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Analysis

A hydro-economic model for the assessment of climate change impacts and adaptation in irrigated agriculture

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ABSTRACT

Recent research has demonstrated the multidimensional and multi-scalar nature of climate change, evidencing the need to develop integrated tools for the analysis of impacts and adaptation. This research presents a hydro-economic model of the Middle-Guadiana basin, Spain, to assess potential effects of climate change on irrigated agriculture and options for adaptation. It combines a farm-based economic optimisation model with the hydrologic model WEAP, and represents the socio-economic, agronomic and hydrologic systems in a spatially-explicit manner covering all dimensions and scales relevant to climate change. Simulated scenarios include a severe A2 climate change scenario up to 2070, two policy-based adaptation scenarios, and autonomous adaptation. Results show that climate change may impact severely irrigation systems reducing water availability and crop yields, and increasing irrigation water requirements. The risk faced by farmers is determined by technology and water use efficiency but also by spatial location and decisions made in neighbouring irrigation areas. The analysis of adaptation strategies underscores the role of current EU water policy in facilitating adaptation. Overall, the applied framework proved to be a useful tool for supporting water and climate change policy-making. It contributes to improve understanding about potential impacts of climate change, multi-scale vulnerability and the scope for adaptation.

1. Context and Objectives

The Mediterranean region is considered a climate change “hot-spot” (Giorgi, 2006; Iglesias et al., 2011), where water resources are likely to be seriously affected by climate change in the form of increased water scarcity and more frequent droughts (Arnell, 2004; Bates et al., 2008). In Spain, semi-arid Mediterranean regions that are vulnerable to water scarcity will have to deal with the additional challenges of climate change that will require the adaptation of economic activities dependent on water resources, such as irrigation agriculture, to new climatic conditions. Dealing with climate change will require a shift in water management and farming decisions towards more sustainable agricultural production and more efficient water allocation, distribution and use.

Along the last decades, the production of knowledge on climate change has been highly fragmented. Recent research on climate change has approached the assessment of impacts, vulnerability and adaptation under biophysical or social perspectives (Downing, 2012; Füssel, 2007). In the field of agriculture and water resources, most assessments have been based on biophysical modelling focusing on one specific dimension of climate change, such as the agronomic dimension (Moriondo et al., 2010; Ventrella et al., 2012), or the hydrological dimension (Joyce et al., 2011; Rochdane et al., 2012). However, the recognition of water management and climate change as multidimensional and multi-scalar concerns (Downing, 2012; Meinke et al., 2009) evidence the need to integrate biophysical and social aspects looking at environmental and human contexts. In line with this, varied types of integrated modelling frameworks have been developed to address the different scales (from the crop to the river basin) and the different dimensions of climate change, water and agriculture (hydrological, agronomic, socio-economic). However, these frameworks have not always represented the socio-economic dimension of water use in sufficient detail and in some cases they have undervalued the role of human response to climate impacts.

Trying to better represent socio-economic issues, hydro-economic modelling has been extensively used along the last decades as a prominent tool for guiding and implementing water policy decisions (Blanco-Gutiérrez et al., 2013; Brouwer and Hofkes, 2008; Heinz et al., 2007). These models are capable to consider the economic behaviour of water users and the economic principles that govern water allocation

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and use among different sectors. This modelling approach has been applied at different scales and has been used for the analysis of varied agricultural concerns (Peña-Haro et al., 2009, and Volk et al., 2008, for agriculture-driven pollution; Blanco-Gutiérrez et al., 2013, and Rosegrant et al., 2000, for water allocation policies; Harou and Lund, 2008; Varela-Ortega et al., 2011, for groundwater overexploitation). Only in recent years, hydro-economic modelling has been applied for the assessment of impacts and adaptation to climate change, and the associated uncertainties (D'Agostino et al., 2014; Hurd and Coonrod, 2012; Jeuland, 2010; Medellín-Azuara et al., 2011). These models are able to represent people's response to climatic stimuli and climate change impacts on water resources and agricultural production guided by economic principles. However, the consideration in these models of crop growth processes has been uneven.

Along this line, this paper presents a novel application of a hydro-economic modelling framework that is used to assess climate change impacts and adaptation in the Middle Guadiana Basin, taking into account the agricultural, socio-economic and hydrology systems. The novelty of the approach presented here lies in the capability of this integrated framework to take into consideration agronomic, economic and hydrologic processes that take place at different scales. This way, this research takes a step forward in hydro-economic modelling to advance in the analysis of climate change implications on irrigation agriculture systems from the crop to the farm and the water system levels. The applied modelling framework includes the development of a farm-based economic mathematical programming model (MPM) of constrained optimisation that illustrates farm-level decision-making, and an application of the hydrology model WEAP (Water Evaluation and Planning System) (Yates et al., 2005) with its agronomic module (the MABIA Method, Jabloun and Sahli, 2012) that represents hydrological, agronomic and water management processes. This model combination permits to make socio-economic and agronomic processes spatially-explicit. Using this integrated approach, this paper evaluates the impacts of a severe climate change scenario (A2) on the water system, on farms and on crops, looking at farmers' capacity to adapt. It also explores the potential of selected water policies in facilitating adaptation, considering the various entities relevant to water management decision-making, including the farm, irrigation community (IC) and river basin levels.

2. Water, Agriculture and Climate Change in the Middle Guadiana Basin

The Middle Guadiana Basin, in the South-Western Spanish central plateau, illustrates the complexities and challenges of climate change adaptation in irrigated agriculture areas where water is scarce. The basin (Fig. 1) covers an area of about 34,000 km^2 and it is characterised by a continental Mediterranean climate with a marked dry season, an average annual precipitation of 500 mm, and a semi-arid humidity regime (CHG (Confederación Hidrográfica del Guadiana), 2008). Rural development policies during the 50's and 60's and recent National Irrigation Plans fostered the development of irrigation districts, primarily based on the development of hydraulic infrastructures. These infrastructures have provided a water storage capacity of 8000 Mm^3 to the basin, which has been crucial for irrigation development and rural socio-economic progress, and for mitigating the effects of the region's recurrent droughts.

