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# WAAPA: A MODEL FOR WATER AVAILABILITY AND CLIMATE CHANGE ADAPTATION POLICY ANALYSIS

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## ABSTRACT

In the water sector, institutions, users, technology and economy cooperate to achieve equilibrium between water supply and demand in water resource systems. The socioeconomic dynamics of the population act as an external forcing that separates systems from equilibrium. Water policy is designed to correct deviations and to recover equilibrium as a response to this socioeconomic forcing. Climate change is and additional forcing that should be considered in this continuously adaptive process. A methodology to identify and evaluate climate change adaptation policies in this context 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)”, 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. Most data are taken from globally-available GIS-based public datasets. 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. The capabilities of WAAPA are illustrated with the application to the Ebro river basin. Water availability is estimated under different climate change projections and is compared to water demand under several policy scenarios. As a conclusion, several adaptation options are proposed and quantified in terms of improvement of basin management, demand reduction or infrastructure development

## 1 WATER AVAILABILITY IN WATER-SCARCE REGIONS

In water-scarce regions, like the Mediterranean, institutions, users, technology and economy cooperate to achieve equilibrium between water supply and demand in water resource systems (Iglesias et al., 2007). In these regions, water availability is highly dependent on water resource systems, which perform functions of regulation, transportation and distribution of water resources. Water resources systems are highly developed and have achieved a profound transformation of the natural characteristics of water resources to accommodate the needs of demands. Hydraulic infrastructure plays a critical role to make water available to users by overcoming the spatial and temporal irregularities of the natural regimes. The goal is to provide adequate reliability in water supply to users through water abstraction, storage, transportation, and distribution and achieve equilibrium between water supply and demand (Martin-Carrasco and Garrote, 2007). The socioeconomic dynamics of the population act as an external forcing that separates systems from equilibrium. Climate change is and additional forcing that should be considered in this continuously adaptive process.

Three factors are at play in regulated water resource systems: streamflow conditions, storage capacity and yield reliability. These are usually linked through storage-yield-performance characteristics, which describe how a system is able to supply its demands and with what reliability. There is a wide range of techniques which can be applied for this purpose, from relatively simple regression functions relating these variables to highly complex water resource systems models (Garrote et al., 2008). Usually, these complex simulation or optimization models are used by water resources engineers in areas prone to water scarcity. The result of the analysis is an estimation of the reliability of supply for each demand present in the system.

Water resources optimization and simulation models have proven very effective to design and manage water resources systems (Andreu et al., 1996, SEI, 2005). However, their applicability to evaluate long term climate scenarios is limited because they require very detailed information on hydraulic infrastructure and they include a representation of system demands which may change over time as a result of adaptation measures. In the context of regional analysis it is not feasible to collect detailed data in the area of study and perform simulations under climate change scenarios to obtain restrictions on the social system imposed to water availability. Water policy, understood as a set of measures designed to correct deviations and to recover equilibrium in water supply systems as a response to long-term forcing, requires a global analysis with less detailed descriptions of demands and infrastructure. In this paper we present WAAPA: a simple water resources mode which has been conceived to analyze quantitatively climate change adaptation policy options in water scarce regions.

## 2 THE APPROACH IN WAAPA MODEL

WAAPA is conceived to provide support for the quantitative analysis of the effect of different water policy options. 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.

Figure 1 represents a simplified scheme of the effects of water policy in water scarce areas. Water policy is relevant in four key aspects: (1) providing water availability through development of water infrastructure and non-conventional resources, (2) distributing available water between environmental flows and water abstraction for consumptive uses, (3) deciding how water available for abstraction is distributed between essential uses (urban supply) and productive uses (hydropower, agriculture, etc.), and (4) defining to what extent water is recycled in different sectors.

