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Economic-hydrologic analysis of water management strategies for balancing water for nature and water for food

Implications for the Guadiana River Basin, in Spain

Tesis Doctoral

Irene Blanco Gutiérrez - Ingeniero Agrónomo

Directores

Consuelo Varela Ortega – Dra. Ingeniero Agrónomo (U. Politécnica de Madrid)

David R. Purkey – Dr. Hidrología (U. California Davis)

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A mi familia

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Abstract

Water scarcity is becoming a major problem in many parts of the world, especially in arid and semi-arid areas, characterized by recurrent droughts and broad climate variability. Severe water stress situations are provoking a mounting competition for water resources across sectors (especially from agriculture), for geographic locations, and among social groups. Alongside this, water resource depletion occurs together with water quality deterioration due to pollution and environmental degradation. Balancing the trade-offs among the different uses and users of water requires an inter-sectoral and multi-disciplinary approach to water resource management. Traditionally, government policies have been concerned with increasing supply. However, in recent years, increased focus has been placed on broader integrated water resources management strategies, policies, and tools. In particular, hydro-economic models constitute useful methods for conducting Integrated Water Resources Management (IWRM). They permit the representation of the complexity of water resource systems within a coherent framework, and offer relevant insights in terms of water planning, institutional and financial design, water allocation, policy development, and implementation.

The scope of this research was to develop an integrated economic-hydrologic modeling framework capable of capturing the multifaceted interaction between socio-economic and environmental processes to guide and support IWRM strategies under risk and uncertain situations. This framework was applied to the Guadiana River Basin, a large-scale intensely-irrigated drought-prone region located on the southwestern plateau of the Iberian Peninsula in Spain, to help policy-makers identify sustainable and cost-effectiveness water management strategies addressed to balance the trade-off between water for food production and water for nature conservation. The modeling framework follows a sequential pattern that gradually integrates the socio-economic and hydrology components. It starts with a multi-scale economic optimization model of farm-decision-making developed using the General Algebraic Modeling System (GAMS), and follows by integrating the economic model with a GIS-based hydrology water management simulation model built using the Water Evaluation And Planning system (WEAP). 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 developed using Visual Basic for Applications (VBA) to facilitate data-exchange and data-interoperability.

The findings obtained indicate from a methodological perspective that the accuracy of the models in predicting farmers’ behavior and hydrological processes improves when the economic and hydrology models are dynamically coupled together, exchanging data on optimal crop combinations, water availability, irrigation water use, and crop water requirements. The results also reveal important disparities across irrigation systems and regions within the Guadiana basin, and stress the convenience of designing site-specific water management strategies adapted to the agro-climatic, structural, and institutional characteristics of the affected territories. This constitutes a challenge for developing the Guadiana River Basin Management Plan under the current EU water policy mandate.

In the Upper Guadiana Basin, overcoming groundwater overdrafting would require an effective combination of regulatory and market measures addressed to reducing excessive groundwater use for irrigation and controlling illegal drilling. In the Middle Guadiana Basin, additional efforts should be made for improving agricultural water use efficiency to maintain the basic ecological functioning of some river reaches and satisfy consumptive water uses. The implementation of the EU Water Framework Directive, clearly geared by the concept of ecological sustainability, will not encourage agricultural water conservation and will be insufficient on its own in reaching a socially-accepted balance for securing water for nature protection and water for maintaining rural livelihoods in the area. In periods of prolonged droughts, the reduction of water availability and an increase in irrigation water demand will certainly exacerbate stresses on agriculture, land resources, and water resources.

The transferable methodological and empirical experiences presented in this Thesis intend to bridge the gap between IWRM theory and practice.

Key words: groundwater, surface water, irrigation, economic model, hydrology model, integrated modeling, water management and policy, drought.

Resumen

La creciente escasez de recursos hídricos está llegando a ser un grave problema en muchas partes del mundo, especialmente en regiones áridas y semi-áridas caracterizadas por sequías recurrentes y una amplia variabilidad climática. Situaciones de estrés hídrico están provocando una gran competencia por el uso del agua entre los distintos sectores de usuarios (fundamentalmente, la agricultura), regiones geográficas y grupos sociales. En muchos casos, la disminución de los recursos hídricos disponibles viene acompañada de un deterioro de la calidad del agua debido a la contaminación y la degradación del medio ambiente.

Intentar equilibrar la creciente competencia entre los diferentes usos y usuarios del agua requiere adoptar un enfoque de gestión multidisciplinario e intersectorial. Tradicionalmente, los esfuerzos han estado dirigidos a aumentar la oferta de agua mediante embalses y pantanos. Sin embargo, en los últimos años, los gobiernos vienen prestando especial atención al fomento de estrategias, políticas y herramientas basadas en la Gestión Integrada de los Recursos Hídricos (GIRH). En particular, los modelos hidro-económicos constituyen herramientas muy útiles para llevar a cabo la GIRH. Estos instrumentos permiten representar la complejidad de los sistemas hídricos dentro de un marco único y coherente, así como obtener estimaciones relevantes sobre la planificación y asignación de recursos hídricos, aspectos financieros e instituciones, el desarrollo y la implementación de políticas.