Irrigation covers an area of around 130,000 ha where the main crops include maize, rice and horticulture, fruit trees, olive trees and vineyards (INE, 2009). Farmers are organised in irrigation communities that are in charge of managing water distribution to all farms, collecting water fees and controlling water use and irrigation. Management at the community level plays an important role with respect to the adoption of technologies and, in turn, to the efficiency of water use in the farms. There are 12 main Irrigation Communities in the Middle Guadiana from which in this research we will focus on three that show different water

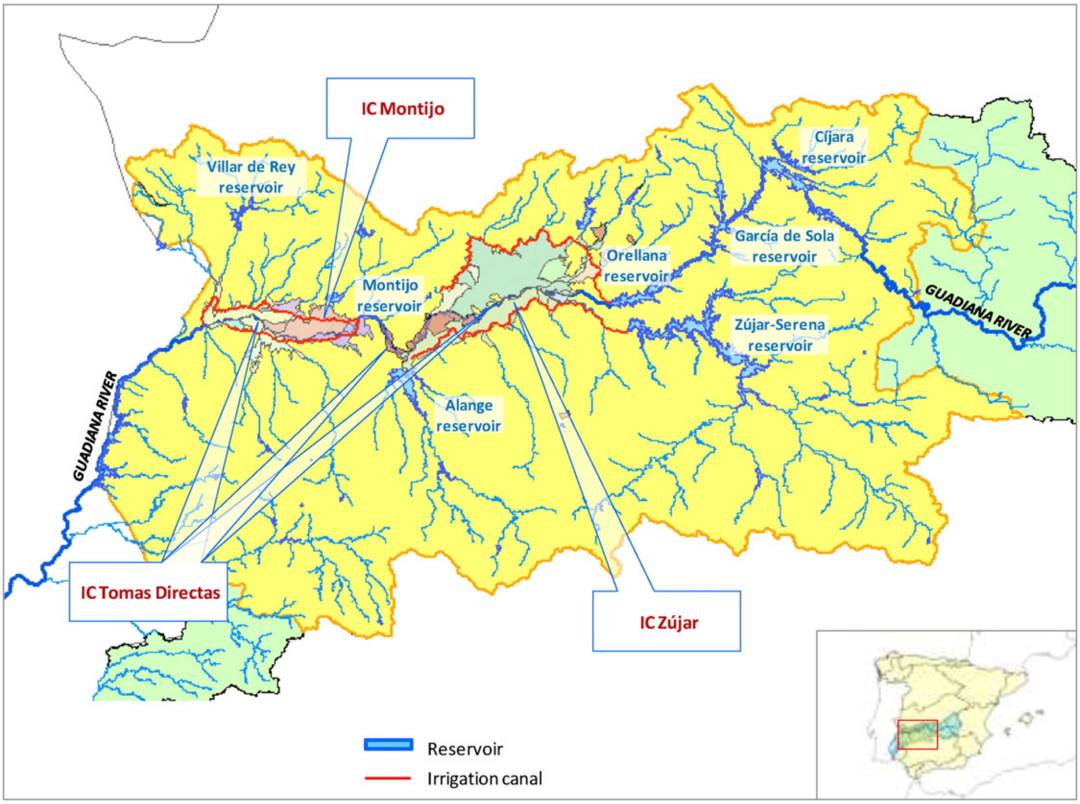

Fig. 1. The Middle Guadiana basin. Source: based on Blanco-Gutiérrez et al. (2013) and MAGRAMA (Ministerio de Agricultura, Alimentación y Medio Ambiente) (2013).

management approaches and technical developments. Zújar IC (21,000 ha) is a modern community located in the upper part with pressurised irrigation systems in which water users pay the official water charges per hectare plus a volumetric water tariff voluntarily established by the community board. Montijo IC (10,500 ha) is a traditional community located in the lower part, in which non-pressurised furrow irrigation is the most frequent irrigation method. Water consumption in this IC is in some cases above the officially permitted levels, and farmers pay a fixed amount per irrigated hectare, independently from real water consumption. Finally, Tomas Directas IC (22,000 ha) is a modern community located all along the river that comprises more varied agricultural production systems. In this community farmers pump water directly from water courses and they pay only for the energy cost of water pumping.

Average water use for irrigation in the basin is around 6000 m^3/ha, with maximum water allotments of 7500 m^3/ha and around 50% of the land irrigated by gravity-based surface irrigation methods. The large volumes of water used for irrigation, the rare use of volumetric water pricing schemes and obsolete water infrastructures and irrigation systems, pose important challenges for farmers and water managers that are compelled to implement the EU Water Framework Directive (WFD) (CEC, 2000). This directive, intended to achieve the good ecological status of all water bodies, requires maintaining minimum environmental flows and recovering all costs of water use through the implementation of economic instruments. These two requirements of the WFD may have potential implications on water availability for irrigation and on farm profitability.

Climate change will add further pressure on the already stressed water system and will pose additional challenges for the irrigation sector. The most recent assessment of climate change impacts on water resources carried out in the context of the Spanish National Adaptation Plan (CEDEX, 2011) identified the Guadiana basin as one of the most impacted river basins in Spain. This report estimates runoff decreases of 28% and 43% for the 2011–2040 and 2041–2070 periods respectively under an A2 scenario (average of models). However, how those changes in physical variables will affect the whole water system and socio-economic systems, and what water management and farm management measures can support adaptation to change have not yet been thoroughly explored.

3. Methods: A Hydro-economic Modelling Framework

To respond to the questions and challenges of climate change, we propose a hydro-economic modelling framework that follows a modular approach. Two stand-alone models, economic (MPM) and hydrologic (WEAP-MABIA), run separately but in coordination as the outputs of one of the models are used as input for the other model. This section explains model characteristics and the selected simulation scenarios.

3.1. The Economic Model

The economic model is a farm-based non-linear mathematical programming optimisation model. It is characterised by a stochastic approach that considers farmer's behaviour towards risk and finds the optimal combinations of land allocation ($X_{c,r}$) to different crops (c) and techniques (r) that maximise farmers' utility subject to technical, structural and policy constrains. It is specified by the equations explained below.

