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A FRAMEWORK FOR IRRIGATION MANAGEMENT DURING DROUGHT: APPLICATION IN TWO CASE STUDIES IN THE TAGUS BASIN, SPAIN

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SUMMARY- Irrigated agriculture is the main user of water in most Mediterranean locations; drought management strategies include irrigation as the key component to modify the capacity of the system to satisfy water demand priorities. Climate is a main source of agricultural risk in many Mediterranean systems, specially the marginal ones.
The purpose of this study is to provide a framework for effective and systematic risk management of water for irrigation during drought. The decision support tool for irrigation management during drought periods integrates hydrological, agricultural and water planning models. The methodology has three components: first, the statistical properties of drought are analysed based on historical series of precipitation and runoff and thresholds of drought alert are determined to serve as triggers for management actions. Second, water demand for agriculture is determined during the normal and drought periods. Extreme drought periods are used to simulate climate change scenarios and project potential situations of water conflict. Third, a water planning model is used to integrate water availability and demand and evaluate the range of possible management actions that minimise the risk of water deficit. The advantages of this methodological approach is that links the dynamic aspects of water availability and demand and its statistical properties needed for risk analysis to operational aspects of water management at the basin level. The methods are then tested in two contrasting case studies in the Tagus basin in Spain, and exemplify many other Mediterranean agricultural systems.

Key words: Water management, drought, operation rules, agriculture

INTRODUCTION

During the last decades water resources are facing severe challenges. The supply and demand imbalances arising from economic development objectives, demographic dymanics and environmental limitations (United Nations, 2006; Gleick, 2003) generate important conflicts and impose hardly controllable stresses on water management. During the second half of the 20th century these pressures have intensified both at the spatial and temporal scale, but, at the same time, the increasing knowledge about degradation and depletion processes have derived to an increased guvernamental and legislative activity to manage and protect water resources (Iglesias and Moneo, 2005).

The trends of decreasing precipitations and increasing temperatures in the Mediterranean region intensify this situation and aren of special international concern in the context of climate variability and change (IPCC, 2001). The large climate variability – characteristic of the region- makes drought events appear as a recurrent phenomenon in the area, causing important damages in both the economy and the environment (Vogt and Somma, 2000; Lázaro et al.; 2001; Iglesias and Moneo, 2005). Mediterranean countries are especially sensitive to climatic conditions because physical factors are less suited for agriculture and technological buffer (Iglesias, 2003b).

Water resources management is a horizontal issue with important implications in different social, environmental and economic aspects, requiring a coordination among sectors that is not easily reached. Pressures derived from agricultural activity or tourism intensification, on one side, and standards imposed by the Water Framework Directive on demand satisfaction and water quality on the other, derive in management conflicts that are hardened and emphasized during drought periods. All policies include environmental objectives and improved management of irrigation contributes to reach them. Increasingly operational objectives for the management system seek to balance water for human use and water for environmental needs (Jamieson, 1986, Bouwer, 2000; Zalewski, 2002; Westphal et al., 2003). Water resources planning, is part of complex, multi-disciplinary investigations overarching a wide range of stakeholders with different interests, technical expertise, and priorities. Successful planning requires effective Integrated Water Resource Management (IWRM) models that can solve these complex problems (Loucks, 1995). Economic factors continuously push the intensification of land and natural resources use even if there is international generalised acceptance of the risk associated to climate change. A better understanding of interactions among climate, agriculture and society is absolutely essential for any modification in these eurpoean policies. (Iglesias et al., 2006d).

Some agricultural policies have resulted in an increased pressure on water resources management (Iglesias and Moneo, 2005, Iglesias et al., 2006b). These pressures generally derive in conflicts and in an apparent lack of political response towards sustainable development due to the complex institutional organization (Iglesias and Moneo, 2005). The analysis of the political context is essential when scientific and technical aspects are intended to influence policy, allowing the results of the technical studies to provide appropriate and timely advice for management decisions. This is particularly important where the issues and problems under consideration are complex and involve interdisciplinary aspects, as is the case with drought management.

Drought is generally considered as severe when it affects water supply systems (hydrological drought); in this case drought managementcalls for operational management and prediction capacity. Agriculture is the principal affected sector due to the direct dependence on surface and groundwater supply. During periods of low runoff, the water that reaches reservoirs shows a higher concentration of nutrients and pollutants, this matter added to the progressive increase in demand for domestic consumption in urban areas and irrigation creates a difficult situation where supply is not able to respond with the needed flexibity during periods of drought.

Governments have traditionally faced drought with a reactive approach, through emergency management. This approach is the one that requires emergency measures to face the problems waiting until the onset of the event to react upon water deficit, when it is already too late to prevent most of the impacts caused by drought (Vogt y Somma, 2000; Bazza, 2002; Rossi, 2003; Wilhite and Buchanan, 2005). The limitations of emergency measures have been thoroughly described in previous works (Bazza, 2002). These types of actions are opposed to strategic actions that imply the planning in advance for the enhancement of supply infrastructures, modifications in management options and regulations.

The potential adoption of strategic measures to avoid or mitigate the impacts of drought depends on the availability of models and tools that allow the simulation of measures' application. One of the main difficulties in drought management policies implementation is the lack of previous experiences in similar conditions and the insufficient data records to foresee the potential results of such policies. The use of simulation models plays a key role and is generalized both for generating of data series, integraing model variables and making projections of future systems' responses. Decision support systems (DSSs) are increasingly being used in water management for the evaluation of impacts of policy measures under different scenarios and are being adopted in decision making processes.

There are two distinct aspects essential for drought management. The factors related to the bio-physical system -climate, land cover, surface water hydrology, groundwater hydrology, soils, water quality, and ecosystems- determine the availability of water and its flow through a watershed. The factors related to the socio-economic system shape how available water is stored, allocated, and delivered within or across watershed boundaries.

