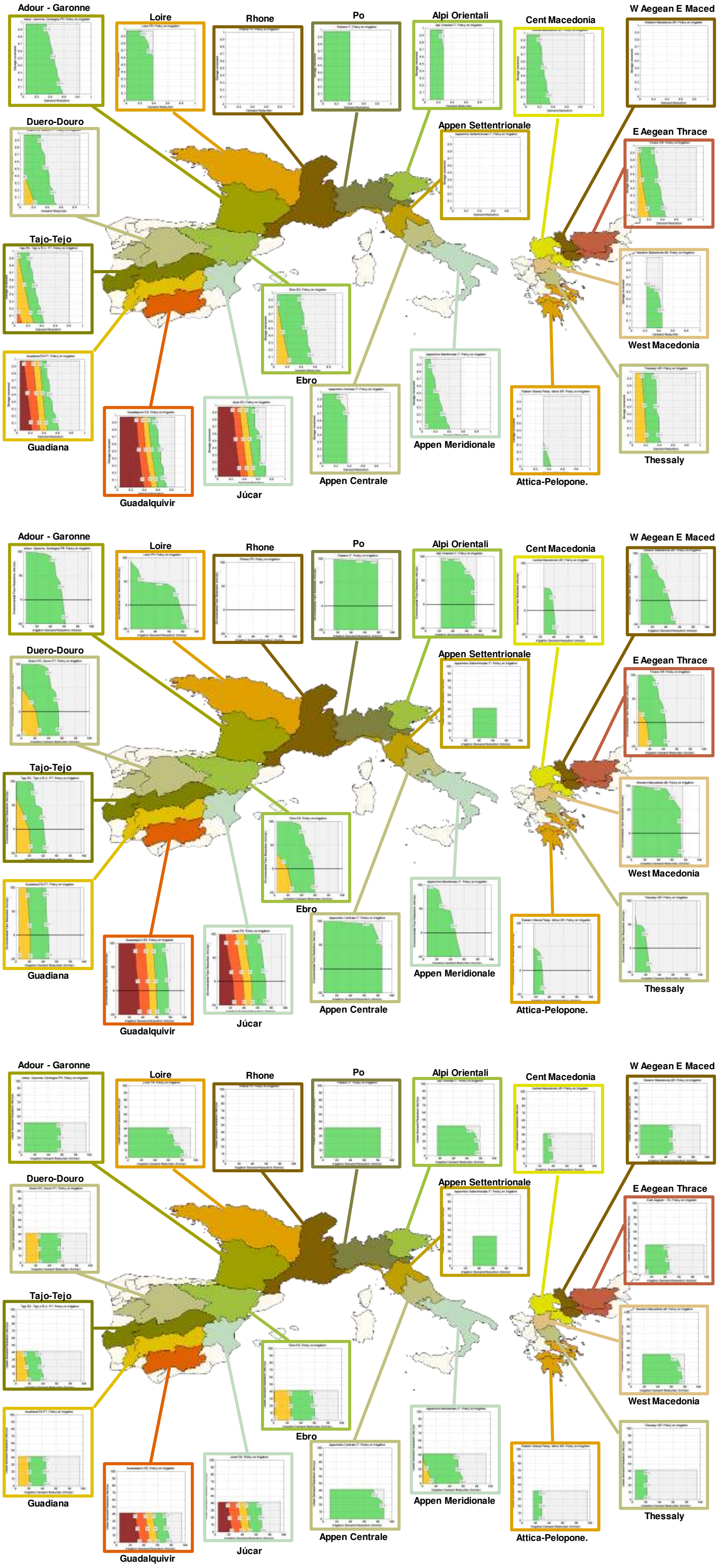

Figure 9. Combined effect of the reduction of irrigation demand with other policy actions for relevant river basins across Mediterranean Europe. The top graph presents the effect of an increase in reservoir storage, the middle graph presents a change in environmental flow requirements and the lower graph presents the effect of the improvement of urban water use efficiency.

The graphs show the reliability of the irrigation demand as a function of the effort in demand reduction (horizontal axis) and the corresponding policy (vertical axis). In the case of storage increment, the variable represented is the fraction of new storage with respect to current storage. In the case of environmental requirements, the variable is the percent of environmental flow reduction with respect to the reference case, which corresponds to the 10% percentile of the monthly marginal distribution of naturalised flows. The reduction may be positive, with less environmental flow requirements, or negative, with more strict environmental regulation. In the case of urban water use efficiency, the correlative variable is percent reduction of urban water demand.

The resulting trade-off lines are compared in Figure 10 for major European river basins. All plots are drawn at the same scale. The lines represent the combined action of demand reduction and the correlative policy alternative to achieve acceptable irrigation reliability in the climate change scenario. The lengths of the lines mark the applicability of the measure, under the hypotheses adopted. The slopes of the lines represent the effect of the policy measure on the required reduction of irrigation demand.