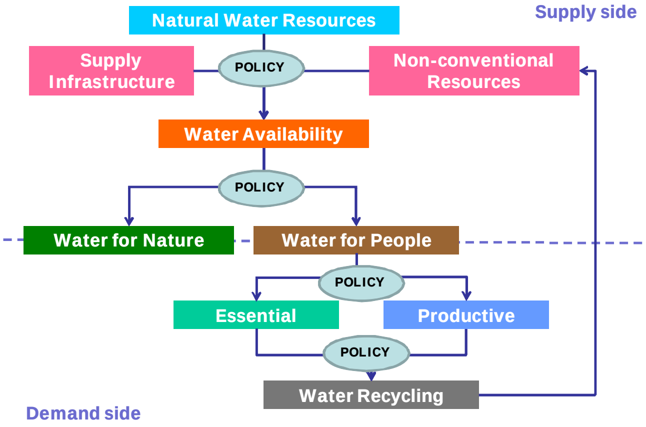

**Figure 1**: Simplified scheme of water policy decisions that may be evaluated with WAAPA

The evaluation of water availability to supply a given demand under certain reliability requirements is the key aspect of WAAPA. It can be obtained through a very simple algorithm to simulate reservoir operation under different management hypotheses. A more detailed analysis can also be obtained through the application of generalized storage–yield-performance (SYP) relationships, which provide a simple way to evaluate water availability under changing conditions. Instead of building a model to allocate water to every demand present in the water supply system, and then compute the reliability of each demand, SYP models perform a global analysis of the capacity of the regulation system to provide water to all demands under different operating rules.

## 3 THE WAAPA MODEL

### 3.1 The single reservoir operation model

WAAPA model is based on a basic reservoir operation model. The reservoir operation model takes as input the monthly inflows into the reservoir, the monthly required environmental flow, the monthly demand values sorted by priority with the corresponding return flow, the reservoir data (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates) and the reservoir initial condition (initial storage).

In each time step, the model performs the following operations:

1. Satisfy the environmental flow requirement with the inflow
2. Compute evaporation and reduce available storage accordingly
3. Increment storage with the remaining inflow, if any
4. Satisfy demands ordered by priority, if possible
5. If the remaining storage is larger than reservoir capacity, compute uncontrolled spills

The result of the reservoir operation model is a set of time series of monthly volumes supplied to each demand, monthly storage values and monthly values of spills, environmental flows and evaporation losses. From this output, demand reliability can be computed applying any conventional procedure.

### 3.2 The joint reservoir operation model

The joint reservoir operation model combines all reservoirs in a basin to satisfy a unique set of demands. It takes as input the monthly inflows in every reservoir, the monthly required environmental flow in every reservoir, the monthly demand values sorted by priority with the corresponding return flow, the reservoir data in every reservoir (monthly maximum and minimum capacity, storage-area relationship and monthly evaporation rates) and the reservoir initial condition in every reservoir (initial storage). Reservoirs are ordered by priority (water is taken preferably from reservoirs with higher priority).

In each time step, the model performs the following operations:

1. Satisfy the environmental flow requirement in every reservoir with the available inflow. Environmental flows are passed to downstream reservoirs and added to their inflows.
2. Compute evaporation in every reservoir and reduce available storage accordingly
3. Increment storage with the remaining inflow, if any. Compute excess storage (storage above maximum capacity) in every reservoir.
4. Satisfy demands ordered by priority, if possible. Use excess storage first, then available storage starting from higher priority reservoirs.
5. If excess storage remains in any reservoir, compute uncontrolled spills

The result of the joint reservoir operation model is a set of time series of monthly volumes supplied to each demand, monthly storage values and monthly values of spills, environmental flows and evaporation losses in every reservoir. From this output, demand reliability can be computed applying any conventional procedure.

### 3.3 System management options

The single reservoir operation model and the joint reservoir operation model are used by WAAPA to evaluate system performance in each basin under three management hypotheses (Figure 2):

*Local management* (LM): All reservoirs in the subbasin are supposed to be jointly operated to supply local demands. System performance is evaluated for each subbasin using the single reservoir operation model locally, assuming an equivalent reservoir with a capacity equal to the sum of capacities of all reservoirs in the subbasin. Downstream basins can only use uncontrolled spills from upstream basins and return flows from upstream demands. It corresponds to a situation where there is well developed hydraulic infrastructure, but of local scope: the system is managed to supply only local demands and there are no system interconnections or large scale water distribution infrastructure.