The objective function (Eq. (1)) shows the maximisation of farmers' expected utility, U, calculated as the expected farm income, Z, minus a risk component that represents utility losses driven by the risk inherent to crop production, following Hazell and Norton's (1986) approach. This risk component is composed of a farmer's risk aversion coefficient, φ, and the standard deviation of farm income, $\sigma(Z)$, according to market and nature variability that will affect crop prices and yields.

$$Max\ \ U = Z - \varphi \cdot \sigma(Z), \tag{1}$$

Eq. (2) shows farm income estimation, where: $gm_{c,r}$: gross margin per crop (c) and technique (r); $X_{c,r}$: production area per crop (c) and technique (r); $sb_{c,r}$: subsidies per crop (c) and technique (r); sfp: EU Common Agricultural Policy (CAP) unitary payment per farm (Single Farm Payment); mdu: CAP modulation rate; fco: family labour opportunity cost; $flab_p$: family labour use per period of the year (summer or winter) (p); hlw: hired labour wage (€/h); $hlab_p$: hired labour per period (p); wpm^3: volumetric water price; WC: farm water consumption; $wpha$: irrigation water fee paid per hectare; $sirrg$: irrigated area in the farm.

$$\begin{aligned} Z = {} & \sum_c \sum_r gm_{c,r} \cdot X_{c,r} + \left(\sum_c \sum_r sb_{c,r} \cdot X_{c,r} + sfp \right) \cdot mdu - fco \\ & \cdot \sum_p flab_p - hlw \cdot \sum_p hlab_p - wpm^3 \cdot WC - wpha \cdot sirrg \end{aligned} \tag{2}$$

This maximisation is subjected to different constraints, including land (Eq. (3)), labour (Eqs. (4 and 5)) and water (Eq. (6)) limitations:

$$\sum_{c,r} X_{c,r} \le surf, \tag{3}$$

$$\sum_{c,r} labreq_{c,r,p} \cdot X_{c,r} \le flab_p + hlab_p, \tag{4}$$

$$flab_p \le flab\_av_p, \tag{5}$$

$$\sum_c (wreq_c / h_{ri}) \cdot X_{c,ri} \le sirrg \cdot wavail \cdot H, \tag{6}$$

where, $surf$: farm size area; $labreq_{c,r,p}$: labour requirements per crop (c), technique (r), and period (p); $flab\_av_p$: maximum family labour available per period (p); $wreq_c$: crop net water requirement; h_{ri}: technical efficiency of the irrigation technique (ri); $wavail$: farm water endowment per hectare; H: efficiency of the water conveyance system.

Model parameters include farm structural characteristics and crop coefficients such as input costs, prices, water and labour requirements, and yields. These were obtained from MAPA (Ministerio de Agricultura, Pesca y Alimentación) (2007) and fieldwork carried out in the study area which included a survey of 101 farms from the three selected ICs.

The basic unit of analysis in the model is the farm. A farm typology for the Middle Guadiana basin was developed according to public statistics (Junta de Extremadura, 2008; INE, 2009; MARM, 2009) and fieldwork. The farm types selected represent the current farm typology, the variety of farm sizes, the most common crops and crop mixes, and the different types of farm irrigation systems and water management in the selected irrigation communities. Two farm types have been selected for Zújar IC (modern) and Montijo IC (traditional) respectively, and three farm types in the more heterogeneous Tomas Directas IC, located along the river. The selected communities and corresponding farm types represent 40% of the basin's irrigated land. The remaining irrigated land is represented by two aggregated farm types, one in the upper part, Vegas Altas, and one in the lower part, Vegas Bajas. Table 1 shows the selected representative farm types.

Model calibration was done using the risk aversion coefficient (φ). For this, it is assumed that the difference between actual cropping patterns and those that maximise income is due to different farmers' perceptions of risk. Therefore, model calibration was done finding the risk aversion coefficient (φ) that match simulated cropping patterns to real cropping patterns in the selected farm types. Model validation was done using comparative data for land and labour parameters in the study area.

Table 1
Representative farm types in the Middle Guadiana basin.

Farm type	IC	Municipality	Farm size (ha)	Irrigation technology	Cropping pattern
FTD1	Tomas Directas (modern, along the river)	Guareña	20	100% SURF[a]	100% rice
FTD2		Badajoz	90	100% DRIP[b]	22% olive, 26% peach, 29% tomato, 19% maize, 2% set-aside
FTD3		Mérida	45	100% DRIP	28% melon, 28% peach, 44% plum
FMON1	Montijo (traditional, downstream)	Montijo	50	17% SP[c], 83% SURF	17% wheat, 34% maize, 23% tomato, 21% peach, 5% set-aside
FMON2		Puebla de la calzada	10	100% SURF	55% maize, 35% tomato, 10% set-aside
FZ1	Zújar (modern, upstream)	Don Benito	40	16% SURF, 12.5% SP, 71.5% DRIP	12.5% wheat, 10% rice, 42.5% maize, 29% tomato, 6% set-aside
FZ2		Villanueva de la Serena	15	100% DRIP	47% maize, 30% tomato, 17% peach, 6% set-aside
FVA	Aggregated farm — Vegas Altas	Don Benito	25	88% SURF, 12% DRIP	32% rice, 30% maize, 16% tomato, 12% peach, 10% set-aside
FVB	Aggregated farm — Vegas Bajas	Badajoz	45	58.5% SURF, 6% SP, 35.5% DRIP	6% wheat, 3% rice, 40% maize, 19% tomato, 4.5% melon, 14.5% vine, 7% plum, 6% set-aside

[a] SURF : surface or furrow irrigation.
[b] DRIP: drip irrigation.
[c] SP: sprinkler irrigation.

3.2. The WEAP Hydrologic Model

The WEAP model is a water-planning tool that operates on the principle of water balance accounting, and represents different catchments, demand nodes, infrastructures, water flows and water transmission links that are interconnected (Yates et al., 2005). Using climate time series, WEAP calculates the components of the hydrological cycle by simulating rainfall-runoff processes at the catchment level.

Each catchment unit is divided in different land use classes for each of which a water balance is computed under assumed uniform climate within the catchment. Catchment characterisation for the Middle Guadiana Basin is based on watershed delineation by Blanco-Gutiérrez et al. (2013) and on land use definition according to the CORINE Land Cover 2006 update (IGN, 2006). For each catchment, the Soil Moisture Method represents a two-bucket scheme in which empirical functions are used to describe and simulate evapotranspiration, runoff and shallow interflows, changes in soil moisture, baseflow routing to the river, and deep percolation to groundwater (Sieber and Purkey, 2011). For irrigation catchments, the MABIA Method included in the WEAP software package simulates daily transpiration and evaporation for each crop and calculates irrigation water requirements and yields (Sieber and Purkey, 2011), based on the "dual K_c" method (Allen et al., 1998). The MABIA Method allows for the simulation of climate change and water availability effects on crop growth, although it does not capture the effect of CO2 fertilization on yields. The time step for MABIA is daily while the normal time step for WEAP is monthly. Therefore, for each WEAP monthly time step, MABIA is run on a daily base and then aggregated to the monthly time step.

