INTEGRATED ECONOMIC-HYDROLOGIC ANALYSIS OF POLICY RESPONSES TO PROMOTE SUSTAINABLE WATER USE UNDER CHANGING CLIMATIC CONDITIONS

BLANCO-GUTIÉRREZ, Irene. (Corresponding author)
Postdoctoral Researcher. Department of Agricultural Economics and Social Sciences. Universidad Politécnica de Madrid, Av. Complutense s/n, 28040 Madrid, Spain.
E-mail: irene.blanco@upm.es Tel.: +34913365798. Fax: +34913365797.

VARELA-ORTEGA, Consuelo.
Professor, Dr. Department of Agricultural Economics and Social Sciences. Universidad Politécnica de Madrid, Av. Complutense s/n, 28040 Madrid, Spain.
E-mail: consuelo.varela@upm.es Tel.: +34913365790. Fax: +34913365797.

PURKEY, David R.
Dr., SEI US Water Group Leader. Stockholm Environment Institute US Center, 133 D Street, Suite F, Davis, CA 95616, USA.
E-mail: dpurkey@sei-us.org Tel.: +1 530 753 3035.

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1. Introduction

Water is a vital resource, but also a critical limiting factor for economic and social development in many parts of the world. The recent rapid growth in human population and water use for social and economic development is increasing the pressure on water resources and the environment, as well as leading to growing conflicts among competing water use sectors (agriculture, urban, tourism, industry) and regions (Gleick et al., 2009; World Bank, 2006).

In Spain, as in many other arid and semi-arid regions affected by drought and wide climate variability, irrigated agriculture is responsible for most consumptive water use and plays an important role in sustaining rural livelihoods (Varela-Ortega, 2007). Historically, the evolution of irrigation has been based on publicly-funded irrigation development plans that promoted economic growth and improved the socio-economic conditions of rural farmers in agrarian Spain, but increased environmental damage and led to excessive and inefficient exploitation of water resources (Garrido and Llamas, 2010; Varela-Ortega et al., 2010). Currently, water policies in Spain focus on rehabilitating and improving the efficiency of irrigation systems, and are moving from technocratic towards integrated water management strategies driven by the European Union (EU) Water Framework Directive (WFD).

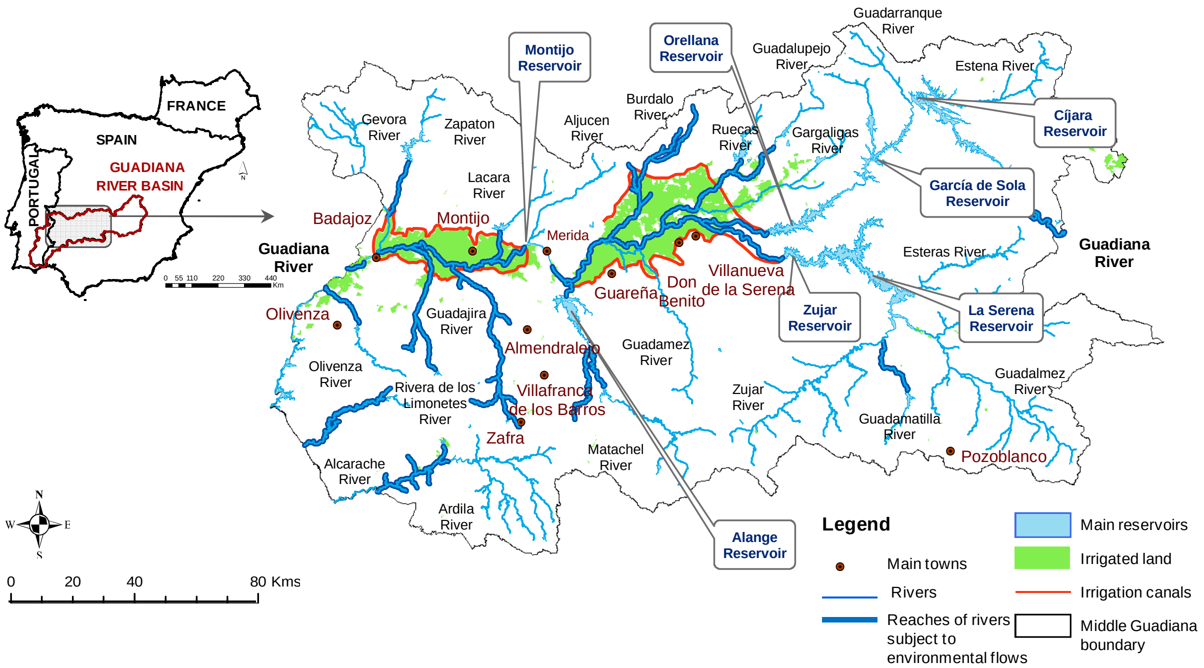
The WFD (EC, 2000) constitutes the common European policy framework on water management. It aims to achieve a sustainable 'good ecological status' (GES) of all bodies across every European river basin district by 2015, and requires member states to develop River Basin Management Plans (RBMPs) to manage the complex ecological, hydrological and socio-economic interactions in an integrated way. The WFD adopts an innovative approach by taking into consideration economic principles, concepts and instruments for water management (Heinz et al., 2007; WATECO, 2002). Its implementation requires interdisciplinary work and offers a unique opportunity to incorporate integrated water management strategies at the river basin level.

In that context, the objective of this research is to develop a consistent integrated methodology able to capture the diverse relations between the economy and the environment to better analyze the potential implications of different water management policies and climate-related issues in complex water and agrarian systems.