*Global management of distribution* (GMD): All reservoirs in a large region composed of several systems are supposed to be jointly operated to supply all demands in the region. System performance is evaluated for each basin using the joint reservoir operation model globally. In each subbasin within the region, the model considers an equivalent reservoir with a capacity equal to the sum of capacities of all reservoirs in the subbasin. The model considers only one single demand which is the sum of all demands present in the region. It is assumed that any demand at a given point in the network can be supplied from any reservoir located upstream of it. It corresponds to a situation where there is little development of system interconnections, but there is a large development of water distribution networks which are managed globally to supply all demands present in the system.

*Global management of supply and distribution* (GMSD): System performance is evaluated for each basin using the single reservoir operation model globally (considering only one equivalent reservoir which takes all inputs and supplies all demands). All reservoirs in the system can be coordinated to maximize the effect of available storage. It corresponds to a situation where hydraulic infrastructure is highly developed, with many reservoir interconnections that allow inter-basin water transfers and large water distribution networks that reach all demands present in the system.

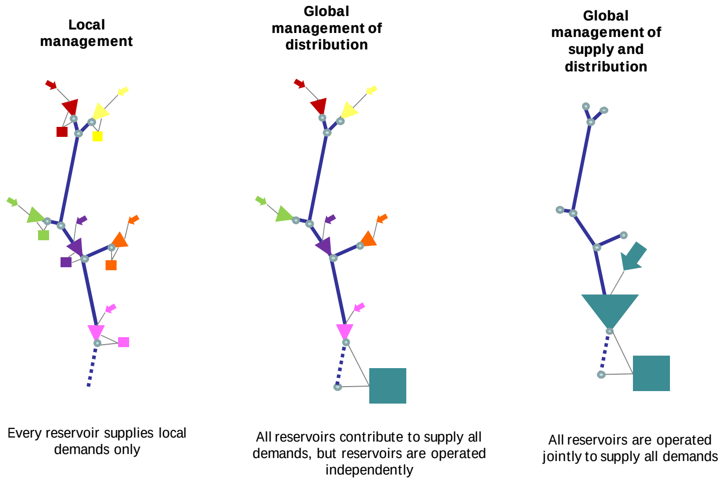

**Figure 3**: Water resources management options in WAAPA

### 3.4 System performance evaluation

System performance may be evaluated using several of the water supply standard measures. If, for demand component k, demand and volume supplied in every time step are $d^k_t$ and $s^k_t$, the following performance measures are computed in WAAPA:

*Gross Volume reliability* $GV^k_r$ is the ratio of total volume supplied to total volume demanded:

$$GV_r^k = \frac{S^k}{D^k} = \frac{\sum_{t\in T} s_t^k}{\sum_{t\in T} d_t^k} \tag{1}$$

*Time reliability* $T^{k,a}_r$ for period of aggregation a and a threshold for acceptable supply $l^{k,a}$, is the ratio of number of periods with acceptable water supply to total number of periods

$$T_r^{k,a} = \frac{N_a^k}{N_{tot}} \tag{2}$$

where, $N^k_a$ is the number of periods with acceptable water supply, that is, periods where: $S_a^k = \sum_{t \in a} s_t^k \geq l^{k,a}$, and $N_{tot}$ is the total number of periods

*Net Volume reliability* $NV^{k,a}_r$ for period of aggregation a and a threshold for acceptable supply $l^{k,a}$ is the ratio of the volume supplied during periods with acceptable water supply to total volume demanded

$$NV_r^{k,a} = \frac{S^{k,a}}{D^k} = \frac{\sum_{a \in T} S_a^k}{\sum_{t \in T} d_t^k} \tag{3}$$

where, $S^{k,a}$ is the volume supplied during periods with acceptable water supply: $S^{k,a} = \sum_{t \in a} s_t^k$ if $\sum_{t \in a} s_t^k \geq l^{k,a}$ and $S^{k,a} = 0$ otherwise