Irrigation catchment specification corresponds to the location and characteristics of irrigation communities, matching the communities, the farm types and the crops selected and described in the economic model. Therefore, the model includes six irrigation catchments: Zújar IC (one catchment, upstream), Montijo IC (one catchment, downstream), the upper and lower section of Tomas Directas IC (two catchments, one upstream and one downstream), and two irrigation catchments that aggregate the remaining irrigation areas of Vegas Altas (upper part) and Vegas Bajas (lower part). For the simulation of rainfall-runoff processes, monthly climate data on temperature, precipitation, humidity, wind speed and solar radiation were obtained from the CRU-TS 3.10 Climate Database (Jones and Harris, 2011). Daily climate data for MABIA irrigation catchment specification were obtained from the Spanish Meteorological Agency. Soil parameters for irrigation catchment characterisation were obtained from the Extremadura Soil Catalogue (UNEX, 2000). Crop and irrigation parameters were based on Allen et al. (1998), on Doorenbos et al. (1979), and on data from the Spanish Ministry of Agriculture. Finally, the River Basin Authority provided technical data for water infrastructure operation and management.

Model calibration was carried out comparing observed and simulated river flows for the period 1973–1990 and validated in the period 1994–2000. The agro-hydrological parameters that specify the rainfall-runoff process were used for the WEAP model calibration, namely crop coefficient, soil water capacity, runoff resistance, conductivity and flow direction. Table 2 shows the calibration parameters used in the model. Model accuracy is measured using the Nash and Sutcliffe's (1970) efficiency coefficient[1] (E) and the standardised Bias score[2] (B). These parameters showed a good level of accuracy with an E coefficient between 0.69 and 0.87 and a bias (B) of less than 20%.

Table 2
WEAP calibration parameters.

Parameter	Value
Crop coefficient[a], Kc	1.1
Soil water capacity (mm)[b]	Ag = 130; Fo = 115; Pa = 140; SNat = 75
Deep water capacity (mm)	1400
Runoff resistance factor	Ag = 8; Fo = 15; Pa = 8; SNat = 4
Root zone conductivity (mm)	75
Deep conductivity (mm)	50
Preferred flow direction	0.8

[a] Average value in non-irrigated catchments.
[b] Ag: agriculture; Fo: forest; Pa: pasture; SNat: semi-natural area.

3.3. The Model Integration and Simulation Scenarios

Fig. 2 shows how the models are connected and how the model iterations take place.

The hydro-economic model simulation starts with the economic model run, in which the MPM optimises cropping patterns ($X_{c,r}$) under the corresponding policy scenario (baseline or adaptation policy-driven scenarios). Then, using cropping patterns ($X_{c,r}$) as input to characterise irrigation catchments, WEAP calculates monthly flows and water diverted from rivers and infrastructures to satisfy water demands in the different climate scenarios. Using the MABIA method, WEAP calculates irrigation water requirements, allocates water to crops depending on water availability and established priorities, and estimates crop yields.

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[1] $E = 1 - [\sum_{t=1}^{n} (Q_{c,t} - Q_{o,t})^2 / \sum_{t=1}^{n} (Q_{o,t} - Q_o)^2]$, where $Q_{c,t}$ and $Q_{o,t}$ are computed and observed flows in time step t and Q_o is the average observed water flow.

[2] $B = 100[(Q_c - Q_o)/Q_o]$, where Q_c and Q_o are the computed and observed average water flows.

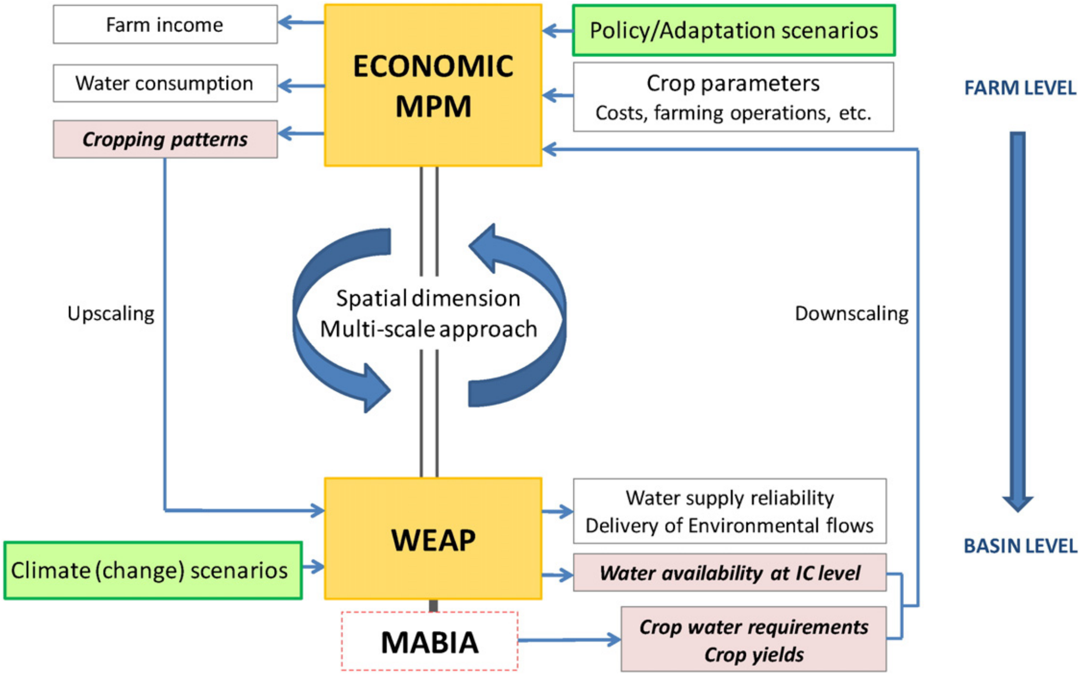

Fig. 2. Model linkage and iteration procedure (bold italic variables are those used to connect the two models).