Among the different existing methods for integrated water management (mental models, Bayesian networks, metamodels, risk-assessment approaches, knowledge elicitation tools, among others), hydro-economic tools provide relevant insights about how to best optimize the use of water resources, and constitute useful tools to help policy-makers identify the most efficient and sustainable water management strategy (Brouwer and Hofkes, 2008). Integrated hydro-economic models have been widely and successfully used to study water quality problems (Volk et al., 2008), global water and food policy questions (Rosegrant, 2002; De Fraiture, 2007), the impact of drought (Maneta et al., 2009), land use changes (Ahrends et al., 2008), and water management and policy strategies (e.g., Jenkins et al., 2004; Qureshi et al., 2008).

The present study analyzes the effects of national and European water policies under normal and dry climate conditions, using a novel hydro-economic model based on the integration of a multi-scale economic optimization model and a hydrology water management simulation model built in WEAP. Application of the model was carried out in the Middle Guadiana basin, a surface-irrigated area located on the south-western of the Iberian Peninsula in Spain (see Fig. 1). This region covers a large territory (of about 29402 km^2) with valuable ecosystems in biophysical, socio-economic and historical terms that faces increasing pressure on water resources caused by growing demands for water, recurrent drought spells, water quality degradation, and significant human-driven alterations of the natural hydrological regime. Balancing the trade-offs between agricultural production and nature conservation is one of the major tasks that face policy makers in Spain, and especially in the Guadiana Basin. This paper contributes to the debate by providing an integrated economic-hydrologic modeling framework that captures the dynamics and outcomes of human-hydrological interactions, from farm-level to river-basin levels.

Fig. 1- Geographical location of the study area.



2. Methodology: An integrated economic-hydrologic modeling framework

2.1. Data collection and analysis

Hydro-economic models, like any other multidisciplinary integrated model, require a vast amount of information and data processing. Table 1 summarizes the type of input data required for the development of the economic and hydrology models, data sources used, and methodology employed to process all the information.

Relevant empirical information regarding the agricultural sector was obtained from field research. The Middle Guadiana basin has 145000 ha and comprises 21 Irrigation Communities (ICs). Overall, 5 ICs and 107 farms (4655 ha) were surveyed from 2008 to 2010 within the framework of the SCENES project[1]. The information obtained served to enrich the characterization of the irrigation districts and types of farms selected for the study, as well as to obtain the technical coefficients of the economic model.

The present study focuses on 12 ICs, which cover an area of 136000 ha (95% of the total irrigated surface) and present very diverse characteristics regarding their year of foundation, surface area, geographical location, granted water allotments, source of water, and irrigation technology. Farmers' behavior has been characterized by a selection of 14 statistically representative farms in terms of the irrigated area, number of farms, soil quality and crop distribution in 7 different ICs covering 11 municipalities and 3 varied agricultural regions in Spain. Farming patterns range from small-scale paddy-based rice farming, mostly concentrated upstream on the right bank of the Middle Guadiana River, to large-scale crop-diversified agriculture characterized by a dominance of high value added crops (fruit trees, orchard crops) irrigated under pressurized irrigation systems and located on the left bank of the Middle Guadiana River (upstream and downstream regions).

[1] The SCENES project Water Scenarios for Europe and for Neighboring States (2007-2011) is funded by the EC 6th Research Framework Program (contract nº: 036822) and aims to develop a set of comprehensive water scenarios up to 2050. The Guadiana basin is one of the project's pilot areas. (www.environment.fi/syke/scenes).

Table 1- Input data required for the development of the economic and hydrology models.

Type of data	Source	Format/ Methodology	Used in hydrology /economic model
Land use data			
- Digital Elevation Model	NASA Shuttle Radar Topographic Mission (SRTM) from US Geological Survey (USGS) (www.seamless.usgs.gov)	90m-resolution elevation data processed in GIS	Hydrology model
- Land cover	CORINE Land Cover database from the National Geographic Institute of Spain (IGN, 2004)	Digital maps (1/100000 scale) processed in GIS	Hydrology model
Climate data			
- Prec., Temp., humidity, wind speed.	CRU TS 2.1 Global Climate Database from CGIAR (Mitchell and Jones, 2005) Spanish State Meteorological Agency (AEMET, 2004)	Monthly-time series processed in GIS	Hydrology model
Water supply data			
- Watersheds, rivers, reservoirs, channels, streamgages, etc.	Guadiana River Basin Authority (GRBA) (www.chguadiana.es) Integrated Water Information systems of Spain (SIA) (www.marm.es) Automatic System of Hydrologic Information (SAIH) (www.saihguadiana.com)	Shapefiles processed in GIS Data records processed in Excel &CSV	Hydrology model
Water demand data			
- Irrigated agricultural sector (Irrigation Communities, farm types)	Spanish Ministry of Environment and Rural and Marine Affairs (Web Map Service) Regional Department of Agriculture of Extremadura (JE, 2007; JE, 2009) Spanish National Statistics Institute (INE) (INE, 1999; INE 2007) Field work	Digitalization in GIS Cluster analysis in Excel Text files	Economic model & hydrology model
- Urban sector * Cities, population	Spanish Spatial Data Infrastructure (IDEE) (www.idee.es) Municipal census from the Spanish National Statistics Institute (INE) (www.ine.es)	Digitalization in GIS Excel files	Hydrology model
* Water use rates	Guadiana River Basin Authority (GRBA) (www.chguadiana.es)	Excel files	Hydrology model
Crop data			
- Technical itineraries (irrigation, crop work, etc.)	Spanish Ministry of Environment and Rural and Marine Affairs (MAPA, 2005) Irrigation Advisory Service of Extremadura (REDAREX) (www.aym.juntaex.es) Field work	Excel, text files	Economic model & hydrology model
- Production costs, yields, crop prices, subsidies, etc.	Guadiana River Basin Authority (CHG, 2006) Spanish Ministry of Environment and Rural and Marine Affairs (MAPA, 2007) Regional Department of Agriculture of Extremadura (JE, 2009) TEPRO (agricultural consultancy group) (www.tepro.es) Field work	Excel, text files	Economic model
Agro-hydrological parameters			
- Crop coefficients, soil water capacity, etc.	Spanish Agroclimatic Information System (SIAR) (www.mapa.es/siar/) Literature review	Excel, text files	Hydrology model