Performance may also be evaluated through an acceptability criterion, which may be based on maximum cumulative deficit:

*Maximum cumulative deficit* $U^{k,a}_{\max}$ for period of aggregation a:

$$U_{\max}^{k,a} = \max_{a \in T} \left( \sum_{t \in a} d_t^k - \sum_{t \in a} s_t^k \right) \tag{4}$$

In many cases, a combination of the above is applied. For instance, the Spanish legislation (MIMAM 2000) requires the following performance measures to be satisfied:

- *For urban demands*: 100% time reliability with maximum monthly deficit of 10% of monthly demand and maximum decennial (10-year) deficit of 8% of annual demand.
- *For irrigation demands*: 100% time reliability maximum annual deficit of 50% of annual demand, maximum biannual deficit of 75% of annual demand and maximum decennial deficit of 100% of annual demand.

### 3.5 Water availability analysis

Given a performance measure, WAAPA can obtain maximum water availability for a certain threshold of performance for demand components; that is, for demand *i* and performance measure *j*, the maximum representative demand value $d^i_{k\max}$ with a given precision $d_{prec}$ which satisfies a minimum required system performance $p^j_{i\min}$, so that $f_i^j(d_{k\max}^i) \geq p_{i\min}^j$ and $f_i^j(d_{k\max}^i + d_{prec}) < p_{i\min}^j$.

Actual water availability $A_k$ for demand component k would be the minimum value of $d^i_{k\max}$, which satisfies the requirement for all demand components:

$$A_k = \min_{i \in I}(d_{k\max}^i) \tag{5}$$

In this study, water availability is evaluated under two hypotheses:

a) *Water availability for urban demands*: Water availability is estimated with only urban demand present in the system. System performance is evaluated as gross volume reliability. The required performance to estimate water availability is a 100% volume reliability.

b) *Water availability for irrigation demands*: Water availability is estimated with a fixed urban demand and variable irrigation demand. System performance is evaluated as a function of irrigation demand. For urban demand, time reliability is applied at monthly and decennial time steps with maximum deficits allowed of 10% of monthly demand and 8% of annual demand respectively. For irrigation demands time reliability is applied at annual, biannual and decennial time steps with maximum deficits allowed of 50%, 75% and 100% of annual demand respectively. The required performance to estimate water availability is a 100% time reliability in all cases.

### 3.6 Demand-performance analysis

Curves of demand-performance analysis may be obtained by selecting a representative demand k and a performance measure j and obtaining the evolution of the performance measure j for any demand i as another variable is changing. There are two options: demand performance as a function of demand values and as a function of storage values.

*Demand performance as a function of demand values*. In this option, WAAPA obtains system performance for all demand components as a function of one representative demand component for a given performance measure, keeping reservoir capacity fixed. System performance $p_i^j$ for demand component *i* and performance measure *j* (for instance, reliability in volume for urban demand) is assumed to be a continuous function of the representative demand component $d_k$ (for instance, irrigation demand): $p_i^j = f_i^j(d_k)$.

*Demand performance as a function of reservoir capacity values*. In this option, WAAPA obtains system performance for all demand components as a function of reservoir capacity for a given performance measure, keeping demand values fixed. System performance $p_i^j$ for demand component *i* and performance measure *j* (for instance, reliability in volume for urban demand) is assumed to be a continuous function of reservoir capacity *S* (for instance, irrigation demand): $p_i^j = f_i^j(S)$.

## 4 CASE STUDY: THE EBRO BASIN

In order to illustrate the capabilities of WAAPA model, it was applied to analyze climate change adaptation measures in the Ebro river basin. The Ebro basin, located on the northeast of the Iberian Peninsula, is the largest river basin in Spain. It has a contributing area of 85,000 km$^2$ and a mean annual runoff of 16.92 km$^3$/yr. Urban supply for 2,700,000 inhabitants and consumptive industrial demand total 0,96 km$^3$/yr and irrigation demand for 800,000 ha is 6,32 km$^3$/yr.