After the first economic-hydrologic model simulation, there is a second economic-hydrologic iteration. The economic model uses WEAP results on water delivered to irrigation communities (water availability constraints at farm level, *wavail* in Eq. (6)), crop yields (used to calculate the gross margin per crop, $gm_{c,r}$, used in Eq. (2)) and irrigation water requirements ($wreq_c$ in Eq. (6)) under the simulated climate scenario (normal climate or climate change) to simulate farmers' adjustment of cropping patterns to a new optimal land allocation. Then, the adapted cropping patterns ($X_{c,r}$) are used again by WEAP to calculate water allocation, demand satisfaction, irrigation needs and crop production under the new conditions.

Two types of scenarios are used: climate scenarios and adaptation scenarios.

Climate scenarios include a “no climate change” (No CC) scenario and a severe climate change scenario. The climate change scenario CNRM-CM3/A2[3] (A2 from now on) was selected from the Third Coupled Model Intercomparison Project (CMIP3, Meehl et al., 2007) and downscaled for the Middle Guadiana basin (Varela-Ortega et al., 2014). This dry and warm scenario provides the most marked changes in temperature and precipitation in the basin in 2070, covering the widest range of potential negative outcomes of climate change in the basin. From this scenario, we used the changes in mean temperatures, precipitation, relative humidity and wind and applied them to the 1971–2000 available climate dataset to obtain two 30-year series for the two periods considered in the hydro-economic model: 2011–2040 and 2041–2070. This procedure entails some limitations as it replicates past climate variability and may, therefore, underestimate some of the changes induced by climate change such as the frequency or intensity of extreme events.

Adaptation scenarios include a baseline situation, two planned adaptation scenarios (policy-driven), based on the Regional Adaptation Plan (Junta de Extremadura, 2013) and on the WFD, and one autonomous adaptation scenario (farmers' initiative triggered by changes in expectations, market or nature conditions):

a) *Baseline scenario*: reference 2008 cropping patterns, current irrigation water allotments (maximum allotment 7500 m^3/ha to farmers) and current level of policy enforcement (consumption above permitted levels in some communities).
b) *Environment-oriented planned adaptation scenario* (*ENV*): establishment of river environmental flows and full compliance with current irrigation water allotments.
c) *Economic-oriented planned adaptation scenario* (*ECON*): implementation of water tariffs for the full cost recovery of water services in the basin. This cost recovery tariff is estimated at 0.055 €/m^3, based on CHG (2013) estimations of financial costs (0.034 €/m^3) and model-based estimations of the resource cost according to the marginal values of water (0.021 €/m^3). This scenario also includes the modernisation of water conveyance and irrigation systems (switch from furrow irrigation to pressurised irrigation) in the traditional ICs of Montijo and Vegas Altas.
d) *Autonomous adaptation* (*AA*): changes in cropping patterns that are undertaken at the farmers' initiative because of observed changes in climate and water availability.

The baseline and planned adaptation scenarios are simulated in combination with the “No CC” and with the A2 climate change scenario. These are policy-based scenarios that can take place with or without climate change. The autonomous adaptation scenario is simulated together with the baseline and planned adaptation scenarios and always combined with the A2 climate change scenario for the 2041–2070 period.

Climate scenarios are primarily simulated through the hydrologic model, as it represents physical characteristics of the crop and water systems, through changes in climate variables. On the other hand, adaptation scenarios that affect human behaviour are firstly simulated by the economic model that represents farmers' decision making, through changes in water availability at farm level (*wavail*), in water tariffs (wpm^3), and in crop yields (that affect crop gross margin, $gm_{c,r}$) and irrigation water requirements ($wreq_c$). River environmental flows (ENV planned adaptation scenario) are settled through the WEAP model but compliance with water allotments (*wavail*) is simulated in the economic model.

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[3] CNRM-CM3 model from the Centre National de Recherches Meteorologiques, Meteo France, SRES A2 scenario.

4. Results

The results of the assessment of climate change impacts and adaptation options in the Middle Guadiana basin are presented for five selected variables: crop yields, crop irrigation water requirements, farm income, unmet water demand (the gap between water demands/requirements and actual water supply), and water demand reliability (percentage of time that water demand in a catchment or demand node is fully covered). These variables reflect the magnitude of climate change impacts and the potential for adaptation, and illustrate the risk faced by the irrigation sector at different spatial levels, namely the farm (including crops), the Irrigation Community and the basin.

4.1. Climate Change Impacts on Crops

Table 3 illustrates the effect of the A2 climate change scenario on crop yields and irrigation water requirements (modelled by the MABIA module within WEAP) for the 2041–2070 period, considering no adaptation. For all crops, higher temperatures and lower precipitations (main features of the A2 climate change scenario) result in decreased crop yields and higher irrigation requirements.

Results shown in Table 3 demonstrate that climate change will likely produce moderate crop yield decreases, ranging between 3% and 8%, for all crops except for irrigated olives that will experience a 20% yield decrease. These changes in yields would be accompanied by around 20% increases in irrigation water requirements, and 27% in the case of olives. These crop yield changes are a consequence of climate conditions but also a consequence of the effective water availability (driven by climate but also by management conditions) in each time step. This means that, being water a limiting factor for crop production, higher water availability could lead to higher crop yields as well.

4.2. Impacts of Climate Change and Adaptation on Farm Income, Water and Land Use

Table 4 shows the effects of climate change and adaptation scenarios on farm income, water use and cropping patterns (percentage area per crop type) at the Irrigation Community level modelled by the economic MPM. It illustrates the expected performance of farms (aggregated for each Irrigation Community) in baseline conditions and in all adaptation scenarios considering climate change impacts on crop yields and irrigation requirements and on water availability. The first three lines for each IC show impacts of planned adaptation strategies without considering climate change, and the other three lines (+AA) show the impacts of those strategies together with autonomous adaptation under the A2 climate change scenario (average for the period 2041–2070).

It should be noted that results of climate change scenarios without autonomous adaptation are not presented in this table. The lack of adaptation at farm level would imply crop failure in most years because of water shortage and negative gross margins. This would represent the ‘*dumb farmer*’ unrealistic behaviour, as described by Füssel and Klein (2006), that assumes that farmers would not change their crop choices in a situation of lack of water.