The main objective of this study is to evaluate the effect of drought on water management integrating hydrological, agricultural and operational aspects and evaluate the potential effectiveness of different management options.The methods developed are then applied to two case studies in the tagus Basin, Spain.

The work is carried out in several phases. First, the analysis of historical precipitation and runoff series and the application of indices allow the characterization of drought periods in both basins. Second, agricultural water demand is calculated for the main crops for the whole series, being able to identify changes from normal years to drought years. Finally supply and demand are introduced into a water management model where different management options can be tested to evaluate their effectiveness in satisfying demands even during drought periods.

Methods

The methodological structure of the study is presented in Figure 1, illustrating the relation among the tools applied for water demand and supply evaluation and the scenarios proposed to analyse the effects of drought on water management.

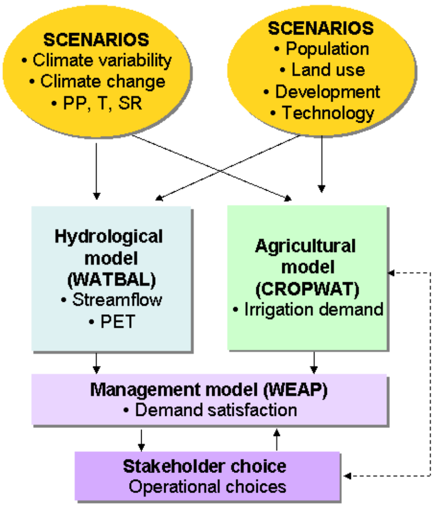


Fig. 1. Structure of work development

As presented in Figure 1 the study follows a secuencial structure that can be summarised in the following steps: (1) Water supply evaluation is done through the application of the hydrological model WATBAL to calculate the river runoff from percipitation and evapotranspiration series. Also drought events are identified through the use of indices. (2) Agricultural demand is characterized using CROPWAT for the main crops in both river basins and evaluating the significance of differences between normal and drought years. (3) Demand satisfaction level is evaluated using WEAP for the average conditions of the system and for drought years. (4) Operational choices are introduced in WEAP to evaluate their effectiveness on demand satisfaction increase during or after drought periods.

Study areas and data

The Tagus river basin is one of the transboundary rivers of the Iberian Peninsula, it is the second largest river basin, covering around 80,000 km2 and with an average inflow of 12,200 hm3/ha. The Tagus basin is divided into 14 sub basins or hidrographic areas in the Sppanish territory that correspond to the natural basins of the Tagus tributaries. For the development of ths work only the Alagón and the Tietar sub basins have been selected as they are the most important in terms of average runoff per area and inflow to the main course of the Tagus River (*Table 1*).

Both rivers are contiguous and located on the right margin of the Tagus in its lower course, right befote the border of Portugal. Alagón is interesting due to the extent of irrigated areas that impose an important demand on water resources; the Tietar on the other hand is interesting due to the limited regulation of the natural flow that leads to periods of difficult management and water shortages for satisfying the existing demand. There are plans for reservoir enlargements and new reservoir constructions, but also the enhancement of agricultural water management can improve the performance of the system.

Both systems are subject to an important variability of precipitation and have very different levels of natural flow regulation. The Alagón has a total regulation capacity over 900Mm^3, which is more than double the total annual demand for water, while the Tietar has a regulation capacity of 80Mm3, which is more or less one third of the total annual demand. Both rivers originate in a quite elevated mountainous range with complicated orography, where the highest average precipitations and lowest evapotranspiration values of the two basins are recorded. In both cases the medium and lower courses of both rivers run along big plains where the main agricultural areas are situated.

Table 1. Hydrographic areas, agricultural use and regulation characteristics of the Alagon and the Tietar river basins. Source: CHT, 2006

	TIetar	Alagon
Area (Km2)	4,460	4,406
Average inflow/area (hm3)	2,005	1,711
Main crops (% irrigated area)		
Maize	5.17	16.32
Fodder crops	16.67	35.23
Tobacco	26.58	2.66
Fruit trees	1.13	11.29
Other	50.45	34.5
Regulation capacity (hm3)	114	1102
Consumptive demand	285	479
Demand/Regulation capacity (%)	250	43

Agriculture is the main use of water resources in both basins and the main extensions are located din the medium and lower courses of both rivers. Irrigated areas are managed by irrigators' communities made up by land owners, farmers and other users who have a right to use water through direct acess to the river or to the irrigation channels. The crops that are used in the agriculture water demand evaluation are fodder, maize, tobacco and fruit trees (Table 1). The diference in proportions of each crop can be of interest for a comparative analysis of the impacts of drought, climate change or land use change (due to changes in the CAP regulation) in the two water management systems.

Fig. 2 shows the main regulation infrastructures in both basins showing the main inflow areas (surface and groundwater where appropriate), reservoirs, meteorological stations, quality measurement networks and irrigated areas. The irrigated land in the Tietar is around 42,000ha and in Alagón it is around 50,000ha, even if these values are not so different, the regulation capacity of the Alagón is more than 10 times that of the Tiétar. The Rosarito reservoir in the Tietar basin plays a double role, both as water reservoir for irrigation and also as an essential instrument for flood lamination, therefore it has to be kept to a minimum level during the spring months when snow from the mountains is melting. Spring, on the other hand, is also a crucial season for summer crops because precipitations during the summer are not enough to satisfy the agricultural demand and water stored during these months is used for irrigation.

The Alagón has a muliti annual regulation capacity with a total consumptive demand that does not reach half of the regulation capacity of the basin while in the Tiétar this demand is a 250% bigger than the total regulation capacity. In semiarid environments, where precipitation is highly variable from year to year and from season to season, this creates a situation of high risk of water scarcity (*Table 1*).