2.2. Development of a hydro-economic model

- **The economic model**

A non-linear mathematical programming model of constrained optimization was developed to simulate farmers' behavior and predict their response to policy and environmental changes. In the present study, farmers attempt to maximize their regional expected utility, subject to a set of technical, economic and policy constraints that portray the conditions under which the decision-making choices on the allocation of land have to be made. The regional expected utility is calculated as the sum of the net income over all farm types that belong to the same IC, minus a variation of that income (risk) due to fluctuations in price and production output. Blanco-Gutiérrez et al., 2011, Flichman et al., 2006, and Henseler et al., 2009, among others, have adopted a similar multi-scale methodological approach in order to analyze the interactions between the economy and the environment within regional farming systems.
Based on the mean-standard deviation method and following the Hazell and Norton (1986) approach, the objective function of the model is formulated as follows:

$$MaxU = \sum_{f} \left(Z_f - \phi_f \cdot \sigma_f \right)$$

where U is the regional expected utility Z_f : average net income, ϕ_f : risk aversion coefficient, σ_f : standard deviation of income. Farm income is calculated as follows:

$$Z_f = \sum_{c}\sum_{r}\sum_{d} gm_{c,r,d} \cdot X_{c,r,d,f} + md \cdot cp \cdot \sum_{d}\sum_{r}\sum_{d} sb_{c,r,d} \cdot X_{c,r,d,f} + sfp_f \cdot md \cdot numf_f$$
$$- oc \cdot \sum_{p} fla_{p,f} - hlp \sum_{p} hl_{p,f} - sirrg_f \cdot wfee - wc_f \cdot (uwc + wpc)$$

where $X_{c,r,d,f}$ is the set of production activities defined by a combination of crop types *(c)*, production techniques (r), soil quality *(d)*, and farm types *(f)*; $gm_{c,k,d}$: gross margin; $sb_{c,r,d}$: coupled CAP subsidies; *md*: modulation rate; *cp:* coupling rate; sfp_f: Single Farm Payment; $numf_f$: number of farm types; *oc:* family labor opportunity cost; $fla_{p,f}$: family labor availability; *hlp:* wage for hired labor; $hl_{p,f}$: hired labor; $sirrg_{i,f}$: irrigated surface; *wfee*: water fees; wc_f: water consumption; *uwc*: unitary water cost; wpc_f: pumping costs.

The standard deviation is calculated as follows:

$$\sigma_f = \left[\left(\sum_{sn}\sum_{sm} Z_{sn,sm,f} - Z_f \right)^2 / N \right]^{1/2}$$

where $Z_{sn,sm,f}$: random income, N: combination of different states of nature ($N=100$).

Land constraints: limit the total grow area ($surf_f$); the potential irrigated area ($sirrg_f$):

$$\sum_{c,r,d} X_{c,r,d,f} \le surf_f \qquad \sum_{c}\sum_{d}\sum_{f} X_{c,ri,d,f} \le sirrg_f$$

Labor constraints: limit the seasonal labor requirements ($lr_{c,r,p}$) to the total available agricultural labor (family and hired labor):

$$\sum_{c,r,d} lr_{c,r,p} \cdot X_{c,r,d,f} \le fla_{p,f} + hl_{p,f}$$

Water constraints: the crop water requirements ($wr_{c,d}$) cannot exceed the volume of water available ($watera_f$), taking into account the technical efficiency of the different on-farm irrigation systems (h_{ri}) and irrigation channels (H):

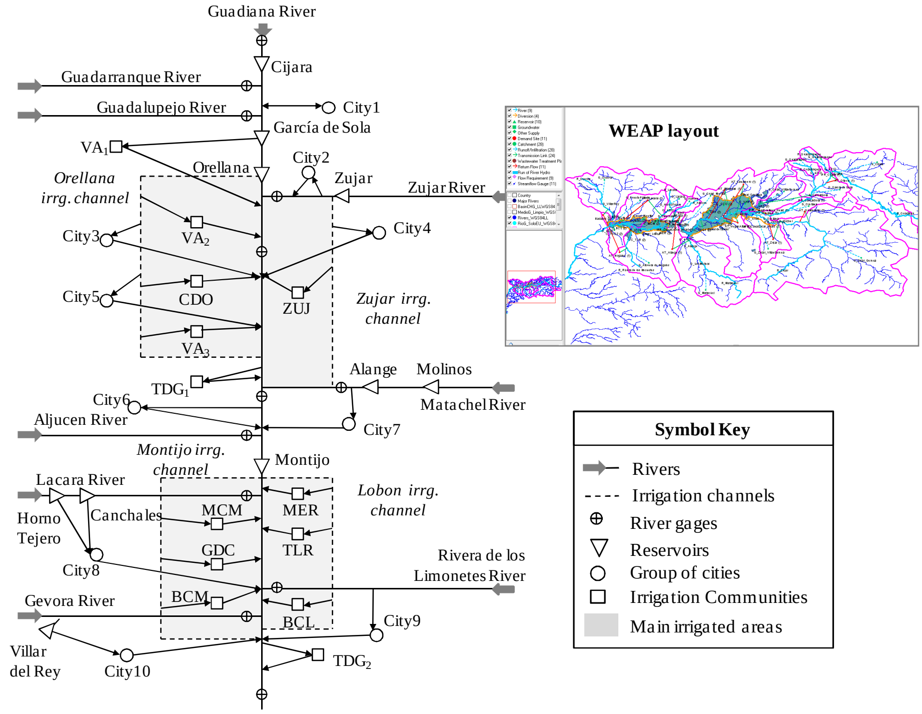
$$\sum_{c,ri,d} wr_{c,d} \cdot X_{c,ri,d,f} / h_{ri} \le watera_f \cdot sirrg_f \cdot H$$

Other policy relevant constraints: such as set aside requirements, cropping permits, etc.