In the baseline scenario, without climate change, farms in the modern Community of Tomas Directas (direct water uptakes from the river) reach higher farm income levels per hectare than in the other communities. This is attributable to the prominent role of permanent crops (olives, peach, plum) – which consume less water and are highly profitable[4] –, and to extended use of modern and efficient irrigation systems in this Irrigation Community. Alongside, the Montijo IC (traditional) and Zújar IC (modern) reach similar levels of income and consume higher amounts of water. Especially, Montijo IC consumes much larger water volumes as a consequence of significant water losses in the distribution network and irrigation systems and of inaccurate control of water use by the IC and by the water authority driven by the lack of water metering at farm level.

With the implementation of the ENV strategy (environmental flows + control of consumption), the traditional Montijo IC experiences income losses of around 2% with an expansion of rain-fed area, as compared to the almost null impact on its modern counterparts, Zújar IC and Tomas Directas IC. However, the impact of the ECON strategy (cost recovery + irrigation modernisation) is more varied across communities. Tomas Directas IC and Zújar IC, both modern, show income losses of 6 and 9% respectively, and significant reductions of water use that trigger the substitution of water intensive rice cultivation. Meanwhile, the traditional Montijo IC shows a 2% income increase and a shift to horticulture cultivation as a consequence of irrigation modernisation.

Under scenarios of climate change, the combination of planned adaptation strategies and autonomous adaptation leads to significant reductions of water consumption and the subsequent lower levels of expected income. Contrary to the results for the non-climate change scenarios, the ECON planned adaptation scenario (economic disincentives) produces similar or even lower impacts on farm income and a more significant reduction of water consumption than in the ENV planned adaptation scenario when both are combined with autonomous adaptation.

4.3. Impact of Climate Change and Adaptation on Unmet Water Demand and Demand Reliability

This section presents the simulation results of the effects of climate and adaptation on total unmet water demand at the basin level (Fig. 3), and on water demand reliability for the different Irrigation Communities (Table 5).

Results show that in the A2 scenario without adaptation (Baseline + A2), there are problems of unmet water demands in the first (2011–2040) and, especially, in the second period simulated (2041–2070), as water storage fails to mitigate the effects of severe hydrological droughts extending over periods of 4–5 years (2042–2047, 2050–2054, 2062–2066).

Looking at the planned adaptation scenarios, results show that both the ENV strategy and the ECON strategy would likely contribute to reduce unmet demand in the basin, especially in the 2041–2070 period, reducing the risk faced by the different communities. The ECON strategy reduces unmet demand to a greater extent than the ENV strategy, due to lower water demand for irrigation triggered by water pricing and the higher water saving potential offered by irrigation modernisation. In this sense, when this strategy applies, irrigation communities are better prepared to face water scarcity driven by climate change.

Autonomous adaptation substantially reduces water demand, contributing to partially close the gap between supply and demand. Maximum level of unmet demand in the Baseline + A2 + AA scenario (period 2041–2070) reaches 1000 Mm^3 in a severe drought year,

Table 3
Climate change impact on crop yields and irrigation water requirements without adaptation.

	% change[a] in 2041–2070 (A2 scenario)	
	Yields	Irrigation water requirements
Maize	−4%	17%
Wheat	−8%	21%
Rice	−4%	18%
Horticulture	0	20%
Fruit trees	−7%	25%
Olive trees	−20%	27%
Vineyards	−3%	20%

[a] Relative to a normal climate scenario in the same period 2041–2070.

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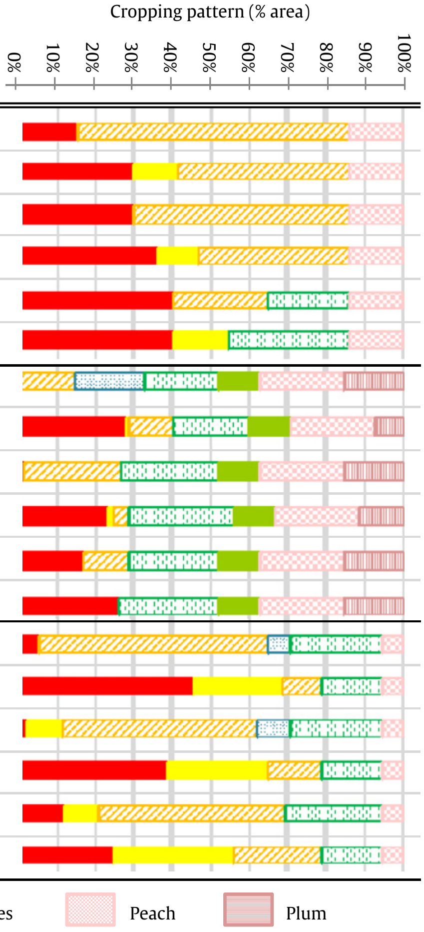
[4] Being an annual model, permanent crops are considered to be under full production and investment costs are not considered. This may overestimate the economic performance of these crops.

Table 4
Impact of planned adaptation strategies and autonomous adaptation in the irrigation communities.

		Farm income (€/ha)	Water consumption (m3/ha)
IC Montijo (traditional, downstream)	Baseline	1970	9423
	ENV	1931 (-2%)	7500 (-20%)
	ECON	2017 (+2%)	3822 (-59%)
	Baseline + AA	1728 (-12%)	8132 (-14%)
	ENV + AA	1701 (-14%)	7313 (-22%)
	ECON + AA	1801 (-9%)	3712 (-61%)
IC Tomas Directas (modern, along the river, high heterogeneity)	Baseline	4086	6247
	ENV	4063 (-1%)	4977 (-20%)
	ECON	3859 (-6%)	3808 (-39%)
	Baseline + AA	2935 (-28%)	4348 (-30%)
	ENV + AA	3166 (-23%)	4033 (-35%)
	ECON + AA	3253 (-20%)	3659 (-41%)
IC Zujar (modern, upstream)	Baseline	1708	7102
	ENV	1702 (≈0%)	7102 (0%)
	ECON	1564 (-9%)	5778 (-19%)
	Baseline + AA	1346 (-21%)	3288 (-54%)
	ENV + AA	1379 (-19%)	3814 (-46%)
	ECON + AA	1355 (-21%)	4801 (-32%)



which is around 50% lower than unmet demand without autonomous adaptation for the same year. The reason for this is that adaptation of cropping patterns at the farmers' initiative reduces significantly water demand and slows down the exhaustion of water storage along the whole drought period.