El objetivo de esta investigación es desarrollar un marco de modelización económico-hidrológico integrado, capaz de capturar las múltiples interacciones que ocurren entre los procesos socio-económicos y medioambientales, para apoyar la toma de decisiones y la aplicación de estrategias GIRH en situaciones de riesgo e incertidumbre. Este marco metodológico ha sido aplicado a la cuenca hidrográfica del Guadiana (una extensa región propensa a sequías y con importantes zonas regadas, situada en el suroeste de la Península Ibérica) con la finalidad de ayudar a los políticos a identificar estrategias y planes de gestión de agua costo-efectivos y sostenibles que permitan equilibrar el agua destinada a producción de alimentos y el agua necesaria para proteger la naturaleza. El marco metodológico desarrollado en esta investigación sigue una pauta secuencial que integra gradualmente los aspectos socio-económicos e hidrológicos. El marco metodológico empieza por un modelo de optimización económica multi-escalar, basado en explotaciones agrarias representativas y diseñado en el lenguaje de programación ‘General Algebraic Modeling System’ (GAMS), y continúa con la

integración del modelo económico con un modelo de simulación hidrológica, basado en SIG y desarrollado mediante el programa Water 'Evaluation And Planning System' (WEAP). La integración del modelo económico y del modelo hidrológico se ha realizado empíricamente, reproduciendo las diferentes demandas de riego y simulando los mismos escenarios en ambos modelos, y técnicamente, mediante una interfaz automatizada desarrollada en Visual Basic para Aplicaciones (VBA) para facilitar el intercambio y la interoperabilidad de datos.

Los hallazgos obtenidos en la presente investigación indican, desde el punto de vista metodológico, que la precisión de los modelos para predecir el comportamiento de los agricultores y los procesos hidrológicos mejora cuando los modelos económicos e hidrológicos están dinámicamente conectados y se produce un intercambio de datos sobre combinaciones óptimas de los cultivos, disponibilidad de agua, uso del agua de riego y requerimientos de agua de los cultivos. Los resultados extraídos también revelan importantes disparidades entre sistemas agrícolas y regiones dentro de la cuenca del Guadiana y subrayan la conveniencia de diseñar estrategias de gestión de agua adaptadas a las características agro-climáticas, estructurales e institucionales de los territorios afectados. Teniendo en cuenta las actuales políticas de agua europeas, esto supone un reto importante para el desarrollo del nuevo Plan Hidrológico de la cuenca del Guadiana.

Resolver el problema de la sobrexplotación del agua subterránea en la cuenca del alto Guadiana requeriría combinar medidas efectivas, económicas y de regulación, dirigidas a reducir el uso excesivo del agua subterránea para riego y controlar las extracciones ilegales. En la cuenca del Guadiana medio, los esfuerzos deberían centrarse en mejorar la eficiencia del uso de riego para mantener el funcionamiento ecológico básico de algunos ríos y satisfacer los usos consuntivos del agua. La implementación de la Directiva Marco del Agua de la Unión Europea, basada en un concepto de sostenibilidad fundamentalmente ecológico, no fomentaría el ahorro del agua para riego y sería insuficiente para promover por sí misma situaciones socialmente aceptables que permitan asegurar el agua para conservación de la naturaleza y el agua para el mantenimiento del desarrollo socio-económico en las zonas rurales de la cuenca del Guadiana. En periodos prolongados de sequía, la reducción del agua disponible y el aumento de los requerimientos hídricos de los cultivos agravarían la presión sobre el sector agrícola, el uso de la tierra y los recursos hídricos.

El desarrollo de metodologías y experiencias empíricas transferibles, como las presentadas en esta tesis doctoral, pueden ayudar a acortar la distancia entre la teoría y la práctica de la GIRH.

Palabras clave: agua subterránea, agua superficial, riego, modelo económico, modelo hidrológico, modelización integrada, política y gestión del agua, sequía.

Résumé

La pénurie croissante des ressources en eau est en train de devenir un problème grave dans de nombreuses régions du monde, en particulier dans les zones arides et semi-arides caractérisées par des sécheresses récurrentes et une grande variabilité climatique. Des situations de stress hydrique causant une vive concurrence pour l'eau entre les différents secteurs utilisateurs (principalement l'agriculture), les régions géographiques et les groupes sociaux. Dans de nombreux cas, la diminution des ressources en eau disponibles est accompagnée d'une détérioration de la qualité de l'eau due à la pollution et à la dégradation de l'environnement.

Essayer d'équilibrer la concurrence croissante entre les différents usages et usagers de l'eau, exige l'adoption d'une approche de gestion multidisciplinaire et intersectorielle. Traditionnellement, les efforts ont été dirigés à augmenter l'approvisionnement en eau par des barrages et des réservoirs. Toutefois, ces dernières années, les gouvernements ont accordé une attention particulière à l'élaboration de stratégies, politiques et outils fondés sur la Gestion Intégrée des Ressources en Eau (GIRE). En particulier, les modèles hydro-économiques sont des outils utiles pour mettre en œuvre la GIRE. Ces outils permettent de représenter la complexité des systèmes hydriques dans un cadre unique et cohérent, et d'obtenir des estimations pertinentes sur la planification et l'allocation des ressources en eau, la conception institutionnelle et financière, le développement et la mise en œuvre de politiques.