- **The hydrology model**

The Water Evaluation and Planning (WEAP) modeling platform was used to represent the hydrological behavior of the Middle Guadiana river basin. WEAP is an object-oriented computer modeling package that operates on the basic principle of water accounting, and determines the optimal allocation of water for each user-defined time step according to demand priorities (e.g. agriculture, municipal users), supply preferences (e.g. groundwater, surface water systems), mass balance, and other physical and regulatory constraints (e.g. capacity of reservoirs, irrigation channels). It has been widely and successfully used to assist stakeholders and decision-makers in water planning and policy analysis in a number of basin locations worldwide (Assaf and Saadeh, 2008, in Lebanon; Bosona and Gebresenbet, 2010, in Ethiopia; Vicuña et al. 2010, in Chile; Young et al., 2009, in USA; among many others). A schematic representation of the Middle Guadiana basin WEAP application is depicted in Fig. 2.

Fig. 2- Schematic representation of the Middle Guadiana basin WEAP application.



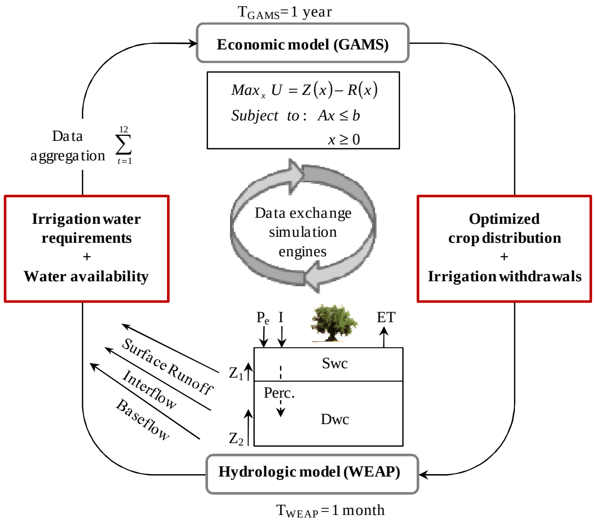
The Middle Guadiana basin WEAP application includes: 9 major rivers; 4 major irrigation channels (Orellana, Zújar, Montijo and Lobón); 10 reservoirs with a total storage capacity of 7500 Mm^3 (95% of the total storage capacity in the Middle Guadiana basin); principal irrigation and municipal water demands (12 ICs and 10 groups of cities); 12 key stream flow gauges. In addition, the study area has been characterized by a contiguous set of 15 sub-catchments divided in fractional sections that represent areas of similar land use classes (non-irrigated agricultural land, irrigated agricultural land, semi-natural areas, forest, and pasture). The irrigated land class include the area distribution of major crops (wheat, maize, rice, tomato, melon, olive, vineyards, peach and plum trees) cultivated in the different Irrigation Communities and representative farm types of the Middle Guadiana basin.

Natural hydrology processes within each catchment unit and fractional area have been simulated on a monthly-time step using the WEAP 2-bucket hydrology module (see Yates et al., 2005a; Yates et al. 2005b for details). Irrigation in WEAP is determined by the crop area distribution, crop irrigation schedules, and threshold values of soil moisture content.

- **Linkage of the models**

The empirical integration of the economic and hydrology models was done by replicating the different Irrigation Communities and farm types within the specific geographical locations of the irrigated catchments of the Middle Guadiana basin, and by simulating the same scenarios in both models. The economic model and the hydrology model communicate with each other via an input/output data exchange interface developed using 'Visual Basic for Applications' (VBA) and the 'Converter XLS' program. The models can operate in a stand-alone mode, which makes management easier, but can be subsequently run following an iterative feedback loop and exchanging data on crop mix, water use and water availability, and crop irrigation requirements (see Fig. 3).

Fig. 3- Diagram of the loop linking the economic and hydrology models and the data-exchange between them.



2.3. Model testing: calibration and validation

The economic model was calibrated with the risk-aversion coefficient (Φ) by comparing the simulated and observed crop mix of the different farm types for the year 2007. The Φ obtained in this study ranged between 0.9 (F_4) and 1.4 (F_8) and ensured the robustness of the model, according to Hazell and Norton (1986), by providing Percentage Absolute Deviation (PAD) values that varied from 7 (F_5) to 19 (F_3) with an average of 12. On the other hand, the hydrology model was calibrated by comparing the stream flows simulated at a monthly time scale with that observed at the selected gauging stations from January 1974 to December 1990. The calibration was performed using several agro-hydrological parameters (runoff resistance factor, crop coefficient, hydraulic conductivity, preferred flow direction, water holding capacity) as calibration factors to modify the seasonal and inter-annual behavior of key hydrological processes (surface runoff, interflow and base flow). The accuracy of the model was quantified using the Bias and the Nash-Sutcliffe efficiency index (Nash and Sutcliffe, 1970). Values of the Bias ranged between -12% and +15% with an average of +2%. The Nash-Sutcliffe parameter varied from 0.73 to 0.88 with an average of 0.81.