The WAAPA model for the Ebro basin consists of 61 subbasins. The subbasins are related through the “drain-to” relationship, and the analysis is applied to all possible basins, from the small headwater subbasins to the largest basin draining to the sea. Naturalized streamflow in each subbasin for the period 1940/41 to 1995/96 was taken from the results of the SIMPA model, which is a distributed rainfall runoff model that was applied to continental Spain with a 1 $km^2$ resolution grid (CEDEX, 2009). Climate change scenarios were taken from the results of regional climate models of the PRUDENCE project (PRUDENCE, 2001). Several model runs are available for the control scenario (1960-1990) and different climate change scenarios (2070-2100). Since runoff obtained from regional climate models usually presents significant bias, data for WAAPA have been generated applying to naturalized streamflow series generated from SIMPA model the changes in annual mean and standard deviation obtained between the control and the climate change scenario in the PRUDENCE project. Environmental flows were computed through hydrologic methods. Monthly minimum required environmental flow was defined as the 10% quantile in the distribution of naturalized monthly flows

A basic input to the model is the storage volume available for regulation in every subbasin. The Ebro basin has an extensive network of hydraulic infrastructure for water storage, transportation and treatment. Total storage volume in the model is 6,34 $km^3$. Data were obtained from the ICOLD World Register of Dams. 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 PRUDENCE project.

### 4.1 Water availability analysis

WAAPA was used to evaluate water availability in current conditions (1940/41-1995/96) under different hypothesis. Figures 3 and 4 show some results obtained in different points along the Ebro river, from headwaters to the basin outlet, in the case of urban demand (uniform monthly distribution of demand and 100% volumetric reliability). Figure 3 corresponds to the analysis in current conditions, for different management hypothesis. Water availability without reservoirs would be only 17% of mean annual flow. Water policy during the 20th century in Spain was focused on increasing water availability by increasing reservoir storage. The role of reservoirs (38% of mean annual flow) can increase this availability up to 55 to 67% of mean annual flow, depending on water transportation infrastructure and system management. Current development in the Ebro basin allows for an intermediate availability between those obtained under the hypotheses of local management and global management of distribution.

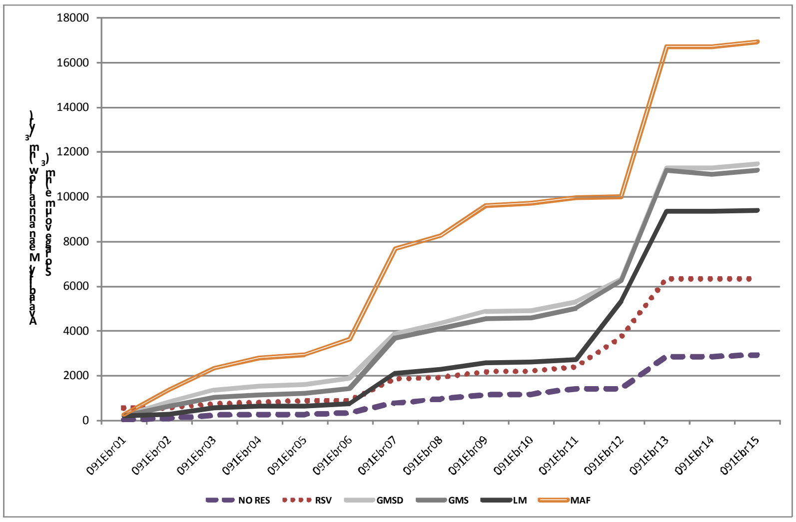

**Figure 3** Results of water availability for urban demand in different points in the Ebro river for current conditions. MAF: Mean annual flow, RSV: Reservoir storage volume, NO RES: Availability without reservoirs, LM: Local management, GMD: Global management of distribution, GMSD: Global management of storage and distribution.