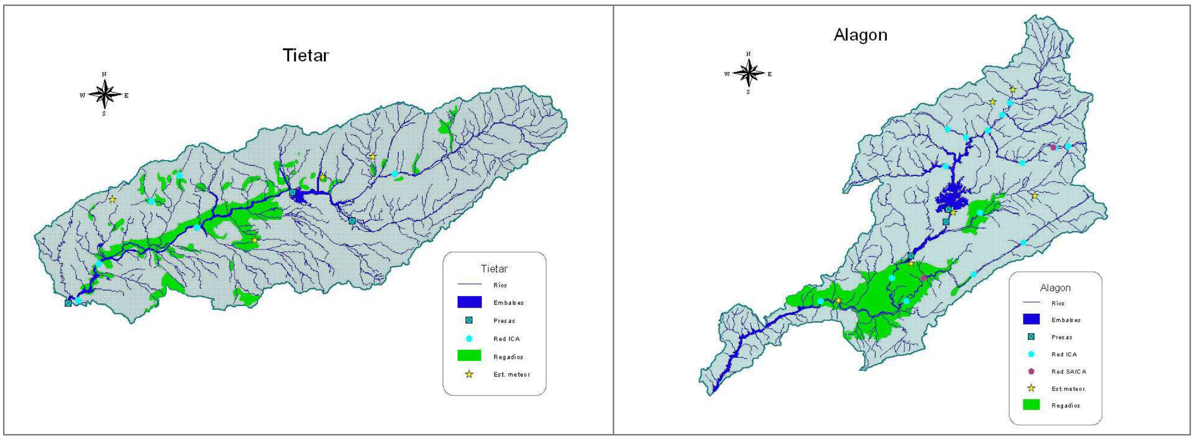


Fig. 2. Regulation infrastructure and irrigated areas in the Tietar and Alagon river basins.

Drought identification

While the methods to study the recurrence of other types of extreme events, such as floods, are well defined and used widely, the methods to analyse drought are more subject to debate, due to its spatial and temporal characteristics and to its interactions with regulated hydrological systems. Furthermore, a single indicator may not be sufficient for the analysis because the implications of drought events are heterogeneous and depend on the ongoing management and mitigation actions.

Droughts are characterized by their time of onset, duration, intensity, and geographical extent. These properties can be estimated deriving statistical properties of historical data on precipitation and other relevant variables such as soil moisture by using different indicators. The main limitation of the statistical analysis is the small number of drought events that occur over the historical time series, and therefore, the "historical" drought characteristics have a large degree of uncertainty.

The use of indices and indicators is widely used among scientists and technical decision makers responsible for natural resource planning (Hayes, 2002). For example, the triggers of mitigation actions included in drought management plans are in part based on drought indicators (Flores et al., 2003).

Drought indices are single values that explain the current sate of an area in relation to the normal climate or water resources conditions. The key strength of drought indices relies on their capacity to establish comparisons among different areas or times (Flores et al., 2003). The information provided by indices is extremely useful for the analysis of historical occurrence of drought, its probability of recurrence, and hence for planning and policy applications (Wilhite, 2000). Indices are often used to trigger both response and mitigation programs at different administrative scales.

Some of the most commonly used indices include: Palmer Drought Severity Index, Surface Water Supply Index, Deciles of precipitation, Standardized Precipitation Index, and Reclamation Drought Index. The description and use of drought indices has been evaluated by Hayes (2002) and Flores et al. (2003). A summary of the characteristics of drought indices in the context of this study is presented below.

Although drought indicators are commonly used to synthesize information they are not very useful in explaining the spatial properties of drought if calculated at a single point. In this study the values have been calculated by several drought indices at the station level to be spatially interpolated to cover large areas or regions. The methods selected for this study are the deciles of precipitation, the SPI and the statistical properties calculated by the run method.

Deciles of precipitation

This method was developed by Gibbs and Maher in 1967 as an alternative to the limitations denoted by the analysis of the "percentage of the normal". Precipitation data are ordered from lowest to highest values and then ranked into deciles (tenths of the distribution of the total number of data), the first decile is the rainfall amount not exceeded by the 10% of the occurrences (Hayes, 2002). By definition the 5th decile corresponds to the median, and is the precipitation amount not exceeded by 50% of the occurrences. This method has been commonly used in Australia to classify droughts. Precipitations are ordered from lowest to highest, representing the first decile the lowest 10% precipitation values of the distribution. The Precipitation Deciles have been used by the National Drought Watch System in Australia because of the simplicity and the low amount of data needed for its calculation. On the other hand, one disadvantage of the decile system is that a long climatological record is needed to calculate the deciles accurately. (Hayes, 2002).

Standarized Precipitation Index

The SPI index was developed by McKee, Doesken and Kleist in 1993 and it is widely used all over the world for drought identification and monitoring due to its versatility and applicability for different purposes (Hayes et al., 1999). The SPI was designed to evaluate the deficit of precipitation for different time scales, and therefore reflect the possible impacts of drought on different water resources stocks. Precipitation deficit on a relative short time scale may affect soil moisture, while deficits on longer time scales may affect groundwater, streamflow or reservoir storage. For these reasons, McKee et al. (1993) originally calculated the SPI for 3–, 6–,12–, 24–, and 48–month time scales.

The SPI is calculated using monthly precipitations. The whole time series is fitted to a probability distribution and then transformed into a normal distribution. This way the mean SPI for any location is 0, positive values indicate precipitation above the mean and negative values indicate precipitation below the mean. Due to this normalization of data comparisons can be easily established among locations with different rainfall patterns. However, the main limitation of the SPI is that may not be adequate when the precipitation patterns of a particular location do not follow a normal distribution.

McKee et al. (1993) used the SPI classification system to define drought intensities resulting from the SPI. McKee et al. (1993) also defined the criteria for a drought event for any of the time scales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude".