Besides that, the economic and hydrology models were coupled together and validated for the base year 2007. The optimal cropping pattern by farm type obtained from the calibrated economic model was replicated into the hydrology model, which, in turn estimated the different net irrigation water requirements (see Table 2).

Table 2- Observed and simulated irrigation water requirements by type of crop and location within the Middle Guadiana basin.

Region		Irrigation water requirements (m^3/ha)							
		Wheat	**Maize**	**Rice**	**Tomato**	**Melon**	**Olive**	**Peach**	**Prune**
Observed*	Whole basin	3202	6584	7508	4712	4418	2567	2888	2888
Simulated	Upstream	3394	5874	7400	4355	4056	2567	2464	2592
	Midstream	3376	6056	7693	4516	4305	2650	2650	2625
	Downstream	3080	6026	7673	4494	4288	2637	2656	2613

* Observed values represent historical average values from 1999 to 2001 obtained from different studies (JE, 2009; MAPA, 2005)

Table 2 shows that observed values overestimate crop irrigation requirements, particularly in the case of fruit trees and maize crops where observed values can be 10-17% higher than simulated values. The new optimal crop distribution obtained from the economic model using the WEAP spatially-distributed irrigation water requirements provided lower PAD values than those obtained using average observed values. The new PAD values ranged from 1 (F_2) to 16 (F_{13}) with an average of 9. These findings indicate that average values for crop irrigation requirements can be misrepresentative and that a coupled hydro-economic model can replicate the reality of water and farming systems better than non-coupled economic and hydrology models.

2.4. Scenario simulation

- **Baseline scenario or 'business-as-usual'** goes from the base year 2007 up to 2015, which corresponds to the deadline established by the WFD for achieving environmental goals. In this scenario, current water policies persist until 2015, direct farm payments are gradually decoupled from production and incorporated into the SFP, compulsory set-aside requirements are abolished by 2010, and the modulation rate increase from 5-10 % by 2012 (EC, 2009). Input costs for agricultural production are supposed to increase up to 5% by 2015 based on the evolution of machinery costs, fertilizer, seed, and pesticide prices observed in the region of study over the last decade (MARM, 2010). Crop prices (mainly for cereals and oilseeds) are supposed to increase up to 7% by 2015 (see Nowicki et al., 2009; OECD-FAO, 2009). Monthly hydrological simulations are performed until 2015 considering two types of climate sequences: normal and dry. The normal climate sequence corresponds to the 10-year period that registered the median total precipitation the past century (1901-2001). The dry climate sequence was associated to the ten-year period that registered 20% less of total precipitation with respect to the previously defined normal situation.
- **Spanish national water policy scenario.** The maximum amount of water delivered to the different ICs is subject to the historical water rights established by the Spanish National Hydrological Plan (NHP) (MMA, 2001): 6600 m^3/ha for those ICs that take water directly from the river and 7500 m^3/ha for the remaining ones.
- **European water policy scenario.** Monthly Minimum Environmental Flow Requirements (MEFR) are included to fulfill the objectives of the EU Water Framework Directive (WFD) in the Middle Guadiana basin by 2015. The GRBA has identified 19 river reaches within the Middle Guadiana basin where some minimum flows should be maintained[2]. The present study includes 10 river reaches (namely, Guadiana IV, V and VI, Zujar II, Matachel II and III, Lacara, Zapaton II, and Rivera de los Limonetes) as being the remaining ones located outside of the study area boundaries.

3. Results and discussion

The results focus on four ICs (CDO, MCM, TDG and ZUJ), which represent 65% (94000 ha) of the total irrigated surface in the Middle Guadiana basin, and the great diversity of farming systems that exist in the area of study in terms of location, crop diversification, and types of irrigation systems. The ICs of CDO and ZUJ are located upstream on the Middle Guadiana River, whereas MCM and TDG are situated midstream and dispersed all along the entire middle Guadiana River, respectively. MCM and CDO are old ICs with gravity irrigation systems, medium-low crop diversity, and small representative farm types, whereas TDG and ZUJ are characterized by being modern ICs with pressurized irrigation systems (sprinkler and drip) and high crop and farm size diversity.

3.1 Baseline scenario: following current trends

[2] A detailed description of the minimum EFR determined by the GRBA to maintain the basic ecological functioning of particular river reaches can be found in CHG (2009).

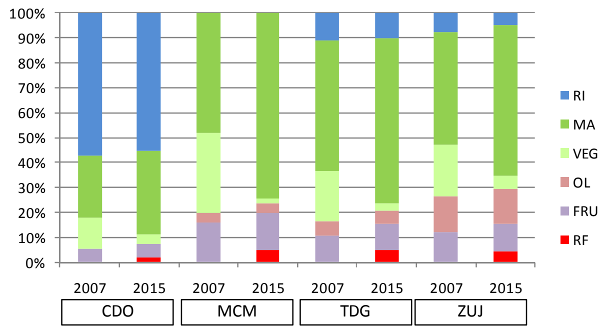
- **Socio-economic impacts**

Table 3- Baseline values for the first and last year of the simulation period (2007-2015) by type of Irrigation Community.