L'objectif de cette recherche est de développer un cadre de modélisation hydro-économique intégré, capable de saisir les nombreuses interactions qui surviennent entre les processus socio-économiques et environnementaux, afin de soutenir la prise de décision et l'application des stratégies de la GIRE dans des situations de risque et d'incertitude. Ce cadre méthodologique a été appliqué au bassin hydrographique du Guadiana (une vaste région sujette à des sécheresses et des grands périmètres irrigués, situé dans le sud-ouest de la péninsule ibérique) afin d'aider les décideurs à identifier des stratégies et des plans de gestion durable et coût-efficace, adressée à équilibrer le compromis entre l'eau pour l'alimentation et celle nécessaire pour préserver la nature. Le cadre méthodologique développé dans cette étude poursuit une suite séquentielle qui intègre graduellement des éléments socio-économiques et hydrologiques. D'abord, le cadre méthodologique est composé d'un modèle

d'optimisation économique multi-échelle, basé sur des exploitations agricoles représentatives et conçu avec le langage de programmation "General Algebraic Modeling System" (GAMS). Ensuite, le modèle économique est integrè avec un modèle de simulation hydrologique basé sur un Système d'Information Géographique (SIG) et élaboré selon le programme "Water Evaluation And Planning System" (WEAP). L'intégration du modèle économique et du modèle hydrologique a été réalisée de façon empirique, repreduisant les différentes demandes en irrigation et simulant les mêmes scénarios dans les deux modèles, et techniquement, à travers une interface automatisée développé en Visual Basic pour Applications (VBA) afin de faciliter l'échange et l'interopérabilité des données.

Les résultats de cette recherche indiquent, du point de vue méthodologique, que la précision des modèles pour prédire le comportement des agriculteurs et des processus hydrologiques s'améliore lorsque les modèles économiques et hydrologiques sont connectés dynamiquement et un échange de données se produit sur les meilleures combinaisons de cultures, la disponibilité l'eau, utilisation de l'eau d'irrigation et les besoins en eau des cultures. Les résultats extraits révèlent aussi des différences importantes entre les systèmes et les régions agricoles dans le bassin du Guadiana et indiquent l'opportunité de concevoir des stratégies de gestion de l'eau adaptées aux caractéristiques agro-climatiques, structurelles et institutionnelles des territoires touchés. Tout cela représente un défi important pour le développment du nouveau plan de gestion du bassin versant du Guadiana en tenant compte des politiques actuelles de gestion de l'eau en Europe.

Résoudre le problème de la surexploitation des eaux souterraines dans le bassin supérieur du Guadiana requiert une combinaison efficace de mesures, économiques et de réglementation, visant à réduire l'utilisation excessive des eaux souterraines pour l'irrigation et à contrôler le pompage illégale d’eau des forages. Dans le bassin moyen du Guadiana, les efforts devraient se concentrer sur l'amélioration de l'efficacité de l’utilisation de l’eau emploée pour l'irrigation pour maintenir le fonctionnement écologique de certains cours d'eau et satisfaire toutes les utilisations consommatrices d'eau. La mise en œuvre de la Directive Cadre sur l'Eau de l'Union Européenne, basé sur un concept de durabilité fondamentalement écologique, ne promouvra pas la conservation de l'eau d'irrigation et serait insuffisante pour assurer l’équilibre, socialement accepté, entre l'eau disponible pour assurer la protection de la nature et le développment socio-économiques des zones rurales. En période de sécheresse prolongée, la réduction de la disponibilité en eau et l'augmentation des besoins en eau des cultures

aggraveraient la pression sur le secteur agricole, l'utilisation des terres agricoles et des resources en eau.

Le développement de méthods et d'expériences empiriques transférables, telles que celles présentées dans cette thèse, contribuera à combler le fossé entre le discurs théorie et l’action pratique de la GIRE.

Mots-clés: eau souterraine, eau de surface, irrigation, modèle économique, modèle hydrologique, modélisation intégrée, politique et gestion de l'eau, sécheresse.

Table of contents

List of Tables

List of Figures

List of Abbreviations

CAP: Common Agricultural Policy

CEA: Cost-Effectiveness Analysis

DEM: Digital Elevation Model

DSS: Decision Support System

EFR: Environmental Flow Requirements

ET: Evapotranspiration

GAMS: General Algebraic Modelling System

GES: Good Ecological Status

GIS: Geographic Information System

IC: Irrigation Community

IWRM: Intergrated Water Resources Management

Kc: Crop Coefficient

MPM: Mathematical Programming Model

NHP : National Hydrological Plan

NRR: Natural Recharge Rate

PAD: Percentage Absolute Deviation

RBA: River Basin Authority

RBMP: River Basin Management Plans

SFP: Single Farm Payment

SPUG: Special Plan for the Upper Guadiana Basin

VBA: Visual Basic for Applications

WAP: Water Abstraction Plan

WEAP: Water Evaluation and Planing system

WEI: Water Exploitation Index

WFD: Water Framework Directive

Mm^3=Hm^3: Million Cubic Meters=Cubic Hectometers

1. General Introduction

1.1. Research's framework

This PhD Thesis is based upon studies conducted from 2007 to 2010 at the Department of Agricultural Economics and Social Sciences, Escuela Técnica Superior de Ingenieros Agrónomos, Universidad Politécnica de Madrid (UPM), within the framework of several European research projects.