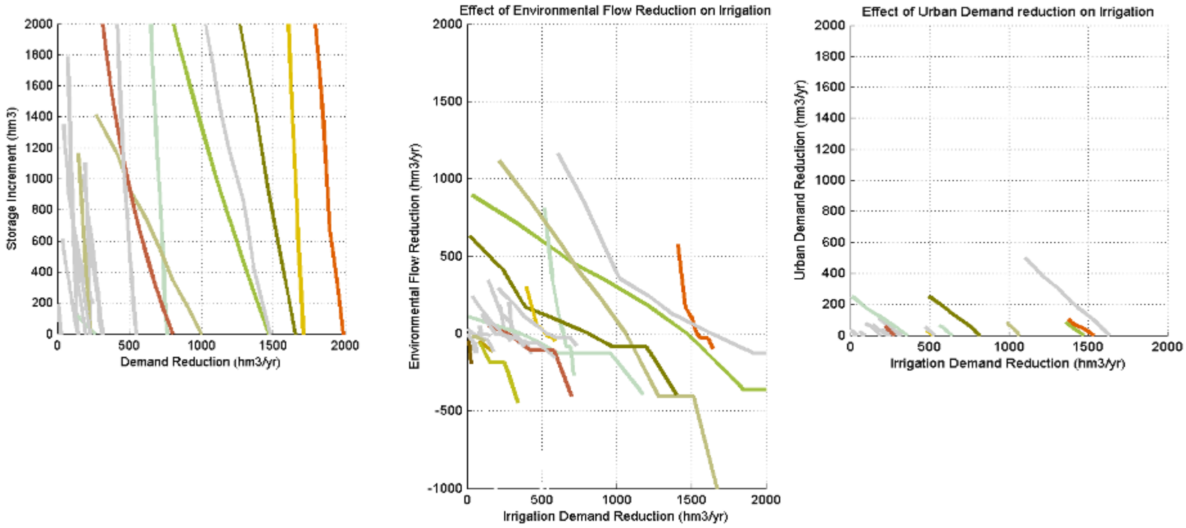

Figure 10. Trade-offs between demand reduction and other public policies: (1) Storage increment (left), (2) Environmental flow reduction (center) and (3) Improved efficiency of urban water use (right). Results obtained with KNMI model under the A1B emission scenario.

In the case of storage increment all lines have very high slopes, meaning that a large increase in storage would be required to compensate for a small demand reduction. The line with lowest slope corresponds to the Duero basin, where 190 hm^3 of additional reservoir storage correspond to 100 hm^3/yr of demand reduction. In the case of change in environmental flows (positive and negative), the basins show great variability. Most lines have variable slopes, generally lower than 45º, meaning that the effect of reductions in environmental flows is amplified on irrigation demands. The lowest slope corresponds to Thrace basin, where 100 hm^3/yr of reduction in environmental flow correspond to 285 hm^3/yr in irrigation demand. In the case of improved urban use efficiency, the lines are very short, which means that the margin for action is very small compared to the other alternatives. The lowest slope corresponds to the Tagus basin, where 100 hm^3/yr of savings in urban demand correspond to 135 hm^3/yr in irrigation demand.

5. CONCLUSION

An analysis of water availability for irrigation under climate change in Southern European River Basin Districts was presented. Climate change vulnerability of irrigation demands was estimated from changes in MPWW for irrigation in current and future scenarios. For all models analysed the

MPWW for irrigation in the climate change period is smaller than in the control period for most basins, meaning that irrigation demand management will be required to adapt to climate change. The reduction is larger for the basins on the Iberian Peninsula and Greece, with the Guadalquivir basin presenting the largest reduction. The need for irrigation demand reduction can be reduced if adequate correlative policies are adopted. The comparative effect of some of these policies was analysed by evaluating the trade-offs between irrigation demand reduction and the corresponding measure. Of the three policy measures analysed, only a change in environmental flow requirements could affect most European river basins in a significant way. This measure, however, would have important negative consequences that would have to be carefully analyzed from an economic perspective.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support received from the European Union through the CIRCE project (contract nº 036961),, from the Spanish Ministry of the Environment, Rural and Marine affairs through the ARCO project (200800050084350), and from CYTED through the VIAGUA action (410AC0399). The ENSEMBLES data used in this work was funded by the EU FP6 Integrated Project ENSEMBLES (contract nº 505539) whose support is gratefully acknowledged.

REFERENCES

Center for International Earth Science Information Network (CIESIN), International Food Policy Research Institute (IFPRI) and World Resources Institute (WRI). 2000. Gridded Population of the World (GPW), Version 2 [online data]. Palisades, NY: CIESIN, Columbia University. Available at http://sedac.ciesin.columbia.edu/plue/gpw

Estrela, T. Marcuello, C. and Dimas M (2000). Las aguas continentales en los países mediterráneos de la Unión Europea. CEDEX. Available at http://hispagua.cedex.es/sites/default/files/aguas_continentales_union_europea.pdf.

Fekete, B. M., Vörösmarty, C. J., and Grabas, W. (2004): High-resolution fields of global runoff combining river discharge and simulated water balances, Global Biogeochem. Cycles, 16(3), 1042.

Garrote L., Iglesias A., Martín-Carrasco F. and Mediero L (2011). WAAPA: A model for water availability and climate change adaptation policy analysis. Proceedings of the VI EWRA International Symposium - Water Engineering and Management in a Changing Environment. Catania, Italy.

Hewitt, C.D and Griggs, D.J. (2004). Ensembles-based predictions of climate changes and their impacts. Eos, Vol. 85, No. 52, pp 566

ICOLD (2004). World Register of Dams. International Commission on Large Dams.

Iglesias A., Garrote L., Flores F., Moneo M. (2007). Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resources Management, 21: 775–788.

Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K., Feick, S. (2005): Development and validation of the global map of irrigation areas. Hydrology and Earth System Sciences, 9, 535-547