RUN Method

The run method allows an objective evaluation of the statistical properties of drought at site and regional levels (Yevievich in 1965). This method is usually applied to the rainfall variable, but may be also applied to composed indices. In a simple case, only precipitation data are needed to obtain an evaluation of drought duration, intensity, and frequency. These parameters are relevant to drought management plans. Despite of some limitations, it is recommended as one of the most efficient approaches because of its objectivity in identifying droughts and its suitability to assess drought characteristics at a regional scale (Rossi, 2003).

According to this method droughts correspond to "negative runs", defined as an interval where a selected hydrological variable remains below a chosen threshold. This threshold is the key aspect of the analysis and must be selected carefully on the basis of the objective of the study. Many times this threshold coincides with the mean of the series for the selected variable, but many other times a fraction of the mean or a fraction of the standard deviation can be chosen (Clausen et al., 1995)

A run can be defined by its length, its accumulated deficit and its intensity. Duration is defined by the number of consecutive time intervals where rainfall remains below the critical level, accumulated deficit is the total sum of consecutive deficits and intensity is given by the ratio (cumulated deficit/duration)

Climate change scenarios

Climate change scenarios used to evaluate the future evolution of frequency and intensity of droughts has been derived from the data bases generated by the Danish Meteorological Institute in the project PRUDENCE. The maps in Figure 3 represent the differences between the results of the models and the observed data (present climate). The map on the left represents the the changes in in temperature for year 2080 compared to the average temperature of the historical series from 1961 to 1990 and the map on the right represents the variation of precipitation for the same year and relative to the average precipitation of the same period. These climate scenarios for 2080 derive from the application of the PRUDENCE regional climate model to the global climate model HadCM3 under the conditions of the socioeconomic scenario A2. This PRUDENCE database has been elaborated for Europe in a grid of 50km x 50km.

According to the results, average annual temperature will increase all over Spain between 1ºC and 5ºC for the selected scenarios and precipitation will decrease between 0.159 mm/day and 0.844 mm/day. The specific variations of the adequate cells will be applied to the observed data from the meteorological stations of the study areas in order to obtain the climate change scenarios.

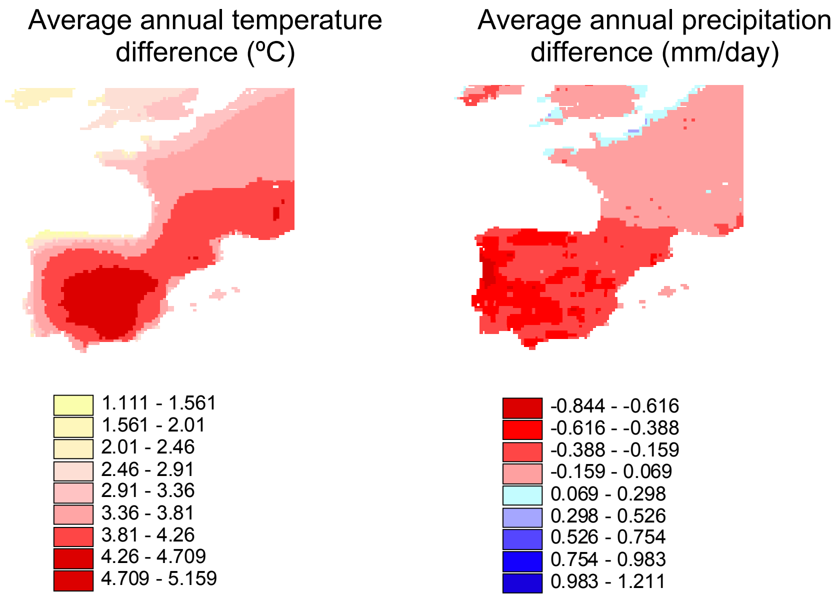


Fig. 3. Average annual temperature and precipitation changes for in relation to the period 1961-1990.

Hydrological models

The hydrological model WATBAL applied in this study is based on the hydrological balance of soil, calculating, in a monthly basis, all the processes that directly modify the water content in the soil (Yates, 1996; Kaczmarek, 1993). It has been used extensively to calculate water availability for agriculture (Strezpeck et al., 1999; Rosensweig et al., 2004). WATBAL calculates the hydrological balance taking both precipitation and temperature into account. The model uses a group of continuous relative storing equations to represent surface flow, sub surface flow and evapotranspiration through diferentia equations.

The water balance is understood by the model as a single hydrological unit with quantifiable inflows and outflows. The Priestley Taylor model is used for the calcularon of potential evapotranspiration (PET), this assures consistency with the agricultural models applied later that use the same approach.

The change in soil water content for the soil profile is calculated on a daily time step using the equation:

$$\Delta S = P + I - EP - ES - R - D$$

Where ∆S is the change in soil water content, P is the precipitation, I is the irrigation, EPis the transpiration, ES is the soil evaporation, R is the surface runoss, and D is the drainage from the soil profile.

The water content in each soil layer varies between a lower limit, and a saturated upper limit. If the water content in a given layer is above the drained upper limit specified for that layer, then water is drained to the next layer with the “tipping bucket” approach, using a drainage coefficient specified in the soil file. A maximum of 20 soil layers can be specified to represent the soil profile. Soil evaporation, root absorption, or flow to an adjacent layer can decrease the water content in any layer, while infiltration of rain, melted snow and irrigation water.

This model was developed to evaluate the imacts of climate change on hydrological balances at the river basin level (Yates, 1996; Kaczmarek, 1993). Climate change projections derived from Global Circulation Models can be applied to this model through changes in monthly precipitation and temperature in order to evaluate the potential impact of such changes on runoff at the river basin level.

Agricultural model

There are also a great number of agricultural models that can be applied to obtain an evaluation of crop water demand and evaluate other aspects such as nitrates or phosphates elimination or the growing stages of the crop. In this cse the agricultural model will be applied in order to evaluate the irrigation demand of the main crops in each of the basins. The model used for this task is CROPWAT (CROPWAT, 2004), which derives this result from inputs of precipitation, evapotranspiration and a characterization of the soil and the crop itself that determine a particular water requirement for each crop and soil.