During that period, two research stays abroad were carried out at different international universities and research institutions, which contributed to the completion of the research work developed at the Universidad Politécnica de Madrid. Firstly, a three-month research stay (sponsored by the Scenes project from October 2007 to February 2008) was conducted during the first stage of the Thesis development at the Mediterranean Agronomic Institute of Montpellier (IAMM) - International Center for Advanced Mediterranean Agronomic Studies (CIHEAM) in Montpellier, France. This stay followed a precedent longer stay at the IAMM and the School of Economics at the University of Montpellier I for the obtention of the MSc and the DEA (Diplôme d'Études Approfondies) degrees. The main findings obtained during the stay in France are included in chapter 2 of the present document, devoted to the assessment of alternative groundwater management strategies. From February to December 2009, another research stay of eleven months (funded by the Social Board of the UPM) was undertaken at the Stockholm Environment Institute (SEI) and the University of California Davis (UCD) in Davis, California, USA, in order to enlarge and enhance the methods and tools used in the analysis of water resources management and planning. The methodology and main results obtained during the research stay in the US are illustrated in chapters 3 and 4.

Throughout the development of the PhD Thesis, different Spanish and EU research projects (and a Spanish complementary fund) related to water management, agriculture and climate change contributed to frame the problem, develop new methods for research and analysis, and disseminate the thesis results inside and outside the academic arena:

- **Cross compliance** (Facilitating the CAP reform: compliance and competitiveness of European Agriculture). STREP (Special Targeted Research Plan) project. European Commission, DG Research. Project nº: FP6-2003- SSP-3-Area 8.1.B.1.1. nº 502152. (2005-2008).

- **NeWater** (New Approaches to Adaptive Water Management under Uncertainty). Integrated Project. European Commission, DG Research. Project nº: FP6-2003-GLOBAL-2-SUSTDEV-6.3.2 – 511179-2. (2005-2009).

- **Análisis de la gestión integrada del agua en la agricultura: efectos socio-económicos, ambientales e institucionales** (I&II). Complementary Action. Spanish Ministry of Science and Innovation. Project nº: SEJ 2005-25755-E/ECON (I) and SEJ 2007-30261-E/ECON (II). 2006-2007 (I) and 2008-2009 (II).

- **Scenes** (Water Scenarios for Europe and for Neighbouring States). Integrated Project. European Commission, DG Research. Project nº FP6-2005-GLOBAL-4 (OJ 2005 C 177/15). (2007-2010).

- **Meditation** (Methodology for Effective Decision-making on Impacts and AdaptaTION to Climate Change). Collaborative project (small). European Commission, DG Research. Project nº: 244012. (2010-2013).

Among these, the EU projects of NeWater and Scenes played a central role in the development of the present Thesis. The already finished EU project **NeWater** (www.newater.info) aimed at developing new methods and tools to help achieve a transition towards adaptive water management in several river basins of Europe (Guadiana, Rhine, Elbe and Tisza), Asia (Amudarya) and Africa (Nile and Orange). On the other hand, the on-going EU project **Scenes** (www.environment.fi/syke/scenes) seeks to develop a set of comprehensive freshwater scenarios to study the future of Europe's waters in the Danube, Baltic, Black Sea and Mediterranean regions until 2025 and 2050, and to alert policy makers and stakeholders about the emerging problems and potential solutions related to water use.

The NeWater project and the Scenes project share an integrated approach for water resources management and consider that active stakeholder involvement in watershed issues is a key element in achieving sustainable and adaptive water management regimes. Stakeholder engagement and involvement were carried out via a series of stakeholder meetings held in specific case studies. In Spain, the Guadiana River Basin was selected as case study in both the NeWater and the Scenes projects due to the significant implications for water management and the conservation of valuable ecological ecosystems of intensive agricultural water use. Research activities in the Guadiana Basin were coordinated by the UPM team led by Professor Consuelo Varela-Ortega, who was in charge of developing an integrated methodology to analyze present and future policy-driven and stakeholder-driven water scenarios, among other tasks. Whereas in the NeWater project, this analysis was restricted to the Upper part of the Guadiana Basin, the whole river basin is currently being studied in the Scenes project and further in the recently launched Mediation project which gives an innovative approach to climate change adaptation issues.

1.2. The context

1.2.1. Water resources and irrigation development in Spain

Water scarcity is becoming a major problem in many parts of the world. The increasing physical and economic water scarcity is provoking a mounting competition for water resources among sectors and social groups (Comprehensive Assessment of Water Management in Agriculture, 2007). Alongside this, environmental degradation of valuable aquatic ecosystems is occurring together with escalating social and human conflicts and increased constraints for attaining economic development and poverty alleviation (Gleick 2009; UNDP, 2006). Additional uncertainty factors, such as climate change and the expansion of biofuels, contribute to the complexity of water resources planning and management problems (Delucchi, 2010; Falkenmark et al., 2009; Fraiture et al., 2008; Iglesias et al., 2009).

In some areas in Europe, the balance between water supply and demand is reaching a critical level, especially in the semi-arid Mediterranean regions of southern Europe (Sagardoy and Varela-Ortega, 2010). In Spain, water is relatively abundant. It presents a renewable water resource rate of about 2413 m^3/capita/year (111000 Mm^3/year), which is higher than the threshold level of 1000 m^3/capita/year commonly used as one of the benchmarks to define water scarcity (Falkenmark et al., 1989). However, Spain is the most arid country in Europe and the third most water-stressed after Cyprus and Bulgaria in terms of water exploitation (EEA, 2009). Spain's national Water Exploitation Index[1] (WEI) is approximately 34 % and can reach 164% and 127% in some areas of the southern river basins of Andalucía and Segura, respectively (EEA, 2009).