Model simulations show that water inflows to the area under the A2 climate change scenario would decrease on average around 15% in the period 2011–2040 and 35% in the period 2041–2070, as compared to 28% and 43% obtained by CEDEX (Centro de Estudios y Experimentación de Obras Públicas) (2011) for the same periods and scenario and for the whole Guadiana basin. However, location, supply preferences, water storage and demand priorities result in a different impact on water demand reliability and determine a different vulnerability at the community level. As Table 5 shows, simulation results demonstrate that upstream irrigation communities (Zújar IC, upper section of Tomas Directas IC, Vegas Altas) are more exposed to

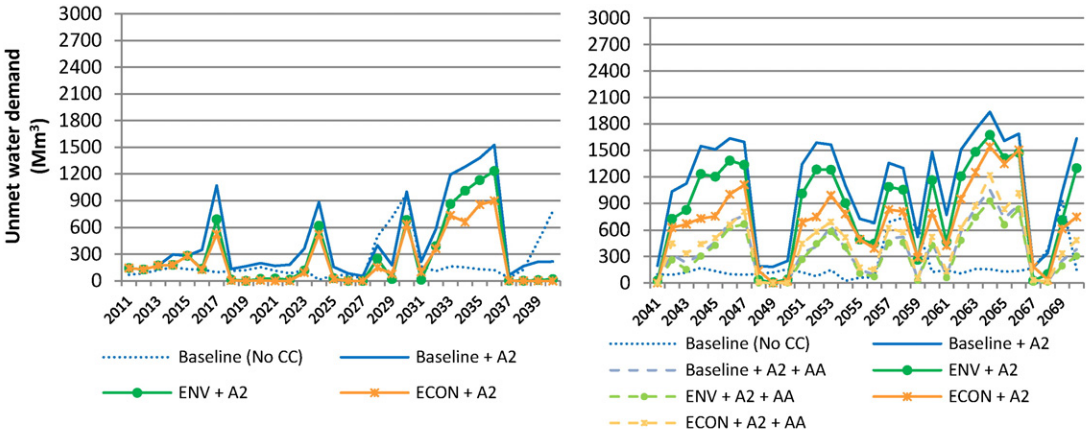


Fig. 3. Impacts of climate change and adaptation on unmet water demand.

Table 5
Demand reliability (%) under climate and adaptation scenarios.

		Baseline			ENV			ECON		
		No CC	A2	A2 + AA	No CC	A2	A2 + AA	No CC	A2	A2 + AA
Upstream	Zújar IC (modern)	94	79	94	95	79	82	96	83	83
	Tomas Directas (upper section)	91	76	81	98	81	84	98	88	89
	Vegas Altas (traditional)	78	67	73	89	74	77	92	76	76
Downstream	Montijo IC (traditional)	82	75	83	94	84	89	97	94	95
	Tomas Directas (lower section)	100	97	98	100	98	99	100	97	98
	Vegas Bajas (mixed, modern and traditional farms)	100	87	91	100	87	91	100	96	96
Total		88	76	83	94	80	83	96	85	85

water shortages than downstream communities (Montijo IC, lower section of Tomas Directas IC, Vegas Bajas) showing lower demand reliability in most scenarios.

Comparing water demand reliability in communities located in the same part of the basin, such as the lower section of Tomas Directas IC (modern, downstream) and Montijo IC (traditional, downstream), or Zújar IC (modern, upstream) and Vegas Altas (traditional, upstream), results show that demand reliability is lower in traditional communities than in their modern counterparts indicating the greater vulnerability of traditional producers.

Both planned and autonomous adaptation produce an increase in demand reliability at the Irrigation Community level, especially in those that initially consume large amounts of water, such as the traditional Montijo IC (downstream) and the traditional Vegas Altas (upstream). In the first case, the different planned and autonomous adaptation scenarios show high risk reductions in terms of demand reliability, especially when irrigation modernisation is carried out (ECON scenario).

5. Discussion

The results of this research show that climate change may impact severely irrigation systems in the Middle Guadiana basin. It will reduce considerably the availability of water resources, will reduce crop yields and increase irrigation water requirements. These results support the need to design and facilitate adaptation processes in the basin taking into account the physical as well as the socio-economic characteristics of the region's irrigation agriculture.

The analysis of climate change impact on crops showed that irrigation water needs may increase significantly (around 20%) while impacts on crop yields will be moderate (less than 10%). Giannakopoulos et al. (2005) and Nelson et al. (2009), show similar results in their analyses of climate change impacts on crops in the Mediterranean region and at global level respectively, when the effect of CO_2 fertilisation is not considered. Carmona et al. (2013) analysed climate change impacts on crops for the Guadiana Basin and showed more positive results than those obtained in this research, with around 20% increase of cereal yield at the end of the century as a consequence of CO_2 fertilisation. However, Carmona et al. do not consider the constraints in water availability driven by climate change. Our model does not consider the effect of increased CO_2 concentrations, but it includes the spatialisation of cropping systems and reflects specific climatic, hydrological and farm management conditions for the area and type of farm where those crops are grown, which are not frequently considered in crop-model-based assessments. In this sense, this analysis is more accurate with respect to climatic, technical and water constraints, but could underestimate the positive impact of increased atmospheric CO2 concentrations on crop yields.

At farm level, the analysis provided by the economic model reflects how farmers respond to lower water availability, lower crop yields and higher irrigation water requirements. When farmers adapt to these new conditions, the new crop choices result in a lower water use (according to lower availability) and lower farm income than without climate change. However, this adaptation reduces the risk of crop failure due to water shortage in the farms, as lower water demands result in increased demand reliability.

The analysis of decisions taken at farm level is proven necessary, as crop model results do not capture the potential of farm level adaptation to mitigate the damaging effects of climate change. The analysis evidences that the characteristics of the farms and of the Irrigation Communities such as technology and water management, are relevant to climate change adaptation as highlighted by Reidsma et al. (2010). In baseline conditions, under climate change with autonomous adaptation (Baseline + AA), traditional farms in the Montijo IC face water consumption reductions of around 14% as income falls by 12%. However, in the same scenario, modern communities, like Tomas Directas and Zújar, are able to reduce water consumption more than two-fold while income will decrease, comparatively to Montijo, by a less than proportional amount. The study shows also that, traditional Irrigation Communities, can adopt relatively inexpensive adaptation strategies at the farm level, such as changing to more efficient irrigation technologies and expanding the area of high value crops. These plans will contribute to reduce water demand, improve reliability, and obtain higher income levels, as shown in other studies (Tanaka et al., 2006).