Figure 4 shows the analysis of climate scenario A2 in the time horizon 2070-2100. Water availability for current conditions in two management hypotheses is compared to the same values obtained with projections from different models in the PRUDENCE project. The figure on the left corresponds to local management (minimum availability) while the figure on the right corresponds to global management of supply and distribution (maximum availability). All models except ICTP imply a significant reduction in water availability. In theory, water policy could obtain maximum availability values without building more reservoirs in the basin, by extending transportation and distribution networks and improving coordination in the management of the water resources system.

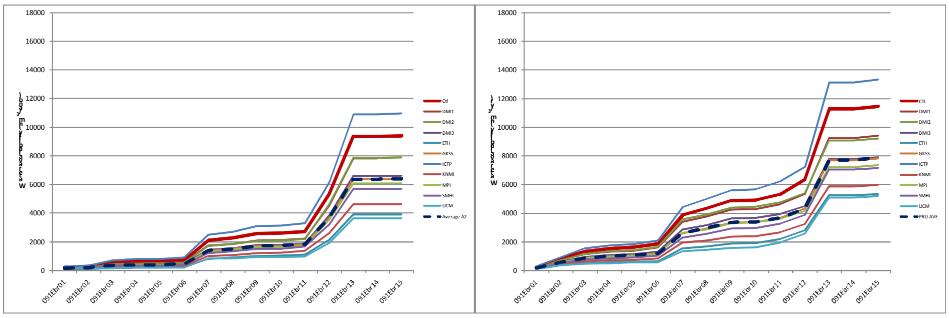

**Figure 4** Results of water availability for urban demand in different points in the Ebro river in climate scenario A2 for local management (left) and global management of storage and distribution (right).

### 4.2 Demand performance analysis

Demand-performance analysis was carried out considering two demand components: urban demands and irrigation demands. In every basin, the analysis was performed as a function of the irrigation demand component with the current value of urban demand and reservoir capacity. In the model, urban demand was assigned a higher priority than irrigation demand.

Results for the demand performance analysis in the entire Ebro basin are presented in Figure 5 and in Table 1. Figure 5 presents the demand-reliability curves for irrigation demand, once urban demand has been satisfied, for current conditions and for climate projections in the A2 scenario. Desired time reliability (98%) is represented as a horizontal dashed line. Intersections of this line with the demand reliability curves in climate change projections correspond to the maximum irrigation demand values that are allowed to maintain the desired reliability. Current demand (6.32 km$^3$/yr) is represented as a vertical line. Intersections of this line with the demand-reliability curves in climate change projections correspond to the reliabilities that would be obtained if irrigation demand was left unchanged.

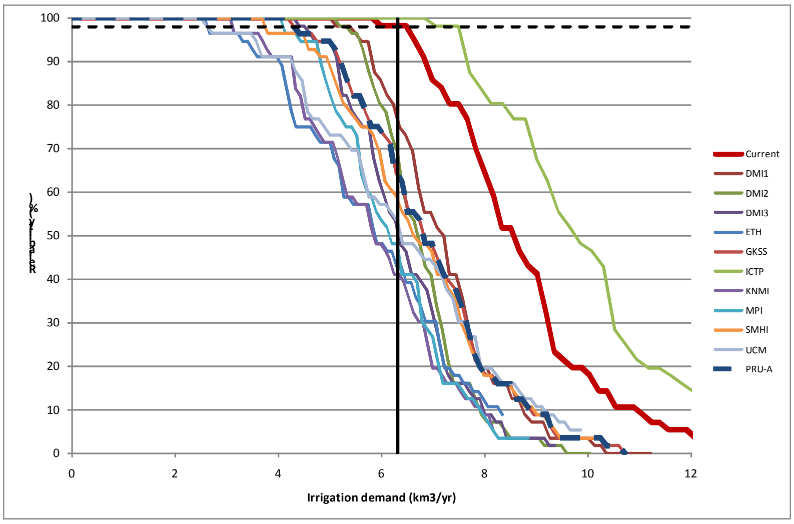

**Figure 5** Demand reliability curves for irrigation once urban demands are adequately satisfied, for current conditions and for climate projections in the A2 scenario.