Most of the Spanish territory is considered arid or semi-arid with an index of humidity between 0.04 and 0.5 (MMA, 2000). Spain, as with the rest of the Mediterranean countries, is characterized by a heterogeneous distribution of water resources and wide spatial and temporal rainfall variability (Margat 2004; Margat 2008; Varela-Ortega et al. 2002). Annual precipitation is about 684 mm (20% below the European average) and annual evapotranspiration is 862 mm (more than 34% of the European average) (MMA, 2000). The climate varies across the Spanish territory, but, in general it is characterized by recurrent drought spells and normal years with hot, dry summers and warm, wet winters. High temperatures and scarce rainfall during the summer usually lead to acute water deficits, which makes the use of additional water for irrigation necessary to fulfill the need for crop water during that season.

In Spain, most of the water resources are used for irrigation. Total water abstractions are close to 38000 Mm^3, of which 22500 Mm^3 are distributed among the agricultural, the domestic and the industrial sectors. The agricultural sector uses around 18500 Mm^3 (82% of all water use) and is followed by domestic and industrial use, which account for 2600 Mm^3 and 1191 Mm^3 and represent about 12% and 5% of all water use , respectively (MMA, 2000).

Irrigation has been a key trigger for the socio-economic development of many regions in Spain during the last 50 years. The development of irrigation has increased agricultural production and crop diversification, enhancing income generation, favoring labor creation, and promoting settlement of the rural population. Presently, irrigated lands cover only 3.7 million ha (15% of all farming land) (MARM, 2009a). However, they are responsible for 60% of the nation's total agricultural production value and 80% of all farm exports (MARM, 2008). The economic productivity (€/ha) in irrigated agriculture in Spain is about five times higher than that of rain-fed agriculture (Real Decreto 329/2002; MMA, 2007a).

[1] The Water Exploitation Index (WEI) is calculated as the ratio of total freshwater abstraction to the total renewable resource. A WEI above 20 % implies that a water resource is under stress, and values above 40 % indicate severe water stress and a clearly unsustainable use of the water resource (Raskin et al., 1997).

In Spain, water supply has been ensured using a combination of reservoirs, several intra and inter basin transfers, and a set of desalination technologies. Spain is one of the only three European (EU) countries (together with Romania and Turkey) that are able to store more than 40% of their renewable resources (EEA, 2009). At present, about 1174 dams and reservoirs are spread throughout the country's territory storing 56000 Mm^3, which is about 47% of the annual renewable freshwater resources. Special attention should be paid to the modernization of water infrastructures: 100 of the dams existed in 1915 and 450 are from before 1960 (MMA, 2000).

Financing for major infrastructural investments in irrigation has historically come from the Spanish government, resulting in high public costs, subsidized water deliveries and water management inefficiencies (Sumpsi et al., 1998). Whereas the average cost of water services in Spain is estimated to be around 0.11 €/m^3, water is paid for with 0.04 €/m^3 (MMA, 2007b). Large water infrastructures have been beneficial for securing supply during recurrent drought spells and increasing the buffering capacity of many regions. Nevertheless, the development of massive water infrastructures has changed regional water cycles, affected the transport of sediments, and altered the habitat of migrating aquatic species (e.g., salmon), increasing environmental damage (Baldock, 2000; Varela-Ortega, 2007).

Similarly, the investment in technology for applying water in the field has usually been carried out by public agencies. However, as pressure to conserve water resources has increased, the adoption of water-saving technologies has been strongly encouraged by other agencies (such as, research groups, environmental conservation groups, and private firms), which have bolstered the rapid implementation of modern irrigation technologies in recent years (Osann et al., in press). The change in irrigation technology has been noticeable in the south of Spain (Andalucía and La Mancha regions), where olives trees and vineyards are predominantly irrigated by drip irrigation. Currently, pressurized irrigation systems span 65% of the total irrigated surface, whereas the remaining 35% is irrigated by gravity (Garrido and Llamas, 2009; Varela-Ortega, 2010).

In parallel, groundwater irrigation has been expanding progressively. Annual aquifer recharge in Spain has been estimated to be about 30000 Mm^3 which accounts for 30% of the total water resources available in the country (MMA, 2000). At present, groundwater irrigates around 1 million ha, which is about 30% of the total irrigated area, mainly in the Spanish Mediterranean littoral (Jucar and Segura Basins) and some inner continental areas, such as La Mancha in the Guadiana Basin (Llamas and Custodio, 2003).