IC code	Year	Indicators						
		Income	Public exp.	Water use	Water product.	Water cost	Labor	Irrigated/ Rainfed
		€/ha	€/ha	m^3/ha	€/m^3	€/m^3	Working days/ha	%
CDO	2007	1911	898	9622	0.200	0.020	9.7	100/0
	2015	1672	786	9622	0.174	0.020	9.6	99/1
MCM	2007	2573	652	7480	0.344	0.029	16.9	100/0
	2015	2475	585	7480	0.330	0.029	13.1	95/5
TDG	2007	2113	645	6725	0.337	0.048	16.3	100/0
	2015	1960	529	6951	0.282	0.048	11.1	95/5
ZUJ	2007	2270	743	5961	0.381	0.046	16.9	100/0
	2015	2151	599	5955	0.361	0.046	14.3	96/4

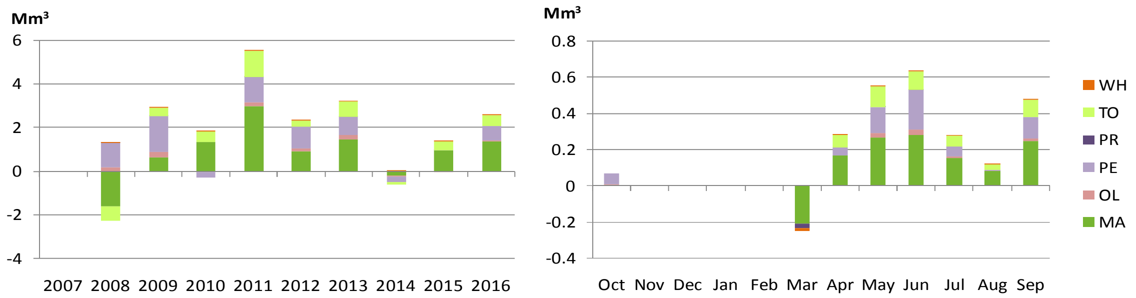
Results indicate that if we continue on our current path, farm income will be reduced by between 12% in the water-intensive farming systems of CDO and 4-5% in the most diversified farms of MCM and ZUJ by 2015. These results are in line with those obtained by the CAPRI model for the Extremadura region, which predicts a decrease of 16% in the gross margin of cereals by 2015 (CHG, 2006). Similarly, the EU foresees an average reduction in farm income of 7% for all EU-27 farmers by 2020 (Nowicki et al., 2009). The future situation in 2015 will also produce a shift in agricultural production. As seen in Table 3, rain-fed farming appears in 2015, but it is not reflected in lower water use rates, except for the highly modernized IC of ZUJ. As also reported in other studies (Acs et al., 2010; Bartolini et al., 2007; Varela-Ortega, 2010), the decoupling of the CAP subsidies from production will reduce production incentives substantially for irrigated crops, which may encourage a shift from irrigated to non-irrigated agriculture. However, the abolishment of the set-aside requirements by 2010 will allow farmers to maximize their production potential and intensify water consumption. Fig. 4 shows that rice is slightly reduced, but tomato, which is highly subsidized in the study area in the present situation, is partly substituted by maize in all irrigation districts. This is due to the loss of its comparative advantage in the production-based coupled payments received within the previous CAP scheme, and to the increase in cereal and energy crop prices expected for 2015.

Fig. 4- Crop area distribution by Irrigation Community in the baseline scenario.



- **Climate impacts**

Fig. 5- Annual total and monthly average crop water demands in a dry climate cycle relative to normal in the midstream IC of MCM.



Results indicate that crop water demands are very sensitive to climate variations. As seen in Fig.5, crop irrigation requirements increase considerably in years preceded by periods of little precipitation (2009, 2013 and 2016). If we look at the average monthly values, we can observe that, under drought conditions, additional water for irrigation is not necessary during the winter season, but increases at the beginning and the end of the crop growing season, especially in May-June and September. As also reported in other studies (Fischer et al., 2006; Maneta et al., 2009), water demand for irrigation will rise in a warmer climate depending on the type of crop and geographical location. Overall, our results reveal that, under drought conditions, irrigation requirements increase moderately for cereals and vegetables (between 4% and 10% with respect to an average normal year) and substantially for permanent crops (between 13% and 25%). Olives and fruit trees are the most affected crops due to the little water requirements shown by these crops during normal years and also because they need to be irrigated in spring and early fall, which are the periods with the highest demand increases, and are the most variable seasons in precipitation terms. As observed for the base year 2007, irrigation needs will be slightly higher (about 10%) in the midstream and downstream regions of the Guadiana River (the driest areas of the basin) than in upstream areas.

3.2. Compliance with the Spanish HNP: reducing water allotments for agricultural use

Table 4- Effects of the application of the HNP water allotments under normal and dry climate conditions by type of Irrigation Community.

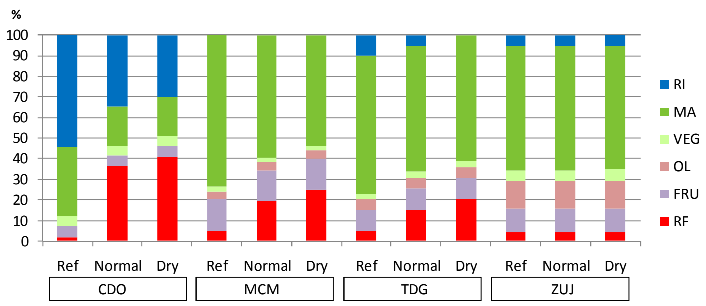
IC code	Water policy*	Climate sequence	Indicators					
			Income	Water use	Water productivity	Water cost	Water shadow prices	Irrigated/ Rainfed
			€/ha	m^3/ha	€/m^3	€/m^3	€/m^3	%
CDO	Ref.	Normal	1672	9622	0.174	0.020	0.026	99/1
	HNP	Normal	1505	6375	0.236	0.031	0.041	65/35
		Dry	1420	6375	0.223	0.031	0.038	60/40
MCM	Ref.	Normal	2475	7480	0.331	0.029	0.031	95/5
	HNP	Normal	2350	6600	0.356	0.034	0.032	79/21
		Dry	2256	6600	0.342	0.034	0.030	73/27
TDG	Ref.	Normal	1960	6951	0.282	0.048	0.019	95/5
	HNP	Normal	1901	6175	0.308	0.049	0.022	85/15
		Dry	1862	6175	0.302	0.049	0.020	80/20
ZUJ	Ref.	Normal	2151	5955	0.361	0.046	-	96/4
	HNP	Normal	2151	5955	0.361	0.046	-	96/4
		Dry	2136	6504	0.328	0.045	-	96/4

* The reference situation refers here to the baseline situation in 2015.