Numerical values of results for all projections are presented in Table 1. Comparing the value of current irrigation demand with those obtained in the climate projections for the acceptable reliability of 98%, there are two basic adaptation options:

*Alternative 1*: Maintain current water allocation for agriculture. In this case, in future climate scenarios supply reliability will be reduced, and farmers will be more frequently exposed to water scarcity during drought years. Frequency of drought conditions may be estimated from the time reliability obtained in the simulations. In normal year agricultural production would be maintained, but in drought years agricultural production would be reduced accordingly.

*Alternative 2*: Reduce water allocation for agriculture, in order to obtain satisfactory water supply reliability. In this case, farmers will not be exposed to water scarcity during drought years, because the water supply system will be able to overcome the drought situation. However, the reduction of water allocation will imply a production loss every year.

The estimated quantitative values of time reliability in alternative 1 and of irrigation demand reduction in alternative 2 are shown in Table 1

**Table 1.** Numerical results of the demand performance analysis for irrigation demand. $\mu$: Mean annual flow, $\Delta\mu$: Change in mean annual flow, $\Delta\sigma$: Change in standard deviation of annual flow, $I_d$: Irrigation demand with acceptable reliability, $\Delta I_d$: Required reduction of irrigation demand to obtain adequate reliability. $T^I_r$: Time reliability of irrigation demand, if left unchanged.

| Projection | $\mu$ ($km^3/yr$) | $\Delta\mu$ (%) | $\Delta\sigma$ (%) | $I_d$ ($km^3/yr$) | $\Delta I_d$ ($km^3/yr$) | $T^I_r$ (%) |
|---|---|---|---|---|---|---|
| DMI1 | 12.18 | -28 | -11 | 5.50 | 0.13 | 80 |
| DMI2 | 11.00 | -35 | -28 | 5.42 | 0.14 | 70 |
| DMI3 | 10.32 | -39 | -2 | 4.61 | 0.27 | 54 |
| ETH | 9.31 | -45 | 58 | 2.67 | 0.58 | 43 |
| GKSS | 11.68 | -31 | 19 | 4.41 | 0.30 | 64 |
| ICTP | 21.66 | 28 | 2 | 7.70 | 0.00 | 100 |
| KNMI | 9.14 | -46 | 38 | 3.15 | 0.50 | 41 |
| MPI | 9.81 | -42 | 6 | 4.14 | 0.34 | 48 |
| SMHI | 11.34 | -33 | 31 | 3.80 | 0.40 | 59 |
| UCM | 10.83 | -36 | 72 | 2.72 | 0.57 | 54 |
| Aver. A2 | 11.68 | -31 | 18 | 4.41 | 0.30 | 64 |

## 5 CONCLUSIONS

This paper presents the Water Availability and Adaptation Policy Analysis (WAAPA) model. WAAPA has been designed to provide guidance on the quantitative analysis of climate change adaptation policy in water scarce areas. WAAPA is based on two simple modules to simulate single and joint reservoir operation to supply a set of demands. The basic module is applied to estimate regional water availability under three management hypotheses, and to obtain the Storage-Yield-Reliability (SYR) curves for a given set of demands.

WAAPA does not require very detailed information on the configuration of the water supply system. It only uses global values of reservoir storage volume and demands in a set of subbasins. It is therefore appropriate to estimate the performance of the water resources system in the long term under a variety of policy actions.

Some of the capabilities of WAAPA have been shown in an application to the Ebro basin. WAAPA allows estimating water availability in current conditions and in climate change projections under a variety of water management hypothesis. It can be used to analyze the comparative effect of basic policy actions, like demand reduction, water efficiency increase or water supply increase through additional regulation, but it can also be used to analyze the effect on water availability of other policy actions, like changes in the allocation of water for environmental flows or increase in the rate of water reuse.

This study illustrates the benefits of quantitative analysis of water resource systems in climate change adaptation. This will aid in guiding policy-making in river basins and determining public investments in water management that facilitate adaptation in the face of climate change.

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