Groundwater in Spain, as in other arid or semi-arid countries worldwide, has been intensely used to irrigate farmland due to its easy access, government subsidies for power and pump installations, low extraction costs, high farming profitability, low vulnerability towards climate variations, and high resilience to drought (Giordano and Villholth, 2007; López-Gunn and Llamas, 2008; Martínez-Santos and Martínez-Alfaro, in press; Shah et al. 2001; Shah et al., 2007). Additional factors, such as the advancement of hydro-geological science and the development of new well-drilling techniques during the 1960s and 1970s, have also contributed to the development of groundwater use through the initiative of a large number of water users with little public support in the so-called 'silent revolution' (Llamas and Martinez-Santos, 2005). Groundwater irrigation is significantly more efficient and profitable than surface water irrigation in Spain, and its expansion has also contributed to an increase in agricultural production and an improvement in rural livelihoods (Hernández-Mora and Llamas, 2001; Hernández-Mora et al., 2007; Llamas and Garrido, 2007). However, the intensive use of groundwater for irrigation has, in some regions, caused the over-exploitation of important aquifers, groundwater contamination, land subsidence, and the degradation of associated aquatic ecosystems and wetlands (Garrido et al., 2006; Llamas, 2003; Mukherji, 2006).

From the mid 1950s to the 1990s, cropping intensity has risen noticeably in Spain and many basins have become over-allocated to support agricultural water use. In semi-arid countries, as economies continue to develop, there is a rising pressure to better allocate water resources, even reallocate water away from agriculture and towards other uses, such as domestic water supply and sanitation, industry, hydropower and the environment (Molle and Berkoff, 2006; Turral et al., 2010). However, in a great number of rural zones in Spain, irrigation is still the only drive for development. The disappearance of irrigated agriculture in these rural zones will imply depopulation and land abandonment with negative environmental impacts and a notorious imbalance in the territorial population distribution (Barbero, 2005).

Global warming will certainly exacerbate stresses on water supplies, water quality, and land use. Climate change projections for Spain forecast an increase in the intensity and frequency of droughts, a temperature rise of 1.5°C-3.6°C, and about a 10-20% decrease in precipitation by 2050 (Abanades et al., 2007). Iglesias et al. (2009) indicates that in all climate change scenarios, water supplies will decrease and irrigation water demand will increase in most of the Spanish territory. According to recent Blue Plan projections, Spain is expected to grow in its total water demand at about 0.3% annually from 2000 onwards, surpassing the benchmark of 40% WEI by 2030, and almost equaling the situation of 'unsustainable water production' of countries such as Egypt, Israel, Libya and the Palestinian territories (Benoit and Cameau, 2005). Therefore, there are important challenges that still need to be faced in order to achieve efficient and sustainable water resources management in Spain.

1.2.2. The policy context

In Spain, as in other southern EU member states, agricultural policies and water policies have played an important role both in surface and groundwater irrigated agricultural systems, and conditioned the use of land and water resources.

Agricultural policies

The EU Common Agricultural Policy (CAP) has been a fundamental driver of farmers' decisions in Spain since 1986. The CAP was initially created to ensure food security and secure a fair standard of living for the EU agricultural community. During the 1980s and the 1990s, the CAP offered aid payments and guaranteed minimum prices to farmers, providing incentives for them to produce. These programs secured a stable income for farmers, enhanced agricultural production, and encouraged the expansion of irrigation as higher yield-coupled subsidies were assigned to irrigated crops. However, they resulted in almost permanent food surpluses, world market distortions, environmental damages, and high public costs (Varela-Ortega, 1998).

In view of the increasing financial burden on the EU budget, the growing concern with environmental quality and natural resource use, and progressive international trade liberalization, the CAP has changed markedly during the last few decades to support more market-oriented and environmentally friendly agricultural production (Petit, 2003; Varela-Ortega et al., 2006b). In 1992, the MacSharry reform introduced substantial support price reductions, direct payments to compensate farmers for their income loss, control production mechanisms (e.g., set-aside requirements), and several accompanying measures to protect the environment. The Agenda 2000 program continued with the MacSharry reform by replacing price support measures with direct aid payments and reinforced these changes with a consistent integrated rural policy (second pillar of the CAP) to promote the multi-functional character of agriculture (EC, 1999). Furthermore, the Agenda 2000 opened the possibility to member states of implementing a modulation of the compensatory payments and establishing 'cross-compliance' schemes. Shortly afterwards, in 2003, the mid-term Luxembourg reform (EC, 2003) decoupled direct payments from production and substituted them with the Single Farm Payment (SFP). Additionally, the implementation of the modulation and cross-compliance measures became compulsory (EC, 2004). Thus, in order to get direct payments, farmers had to comply with specific environmental and safety regulations (Statutory Management Requirements, SMRs) and to maintain land in Good Agricultural and Environmental Conditions (GAECs). The last CAP reform, the 'Health Check' in 2010 (EC, 2009a; EC, 2009b; EC, 2010), seeks to increase the competitiveness and sustainability of EU agriculture and aims to prepare it for facing new challenges such as climate change, water management and bio-energy. It reinforces the figure of the SFP and the decoupling of payments from production, as well as incorporating specific water requirements that promote the integration of sectoral and regional policies (Osann et al., in press).

In Spain, the evolution from strong price support mechanisms to almost fully decoupled direct payments has reduced the surface dedicated to the cultivation of high water-consuming crops (such as maize), increased the acreage of low-water-intensive winter cereals, and indirectly, has encouraged the cultivation of well adapted crops (such as olive trees and vineyards) (Varela-Ortega, 2010). However, the impacts of the new CAP on water consumption and water savings have not yet been clearly traced.