As seen in Table 4, water use is reduced by 34% and 12% in the old ICs of CDO and MCM respectively, and by 11% in the modern IC of TDG when HNP water allotments are implemented. Results also show that farm income decreases of 10% in CDO, 5% in MCM, and 3% in TDG, and indicates that this situation will worsen in dry periods, when an increase in crop water requirements is expected to produce a further reduction in farm revenues. Nonetheless, different behavior can be observed in the very modern IC of ZUJ. The highly efficient use of water in ZUJ during normal years allows this irrigation district to consume larger quantities of water during dry periods to mitigate the impact of drought.

Table 4 indicates that the marginal value of water is not constant and increases when more restrictive water allotments are implemented. On the contrary, the marginal value of water decreases in dry periods, as increased evaporation enhances farmers' demand for water. Similar results were obtained by Medellín-Azuara et al. (2010) and Pulido-Velázquez et al. (2008), which analyzed the variation in time and space of the economic value of water under different levels of water scarcity and demands in Spain and Mexico, respectively. Likewise, Varela-Ortega et al. (2010) assessed the impact of water conservation policies using water shadow prices, and demonstrated that shadow values increase as less water is delivered because farmers adapt to water stress conditions. In this study, farmers adapt to changes in weather patterns and water availability by changing their crops and technologies to minimize expected adverse impact (see Fig. 6).

Fig. 6- Cropping patterns adopted by farmers in the reference situation when the HNP water allotments are implemented under normal and dry climate conditions.



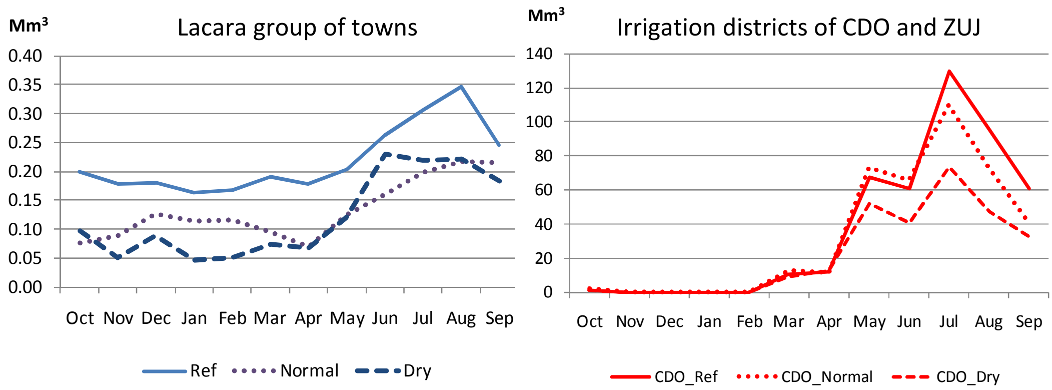
As seen in Fig. 6, rice areas are sharply reduced, whereas the surface provided for less water-demanding crops (vegetables and permanent crops) is kept constant. Water intensive cereals (maize) are also substituted by rain-fed cereals (wheat), although this trend is mitigated in the modern and diversified ICs of TDG where water is saved by replacing gravity-fed maize with sprinkler-irrigated maize. Changes in crop production stress during dry periods are observed.

These results demonstrate that the oldest and less diversified ICs of CDO and MCM will be the most economically affected by the implementation of more restrictive water allotments, and the most vulnerable when facing dry climate conditions. As also reported in other studies (such as Reidsma and Ewert, 2008; Smit and Skinner, 2002), the diversity of farm sizes, cropping mix potential, and farming operation options reduce vulnerability and increase farmer's capacity to adapt to different climate and political stimuli.

3.3. Compliance with the WFD of the EU: establishing environmental flow requirements

Results indicate that complying with the good ecological status of water bodies implies a reduction in the supply for other uses in the basin, especially during dry periods, giving rise to opportunity costs (see Fig. 7).

Fig. 7- Average water supply deliveries to different urban and agricultural users under normal and dry climate conditions when complying with the environmental flows.



As seen in Fig. 7, the urban demand site of Lacara, with approximately 30000 inhabitants, receives 38% (1 Mm^3/year) and 45% (1.2 Mm^3/year) less water under normal and dry climate conditions, respectively, when environmental flows are implemented. These reductions will be more severe during the winter and early spring months, from November to April. On the other hand, when minimum instream flows are imposed, the amount of water supplied to the irrigation district of CDO to satisfy crop water needs decreases by 17% (70 Mm^3/year) and 40% (177 Mm^3/year) under normal and dry climate conditions, respectively, with regard to the reference situation. Irrigation deliveries increase slightly in May and decrease moderately from July to September under a normal climate cycle, whereas they are sharply reduced from May to September if a dry climate cycle occurs. In the upstream region of CDO and under all climate scenarios, the months of July and August are periods with significant unmet environmental demands and high irrigation water requirements, evidencing a clear clash between environmental and agricultural water uses during summer low-flow periods.