CROPWAT is a decision support system developed by the Land and Water Development Division of FAO and its main functions are (FAO, 2006): Calculate reference evapotranspiration, crop water requirements and crop irrigation requirements, develop irrigation schedules under various management conditions and design scheme water supply, and evaluate rainfed production and drought effects and the efficiency of irrigation practices.

CROPWAT is an empirical model developed by FAO to calculate water requirements and develop irrigation schemes at a regional level from climate and crop data (CROPWAT, 2004). It is a less demanding model in terms of input data than many others used with the same objective and it allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rainfed conditions or deficit irrigation.

Data for the application of the model have ben obtained from several sources, meteorological data on precipitation and evapotranspiration have ben provided by the Tagus River Basin Authority. The characterization of crops for the CROPWAT model is done through the crop coefficient that determines the water requirements of the crop for each month of the year, these data have been obtained from the field work of previous studies (DEMETER, 2002, Zapata, 2005, Kuo et al., 2006, Wolf et al., 1996). A soil with average field capacity and neutral pH has been selected for the soil characterization.

Water management model

The Water Evaluation and Planning Version 21 (WEAP21, Stockholm Environment Institute (SEI), 2005) model addresses water management at the river basin level attending to both hydrology and and socioeconomic aspects, trying to contribute to an effective Integrated Water Resources Management that is useful, easy to use, available and understandable to a broad audience of managers and technicians.

The model integrates physical hydrologic processes with the management of demands and existing infrastructure in a coherent manner. It allows for multiple scenario analysis, including possible climate scenarios and changing socioeconomic factors, such as land use variations, changes domestic and industrial demands or alternative operating rules.It is not designed to be a detailed water operations model used to optimize. The model simulations are constructed through scenarios, where simulation time steps can be as short as one day to more than 100 years.

RESULTS

Drought events

Table 2 summarizes the average values, standard deviation and variation coefficients for the historical series. In both cases average precipitations are higher in the station situated in the upper course of the rivers and variability remains more or less constant with a relative trend to decrease along the course of the rivers

Table 2. Precipitation variability in the Tieta and Alagon river basins

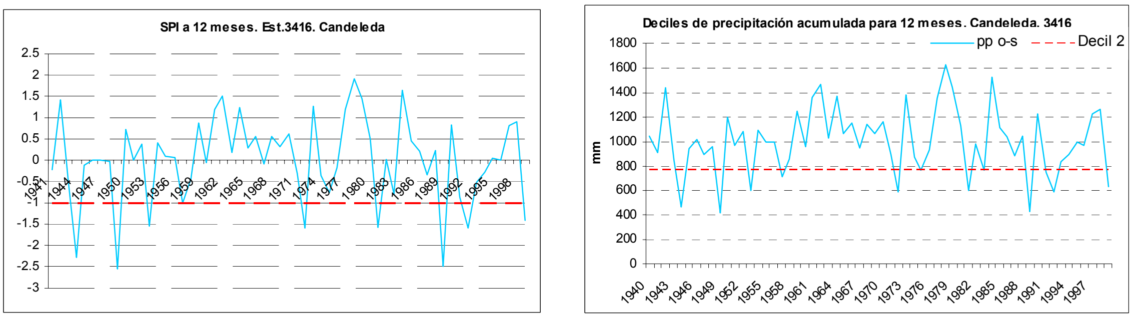
Tiétar				**Alagón**			
Station	**Average**	**St. Dev.**	**Var. Coef.**	**Station**	**Average**	**St. Dev.**	**Var. Coef.**
3408	1345.04	453.43	0.34	**3484**	1032.35	321.64	0.31
3416	1015.49	326.81	0.32	**3504**	1043.64	325.32	0.31
3426	873.63	277.62	0.32	**3525o**	629.61	186.27	0.30
3439	1213.72	332.62	0.27				

Meteorological drought is characterised using the SPI and the deciles method, whici is a generalised method in all drought studies (Wilhite and Buchanan, 2005). Hydrological drought is characterised through the RUN method. These two types of drought have different evolution periods and therefore originate different impacts. Meteorological drought is directly responsible for yield decreases in rainfed agriculture, while irrigated crops can stand drought periods as long as supply systems are not affected (Wilhite 2000, Garrote et al., 2006).

The SPI was calculated for accumulated precipitations every 12 months in order to prevent the clasiffiaction of the summer months as drought periods and identify the really dry years. This index has been calculated for all the meteorological stations in both basins. The threshold level for drought characterization is -1 according to previous studies in the Iberian Peninsula (Paulo et al., 2003). This means that all values below one standard deviation from the average for the historical series have been characterised as drought.

Figure 4 shows the SPI values for the station 3416 in the Tietar basin. As shown in Fig. 4 the years 1951 and 1991 are of extreme drought. Drought years are less coincident in the upper course of both rivers with the rest of the basin, but there is a general trend that can be observed in most of them, a period of high drought frequency in the beginning of the series followed by a general increase in precipitations and another period of decrease during the 90s. Some studies suggest limitations of applying this index to Mediterranean areas due to the non normal distribution of precipitation probability associated to Mediterranean climate.

Fig. 4 is an example of the drought identification using deciles of precipitation; also accumulated every 12 month as in the previous case. The selected threshold level for drought characterisation is the second decile; the 20% of the years that show the lowest annual precipitation determine the precipitation value that defines drought. The same trends of precipitation increases and decreases can be appreciated.