In recent years, the Spanish administration has tried to adapt to the new EU system of agricultural support and integrate environmental, economic and social objectives to promote the sustainable development of many rural zones in Spain. The completion of the Spanish National Irrigation Plan (2002-2008) has been a high priority for national agricultural policy due to the importance of irrigation in Spain (Real Decreto 329/2002). Yet, it has been oriented, not to increase the area of irrigated land, but rather to accelerate the process of modernization linked to water efficiency savings, cost reductions and reduced environmental impacts. In 2006, under several drought conditions, a special urgent action plan for irrigation modernization (2006-2008) was enacted by the Spanish government to strengthen the modernization of traditional irrigation systems (Real Decreto 287/2006). These irrigation modernization plans have invested a total of 7400 million € during this decade to improve the irrigation structures of nearly 2 million ha (about 55% of all the nation's irrigated lands) and save 3000 Mm^3/year (15 % of the yearly average national agricultural water use) (MMA, 2007b). Recently, in 2009, the EU priorities indicated in the CAP Health Check (climate change, water management, renewable energies, and biodiversity) have been translated into the Spanish context through the National Strategy Plan for Rural Development (2007-2013), under which different Rural Development Programs have to be established at a regional level by Spain's Autonomous Communities (MARM, 2009b).

Water policies

The gradual change in agricultural policies has been interacting with other EU and national water policies. The Water Framework Directive (WFD) (EC, 2000) constitutes the common European policy framework in irrigation water management. The WFD aims to achieve the 'good ecological status' (GES) of all water bodies across European river basins by 2015 (2027 at the latest), and encourages the active participation of all interested parties (stakeholders) in its implementation. Among other requirements, member States must develop River Basin Management Plans (RBMP) and specify an integrated program of measures to achieve the Directive's environmental objectives, although these objectives may be derogated or postponed if disproportionate costs are identified (Art. 4). The WFD establishes River Basins as the basic unit for all water planning and management actions, and adopts an innovative integrated approach by taking into consideration economic principles, concepts, and instruments for water management (Heinz, 2007; WATECO, 2002). In accordance with cost recovery and the polluter-pays principle, the Directive urges the use of economic instruments (e.g. water pricing policies) as part of these programs of measures (Art. 9). For that purpose, an economic analysis of water use must be carefully developed for each river basin district (Art. 5 and Annex III). In addition, according to the Article 11 of the Directive, a cost-effective analysis should be performed to identify the set of measures that would fulfill the WFD's objectives at minimum costs. It is accepted that the ecological status of a water body is intimately related to specific bio-geophysical conditions and socio-institutional factors (Acreman and Ferguson, 2010). Therefore, the definition of the environmental standards for GES of water resources (minimum environmental flows or other), as well as the specification of the measures needed to restore and maintain the GES, are left to individual states, or more specifically, river basin districts.

The WFD has a strong focus on water quality and ecology, although in the case of groundwater, ‘good quantitative status’ is explicitly included in the definition of GES in Art. 2, Annex V (Mostert, 2003). All in all, the WFD is clearly geared by the concept of ecological sustainability, whereas other dimensions (social, economic, institutional, and political) are poorly developed and only normatively defined (Steyaert and Ollivier, 2007). This may prove to be a major challenge in semi-arid southern Mediterranean countries, where water quality problems are closely linked to the excessive use of water for irrigation. In these regions, the application of the WFD might dramatically reduce irrigation water consumption, leading to land abandonment and severe economic hardship in fragile rural areas (Mejías et al., 2004; Varela-Ortega et al., 2006b). Furthermore, the restoration of contaminated aquifers by agricultural nonpoint source pollution can be an extremely costly and technically difficult task in practice (Llamas and Garrido, 2007). Undoubtedly, the implementation of the WFD should consider specific bio-geophysical conditions and socio-institutional factors within Member States and River Basins.

The Spanish administration faces the difficulty of meeting society’s needs for water, as established by the Spanish Water Law (Real Decreto Legislativo 1/2001), while at the same time conserving and protecting the environment to comply with the WFD requirements of GES.

As seen in the previous section, water management in Spain has been strongly based on the increase of water supply through the development of large scale hydraulic projects during the last century. Still, the National Hydrological Plan (NHP) of 2001 approved the construction of about 100 new dams and the development of important inter-basin water transfer projects (Ley 10/2001). At present, national water policies are incorporating novel legal provisions to introduce alternative strategies to solve water problems and facilitate the implementation of the WFD. Thus, in 2004, the new NHP (Real Decreto Ley 2/2004) repealed a major inter-basin water transfer project, the so-called Ebro water transfer, and launched a set of desalination projects as a sustainable alternative to inter-basin water transfers. Alongside this, the successive reforms of the Spanish Water Law facilitated the implementation of solid demand-oriented management schemes (Garrido and Llamas, 2010). Particularly, in 1999, a Spanish water law reform permitted water right holders to engage in voluntary water trade arrangements and River Basins to establish Water Rights Exchange Centers, or water banks, in cases of prolonged drought (Ley 46/1999).

On the one hand, future trends in water policies, and agricultural policies on the other, will heavily affect European irrigated systems in general, and particularly Spanish farmers (Mejías et al., 2004; Riesgo and Gómez-Limón, 2006; Gómez-Limón et al., 2009). This complex policy context implies the need for achieving a well-balanced and sustainable integration of the agricultural, environmental and water sectors.