Results of the application of environmental flows regimes on farm income, water and land use, water productivity, water costs and water shadow values by IC are summarized in Table 5. As seen in Table 5, in CDO, complying with the environmental flows entails a decrease of 17% and 40% in the amount of water per hectare delivered to farmers and a reduction of 7% and 20% in farmers' income under normal and dry climate conditions, respectively. Severe water shortages and increased evapotranspiration force CDO farmers to change their crop choice, mainly based on rice cultivation, and substitute rice crops with rain-fed crops. Thus, in dry periods, rain-fed surface represents 55% of the total area used for agricultural production in the low diversified farming systems of the CDO IC. Water shadow prices for CDO (0.039 €/m^3 and 0.041 €/m^3 in a normal and a dry climate cycle, respectively) indicate the opportunity cost of complying with environmental constraints.

Table 5- Effects of the application of environmental flows under normal and dry climate conditions by type of Irrigation Community.

IC code	Water policy	Climate sequence	Indicators					
			Income	Water Use	Water Prod.	Water cost	Water shadow prices	Irrigated/ Rainfed
			€/ha	M^3/ha	€/m^3	€/m^3	€/m^3	%
CDO	Ref.	Normal	1672	9693	0.172	0.020	0.026	99/1
	Env.F	Normal	1555	8045	0.194	0.028	0.039	72/28
		Dry	1336	5816	0.229	0.037	0.041	55/45
MCM	Ref.	Normal	2475	7480	0.331	0.026	0.031	95/5
	Env.F	Normal	2475	7480	0.331	0.026	0.031	95/5
		Dry	2326	7480	0.310	0.026	0.029	82/18
TDG	Ref.	Normal	1960	6951	0.282	0.048	0.019	95/5
	Env.F	Normal	1960	6951	0.282	0.048	0.019	95/5
		Dry	1900	7260	0.262	0.047	0.016	90/10
ZUJ	Ref.	Normal	2151	5955	0.361	0.046	-	96/4
	Env.F	Normal	2151	5955	0.361	0.046	-	96/4
		Dry	2134	6297	0.339	0.045	0.015	94/6

* The reference situation refers here to the baseline situation in 2015.

In the ICs of MCM, TDG and ZUJ, environmental flow requirements are not adding water-binding restrictions. As shown in Table 5, farmers that belong to the old and low diversified IC of MCM lose up to 6% of their income in dry periods. This reduction is slightly higher than that observed in the HNP scenario between a normal and a dry climate situation (4%), in which farmers are subjected to tighter water supply regimes. On the contrary, the modern and diversified ICs of TDG and ZUJ increase water consumption slightly in dry periods, by 4% and 6%, respectively, which help farmers to mitigate the impact of a drought. Farmers located in TDG and ZUJ dispose of flexible adaptation mechanisms to water stress situations, which allow them to irrigate their most profitable crops whenever possible. In dry periods, farm incomes decrease only by 1% and 3% in the ZUJ and TDG irrigation districts, respectively.

4. Conclusions and reflections

The present study has illustrated the application of a hydro-economic model to evaluate the potential implications of different water policies under normal and dry climate conditions on the large-scale irrigation systems of the Middle Guadiana basin in Spain.
Farmers' behavior was simulated using a multi-scale economic optimization model, whereas the Water Evaluation And Planning system (WEAP) was employed to replicate catchment-scale hydrologic processes and represent basin-scale water system operations. The integration of the economic and hydrology models was made empirically by replicating the different irrigation demand nodes and simulating the same scenarios in both models, and technically by an automated wrapper interface used to facilitate the exchange of data between the two models. This study proves that the accuracy of the models in predicting farmers' and water systems' behavior improves when the economic and hydrology models are coupled together, evidencing the potential of integrated tools in replicating the reality of complex water systems.
Taking into account a recent base year (2007), the research suggests that expected future trends in agricultural policies and markets will reduce farm income and produce a shift in agricultural production by 2015. Rain-fed farming is encouraged, but changes in land-use practices might not be reflected in lower water use rates, which indicate that further integration between water policies and agricultural policies is needed.
A downward revision of the existing water concessions for agricultural use (Spanish HNP scenario) will entail significant farm income losses in the oldest and less modernized ICs of the Middle Guadiana basin, regardless of their geographical location. These income losses will be accentuated in dry conditions, under which irrigation requirements increase slightly for cereals and vegetables and substantially for permanent crops, especially in the driest areas of the basin (midstream and downstream regions). This situation is mitigated in modern and diversified ICs, where the high variety of farm sizes, crops and irrigation systems reduces vulnerability and increases the capacity that farmers have to adapt to climate and political stimuli.
Complying with minimum environmental flow requirements (EU WFD scenario) implies a reduction of water supplied to agricultural and urban uses, giving rise to opportunity costs. Upstream on the Guadiana River, low summer flows are insufficient for maintaining the basic ecological functioning of some river reaches and fulfilling the irrigation requirements of intensive irrigated paddy fields. These irrigated areas will be the most economically and physically affected by the implementation of minimum environmental flows. The clash between environmental and agricultural water uses in this situation will be stressed in dry periods.
In the study area, as in many other arid regions where agriculture is by far the main water user, water management strategies are trying to curb this trend by encouraging a more efficient use of water for irrigation. As evidenced in this study, the EU WFD does not discriminate between efficient and inefficient irrigation models, and therefore it will not encourage substantial changes in current irrigation patterns. On the other hand, the Spanish HNP will promote a more efficient and equitable use of water for irrigation by supporting modernized irrigation systems and by assigning more equitable water allotments among the different agricultural users.
Our analysis clearly relies on modeling assumptions which warrant further investigation; however it demonstrates the potential of hydro-economic tools for policy and climate impact analysis. Hydro-economic provides a more comprehensive vision of the many factors affecting water resources both in present and uncertain future situations, and therefore, they constitute useful tools to assist policy-makers and stakeholders in the development of rational policies for sustainable water resources.

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