(a) (b)

Fig. 4. SPI (a) and recipitation values and 2nd declie (b) values calculated for a 12 months time scale for station 3416 in the Tietar basin

Hydrological drought is more complex to characterize and the run method was used to evaluate the statistical properties of inflow (Fig. 5). The analysis of runoff or reservoir inflow is also interesting for the evaluatin of water supply in the basin. This method is applied to the accumulated inflow for a selected point of the basin, generally just before a reservoir. The threshold selected case for drought identification is one standard deviation below the average inflow of the series. The water inflow is calculated with the hydrological model WATBAL (see next section) but it is presented here in order to compare different types of drought.

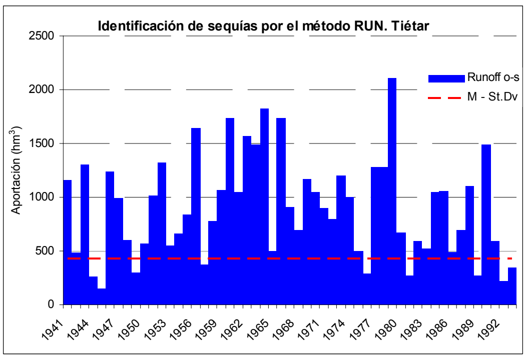


Fig. 3. Inflow values accumulated at the Rosarito reservoir in the Tietar basin

Results from drought characterization have been summarised in Figure 6, which includes all the indicators in order to facilitate interpretation and observation of the drought years identified through each of the proposed methods.

All three indices show a quite high level of coincidence although in some cases a small delay of the hydrological droughts can be appreciated with respect to the meteorological ones. This makes sense from the hydrological point of view because decreases in runoff and inflow generally show a certain delay from decreases in precipitation depending on the characteristics of the system. Depending on the time of the year when the drought started, the hydrological expression will appear either in the same hydrological year or the next one.

There are some clear differences in the years identified as drought by the different indices; however there are also distinctive coincidences within each basin and among the two basins. This is the case of year 1944, between 1948 and 1949, 1953, 1972 and after that, better documented drought periods in thematic literature (Flores et al., 2003) such as 1981, 1989, 1992 or the last year of the series 1999. Year 1989 is identified as a dry year by all the indices in all meteorological stations and wasa therefore selected as a prototype drought scenario for the case studies.

TIETAR									ALAGON						
3408	3408	3416	3416	3426	3426	3439	3439		3484	3484	3504	3504	3525o	3525o	
SPI	Deciles	SPI	Deciles	SPI	Deciles	SPI	Deciles	RUN	SPI	Deciles	SPI	Deciles	SPI	Deciles	RUN
1941	1941	1941	1941	1941	1941	1941	1941	1941	1941	1941	1941	1941	1941	1941	1941
1942	1942	1942	1942	1942	1942	1942	1942	1942	1942	1942	1942	1942	1942	1942	1942
1943	1943	1943	1943	1943	**1943**	1943	1943	1943	1943	1943	1943	1943	1943	1943	1943
1944	**1944**	**1944**	**1944**	**1944**	**1944**	**1944**	**1944**	**1944**	**1944**	**1944**	1944	**1944**	1944	**1944**	**1944**
1945	1945	1945	1945	1945	1945	1945	1945	**1945**	1945	1945	**1945**	1945	**1945**	**1945**	**1945**
1946	1946	1946	1946	1946	1946	1946	1946	1946	1946	1946	1946	1946	1946	1946	1946
1947	1947	1947	1947	1947	1947	1947	1947	1947	**1947**	**1947**	1947	1947	1947	1947	1947
1948	**1948**	1948	1948	**1948**	**1948**	**1948**	**1948**	1948	**1948**	**1948**	1948	**1948**	1948	1948	1948
1949	1949	**1949**	**1949**	**1949**	**1949**	**1949**	**1949**	**1949**	1949	1949	**1949**	1949	**1949**	**1949**	**1949**
1950	1950	1950	1950	1950	1950	1950	1950	1950	1950	1950	1950	1950	1950	1950	1950
1951	1951	1951	1951	1951	1951	1951	1951	1951	**1951**	**1951**	**1951**	1951	**1951**	**1951**	1951
1952	1952	1952	1952	1952	1952	1952	**1952**	1952	**1952**	**1952**	1952	1952	1952	1952	1952
1953	**1953**	**1953**	**1953**	**1953**	**1953**	**1953**	**1953**	1953	**1953**	**1953**	**1953**	1953	**1953**	**1953**	1953
1954	1954	1954	1954	1954	1954	1954	1954	1954	1954	1954	1954	1954	1954	1954	1954
1955	1955	1955	1955	1955	1955	1955	1955	1955	1955	1955	1955	1955	1955	1955	1955
1956	1956	1956	1956	1956	1956	1956	1956	1956	1956	1956	1956	1956	1956	1956	1956
1957	1957	**1957**	**1957**	1957	1957	1957	1957	**1957**	1957	1957	1957	1957	1957	1957	**1957**
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1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963	1963
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1969	1969	1969	1969	1969	1969	1969	1969	1969	1969	1969	1969	1969	1969	1969	1969
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1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971
1972	**1972**	**1972**	**1972**	**1972**	**1972**	**1972**	**1972**	1972	**1972**	**1972**	**1972**	**1972**	**1972**	**1972**	1972
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1981	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**	**1981**
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1983	1983	1983	**1983**	**1983**	1983	**1983**	**1983**	1983	1983	1983	**1983**	**1983**	**1983**	**1983**	1983
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1989	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**	**1989**
1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990	1990
1991	**1991**	1991	**1991**	1991	**1991**	1991	1991	1991	1991	1991	1991	**1991**	1991	1991	1991
1992	**1992**	**1992**	**1992**	**1992**	**1992**	**1992**	**1992**	**1992**	**1992**	**1992**	**1992**	1992	**1992**	**1992**	**1992**
1993	1993	1993	1993	1993	**1993**	1993	1993	**1993**	1993	1993	**1993**	1993	**1993**	**1993**	
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1998	1998	1998	1998	1998	1998	1998	1998		1998	1998	1998	1998	1998	1998	
1999	**1999**	**1999**	**1999**	**1999**	**1999**	**1999**	**1999**		**1999**	**1999**	**1999**	**1999**	**1999**	**1999**	