The analysis of planned adaptation shows that the two simulated scenarios involve significant reductions of water consumption (Table 4), lower unmet demands (Fig. 3) and greater demand reliability (Table 5). However, these strategies produce different impacts at farm level. In the absence of climate change the ECON strategy generates more negative impacts on income than the ENV strategy. Under climate change and autonomous adaptation both strategies produce similar impacts on farm income, but the ECON strategy reduces water consumption to a greater extent. This underlines the positive effects of policies such as water pricing in improving preparedness for climate change as suggested in other studies (Agrawala and Fankhauser, 2008; De Loë et al., 2001; Tanaka et al., 2006). This type of measure that frequently results in significant income losses is not as negative in a context of climate change when compared with other measures as illustrated by our results.

The case of traditional ICs, such as Montijo, is slightly different. In line with other authors (Berbel and Gómez-Limón, 2000; Berbel et al., 2007), results for this community show that the implementation of water pricing policies, that normally would have disastrous impacts in these types of Irrigation Communities, does not inflict large income losses when they are introduced with a modernisation plan. In fact, Kahil and Albiac (2012) consider irrigation modernisation to be a climate change adaptation measure that produces positive effects for farm income and social welfare. They also report how irrigation modernisation incentivises horticultural and permanent crops as these are highly profitable crops that can easily support the required investment costs. On the contrary, in modern communities that cannot improve further their irrigation technologies, the large economic impacts of water prices may hinder the implementation of such measures as for some types of farms income losses will be huge. Nonetheless, considering that cost recovery is a requirement of the WFD, it can be argued that this Directive is already promoting adaptation to climate change-driven water scarcity as discussed by Urwin and Jordan (2008).

Looking at demand reliability (Table 5), results showed that water distribution, location, supply preferences, water storage and demand priorities determine different impacts of climate change across irrigation communities. In the Middle Guadiana basin spatial location outweighs the technical characteristics and the farmers' decisions on water use in the different communities. The Irrigation Communities located upstream are more vulnerable than downstream communities as they face lower demand reliability. In particular, the modern Zújar IC located upstream, experiences a large reduction of water supply even if water storage capacity is greater in this area of the basin than downstream. This is a consequence of the high demand for water of the neighbouring rice growing districts. Thus, the lack of implementation of rules or control methods for limiting water uptake in those irrigation areas increases the exposure of the Zújar IC. This illustrates the dynamic and multi-level nature of vulnerability and adaptation (Westerhoff and Smit, 2008; Reidsma et al., 2010), showing how decisions taken in some communities (Vegas Altas) together with policy decisions on water management increase risk in other communities (Zújar IC) in spite of a greater water use efficiency and a lower water demand in the latter. These results, in line with those presented by Blanco-Gutiérrez et al. (2013), may be counter-intuitive as it is generally assumed that downstream water users are negatively affected by upstream activities. However, in this basin, the high level of fragmentation (river's natural flow highly modified due to water infrastructures and water withdrawals) make downstream users less dependent upon upstream activities.

These results evidence the multi-dimensional effects of climate change and adaptation and, despite limitations, demonstrate the large potential of integrated hydro-economic models for representing the multi-scale processes related to climate change and water management. Among the shortcomings of the methodology developed some of the most evident include the lack of consideration of some important features of climate change such as the effect of increased atmospheric CO2 concentrations or the changes in climate variability (e.g. changes in the frequency of extremes) that the simulated scenario does not account for. Although not including these elements may alter the magnitude of the impacts reflected by the models, they are still capable to reflect the multiple dimensions and the cross-scale effects inherent to climate change processes. In this sense, the modular approach followed in this research (two independent models externally linked through selected input and output variables) permitted to develop more complex and detailed economic and hydrologic modelling components than holistic models (Harou et al., 2009) where all components are integrated into a single model. Nonetheless, a more fluid link between components (as in holistic models) could have contributed to an easier representation of causal relationships and more direct scenario analyses (Harou et al., 2009) that would not require several model iterations.

6. Conclusions

This research has tried to contribute to the analysis of climate change impacts and adaptation by addressing the processes that occur at different scales including crop, farm, irrigation community, and basin levels. The integrated modelling approach that has been applied, which combines biophysical and socio-economic analysis, can support adaptation decision making. The hydro-economic framework developed made it possible to reflect upon the interconnectedness of water, agriculture and socio-economic processes. The economic model is crucial for understanding water demand and the behaviour of water users, and provides meaningful results for policy-making using economic indicators. The hydrology model WEAP provides a representation of the physical and spatial dimensions of water resources and climate, which is essential for the assessment of climate change and, specifically, for the representation of the supply side of water management. The agronomic module within WEAP allows for an evaluation of the effects that biophysical conditions and farm management can have upon cropping processes. In this way, this integrated platform is able to reflect all dimensions and scales.

The Guadiana Basin case study, an illustrative example of critical water and climate interactions, permitted to illustrate this multi-scale and interrelated nature of climate change vulnerability and adaptation. The risk posed by climate change and adaptation in one irrigation community depends on farm cropping and technical characteristics, water management within the community, decisions made in neighbouring irrigation areas, and spatial location in the basin.

The different planned adaptation measures analysed proved to be effective in reducing the risk of irrigators and facilitating adaptation. Both the ENV strategy (based in preserving environmental flows) and the ECON strategy (based on water pricing) can importantly reduce water demand, although the economic impact for farmers may be high. On the other hand, preserving environmental flows and cost recovery are measures considered by the WFD. Therefore, this research demonstrates that the implementation of such policy, compulsory for all the EU member states, can support adaptation and reduce the risk faced by farmers in light of climate change.

In summary, this research has contributed to supporting water management and adaptation policy-making, reflecting relevant aspects that shape the risk posed by climate change at various spatial and decision-making levels and highlighting relevant technical and socio-institutional aspects that adaptation policy must address.

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