Fig. 4. Temporal (y axis) and spatial (x axis) scales of hydrological and meteorological droughts in the study areas

Water suply evaluation

The evaluation of water availability in the basins has been carried out through the application of WATBAL that calculates the inflow of the basins at a certain point from precipitation, evapotranspiration and a certain number of coefficients that describe the initial conditions of the soil and the geographical situation of the area. Evapotranspiration has been calculated throught the Pristley – Taylor method, selected for consistency reasons with the CROPWAT model. The Tagus River Basin Authority provided a number of series of inflows from 1949 to 1992 at different points of the two basins, coinciding with the main reservoirs, the Rosarito in the Tietar and Gabriel y Galán in the Alagón. The length of the series provided allow for the use of periods for model calibration and validation. Fig. 8 shows how simulated inflow and observed inflow from the provided series fit relativelly well.

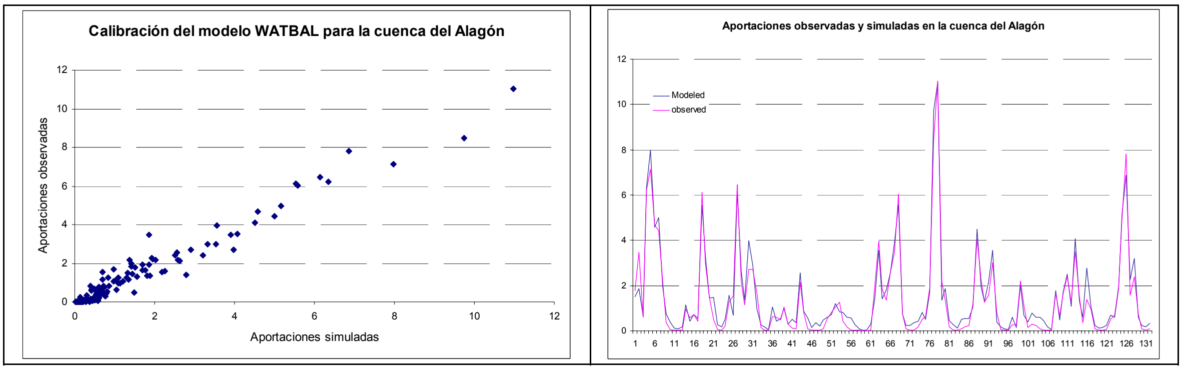

Fig. 8. Calibration of WATBAL and comparison of simulated and observed inflow values in the Alagon basin

Water demand for irrigation

Irrigation demand has been calculated assuming a 100% efficiency of irrigation supply and 100% efficiency of water absortion by the plant. Even if these efficiencies never get to be 100%, taking these assumptions is the best way to establish comparisons among the different crops and study areas avoiding the potential variations due to non climatic aspects. A direct consequence of these assumptions is that resulting demands are significantly lower than expected because all possible inefficiencies are not taken into account.Irrigation demand was calculated for non-drought years and drought years as identified in the previous section (year 1989) (Fig. 7).

Fig. 9 shows the differences in irrigation demands between drought and non-drought years for the four selected crops. Maize is the one that shows the highest water requirements, followed by the forrajeras, tobacco and finally fruit trees show values much lower than the rest of crops, this is probably due to the adaptation of these species to the Mediterranean environment and because their highest water demand does not coincide with the summer, which is the most stressful season in water availability.

During normal years crops in the upper course of the rivers show lower water requirement because effective precipitation is higher in these areas due to the low level of evapotranspiration. In the case of maize, the difference between water requirements can be up to 20% from the upper to the lower course of the river. In the case of tobacco and fruit trees this difference is even higher, reaching up to a 70%or 60% respectively

Fig. 9 shows the differences in percentage of precipitation, PET and specific crop water requirements between an average year and year 1989. The decrease in precipitation is clear in all the stations and PET values are quite stable except for one station in the Tietar. Precipitation decreases between 15% and 53%. For precipitation dcreases among 16% and 53% there is a general increase in water demand for every crop without exception. Maize and forrajeras seem to be the most stable with increases around a 15%, tobacco suffers a bit higher increases between 405 and 60%, but fruit trees are largely the most affected crop with water demand increases up to a 223%. This is due to the variability showed by spring precipitation which is the most important for this crop and the low absolute value of water demand during normal years.

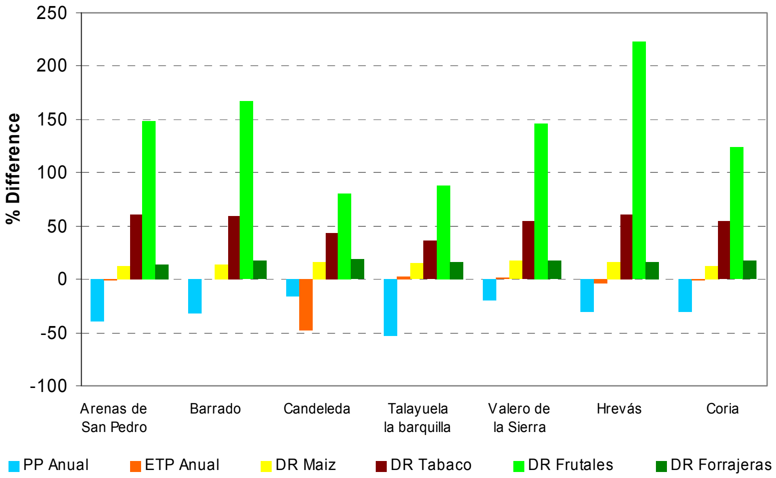

Fig. 9. Differences in precipitation, PET and irrigation demands between normal and dry years in the Tietar and the Alagón river basins

Water management

All previous results were introduced in the model WEAP in order to integrate all the water supply and demand results and obtain a complete picture of the situation of the basin. The use of WEAP –a water management model- is of particular interest due to the dynamic approach that can be obtained, giving the possibility of analysing the effects of droughts that last for more than one year or one season. Figure 10 shows the main supply and demand elements in the Tietar and Alagon basins as specified in the model.

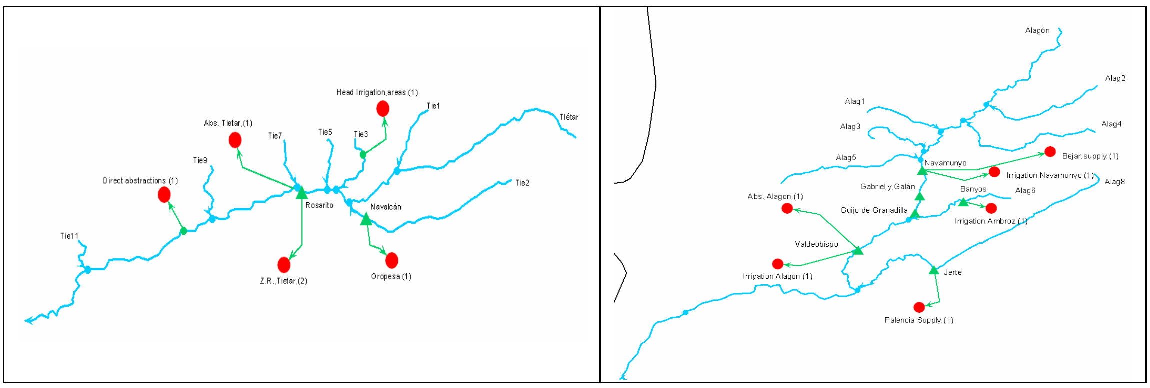

Fig. 5. Supply and demand components introduced in WEAP for the Tietar and Alagon river basins

In this case, the objective is to simulate the use of potential management actions to mitigate the effects of drought on the level of demand satisfaction. For this reason, it is necessary to define the management options on one side, priority of use (which is always maximum for domestic consumption), return flows and management rules of reservoirs and groundwater, and the biophysical conditions on the other, inflow to the reservoirs, PET, infiltration, etc. Once these average conditions are established, it is possible to simulate different scenarios where environmental conditions change, for exaplme to simulate a year of drought, and evaluate the results on demand satisfaction levels. Furthermore, on top of these scenarios also management options can be changed in order to evaluate again the effects on demand satisfaction.

The two selected case studies have very different regulation capacity (*Table 3*), in the Alagón river basin there is a set of reservoirs able to regulate more than double the total annual demand, while the regulation infrastructure in the Tietar is not able to regulate the total annual demand for one year

(Fig. 10). Potential measures for drought management are therefore quite different depending on these aspects and models like WEAP are extremely useful to evaluate the appropriateness of different options.

The different physical and management characteristics of each basin determine the potential operational options that can be applied in each case, if the same measures evaluated for one of the cases were applied to a different system, results could be very ineffective or even negative. There are some measures that have been traditionally applied in these two basins in order to face drought. *Table 3* shows the main characteristics of the two systems, underlining the strengths and weaknesses of each one. These simple alternative management options were selected taking into account the bio-physical and social aspects of the Tagus river basin and the operational rules documented historically by the Tagus River Basin Authority (2003).

Table 3. Management characteristics of the Tietar and the Alagón river basins.

	Tietar	Alagon
Consumption/Regulation	250%	43%
Potencial sources	Detritic aquifer of the left shore	Transfer from the Jerte basin
Decision making process	Seasonal	Interannual
Anticipation capacity	Shorter than one year	Longer than one year

Models such as WEAP result extremely useful to simulate possible responses during drought scenarios and evaluate the effectiveness of drought management actions. Using these tools there are different aspects that can be evaluated: Increase in water demand satisfaction, effectiveness depending on the timeframe of application, and differential impacts for the range of water uses in the basin.

Table 4 shows and describes the main characteristics of the selected scenarios simulated in WEAP to evaluate the effects of climate and management. Simulating a drought year, we can observe the potential impacts on water demand satisfaction, while modifying management optios as well as climate we can onbserve the effectiveness of such measures compared to the traditional management of the basin.

Table 4. WEAP scenarios characterized by precipitation and drought management actions applied for the Tietar and the Alagon basins

		Tietar		Alagón	
Scenarios	PP	Measures	WDS*	Measures	WDS*
Scenario 1 (BAU)	SPI = 0	None	100%	None	100%
Scenario 2 (SPI-1)	SPI< -1	None	90%	None	100%
Scenario 3 (SPI-1-M)	SPI< -1	Urban demand reduction (10%) Restrictions on irrigation (10%) Aquifer abstraction (10 Hm3)	100%	Urban demand reduction (10%) Transfer from Jerte (10Hm3) Restrictions on irrigation (10%)	100%
Scenario 4 (SPI-2)	SPI< -2	None	60%	None	80%
Scenario 5 (SPI-2-M)	SPI< -2	Urban demand reduction (10%) Aquifer abstraction (10 Hm3) Restrictions on irrigation (10%)	90%	Urban demand reduction (10%) Transfer from Jerte (10Hm3) Restrictions on irrigation (10%)	100%

* WDS. Water demand supply. PLEASE NOTICE. These values are first estimates that are under revision.

The results of the study show that the demand satisfaction of the Alagon basin is a direct consequence of the higher regulation capacity of the system.

The reduction in urban demand does not make significant differences in the results due to the small size of urban areas in the selected basins where agriculture is the main use and is therefore the one that can act as the key component to react upon drought situations.

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