1.2.3. Future directions in water management

The evolution of irrigation agriculture has relied to a great extent on technical solutions for water supply enhancement. For decades, water has been considered an unlimited resource whose availability could be boundlessly increased by the construction of massive hydraulic engineering projects (reservoirs, dams, etc.). Nowadays, there is ample consensus that water is an integral part of the ecosystem, a scarce natural resource, and therefore, an asset with social, environmental and economic values (Agudelo 2001; Saleth and Dinar, 2004; Turner et al., 2004). This fundamental concept has fuelled a dramatic shift in water management in many parts of the world. Over the past few years, technicist approaches are giving way demand-oriented water management strategies. As new water sources have become increasingly inaccessible and the cost of projects to augment water supply has become very high, the emphasis has been shifted to other alternatives of efficient water use, such as the modernization of irrigation and the implementation of demand management instruments (water pricing, water quotas, water banks, and water markets) (Sumpsi et al., 1998; De Fraiture, 2007; Rosegrant et al., 2002). Such demand-side approaches aim at minimizing the need for additional supplies to break the vicious circle of 'supply creates demand'.

At the same time, increasing water demands and competition among water uses have called for more integrated and sustainable water management policies. In the last 20 years, there has been a worldwide concerted movement towards integrated approaches materialized, in the case of water resources, into the Integrated Water Resources Management (IWRM) policy approach. IWRM was prompted at the 1992 United Nations Conference on Environment and

Development (UNCED) Dublin-Rio conference on water, and became part of Agenda 21, a wide-range UN agreement for sustainable development (UN, 1992).

Although the IWRM concept has been widely accepted, there is not yet common agreement about its definition. The most commonly accepted definition of IWRM is that given by the Global Water Partnership (GWP). IWRM is defined as '*a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*' (GWP, 2000). Therefore, the IWRM approach is seen as a holistic and comprehensive approach that strives for integrating ecological, technological, socio-economic, and institutional criteria, while ensuring the sustainability of water resources for future generations (Jonker, 2002; Matondo, 2002).

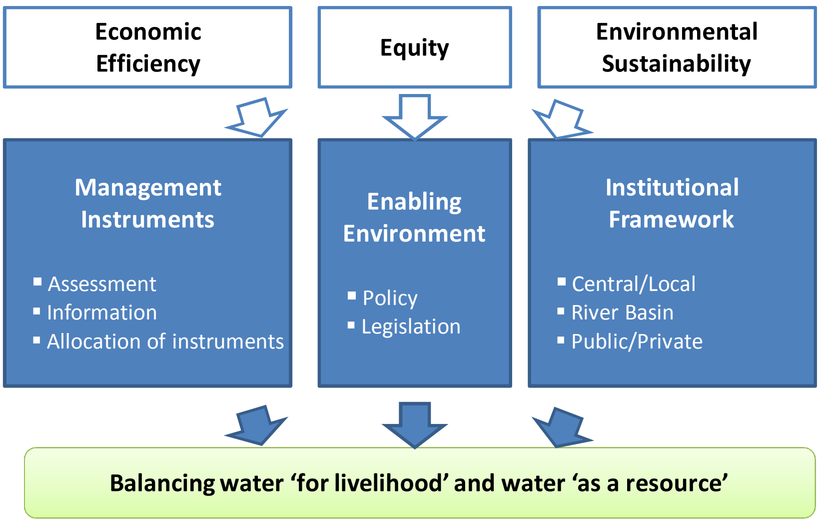
IWRM takes into account different perspectives and dimensions. Several authors have discussed the aspects and dimensions that should be integrated under the IWRM umbrella (see e.g., Biswas, 2004; Matondo, 2002; Fischhendler and Heikkila, 2010; Kidd and Shaw, 2007; Medema and Jeffrey, 2005; Savenije and Zaag, 2008; Thomas and Durham, 2003; among many others). The most important are the following:

- The *natural dimension,* which includes all types of water resources (salt, brackish, green, blue, fossil) and takes into account the whole hydrological cycle.
- The *temporal dimension*, which refers to the temporal distribution of fresh water resources and the distribution of the demands over time.
- The *spatial dimension*, which recognizes a river basin as the main natural unit for water resources management, but implies coordination at different physical scales: river basins, sub-catchments, watersheds, and hydro-geological units.
- The *human dimension*, which is comprised of all water users (households, industries, agriculture, fisheries, ecosystems, hydropower, navigation, recreation, etc.).
- The *stakeholders dimension,* which highlights that stakeholders should be informed about and involved in the planning, development and management of the water resource.

- The *organizational and institutional dimension*, which integrates the government units, agencies, water user associations, and private organizations that have responsibilities in water management. Physical and administrative boundaries need to be integrated. Appropriate institutional arrangements (such as, laws, and management agreements) should be put in place to provide effective coordination between water use and water management.

IWRM aims to improve efficiency in water use (economic rationale), promote equity in access to water (social rationale), and to achieve ecological integrity (environmental rationale) (Butterworth et al., 2010; Postel, 1992; Savenije and Zaag, 2008). Based on these policy principles, the IWRM approach focuses on three basic pillars to operationalize sustainable water resource development strategies (see Jønch-Clausen, 2004; Medema et al., 2008): 1) *enabling environment* of suitable policies, strategies and legislation; 2) establishing *the institutional framework* to put legal actions into practice; 3) providing the *management instruments* to facilitate the operation of institutions. The fundamental pillars of the IWRM are depicted in Fig. 1.

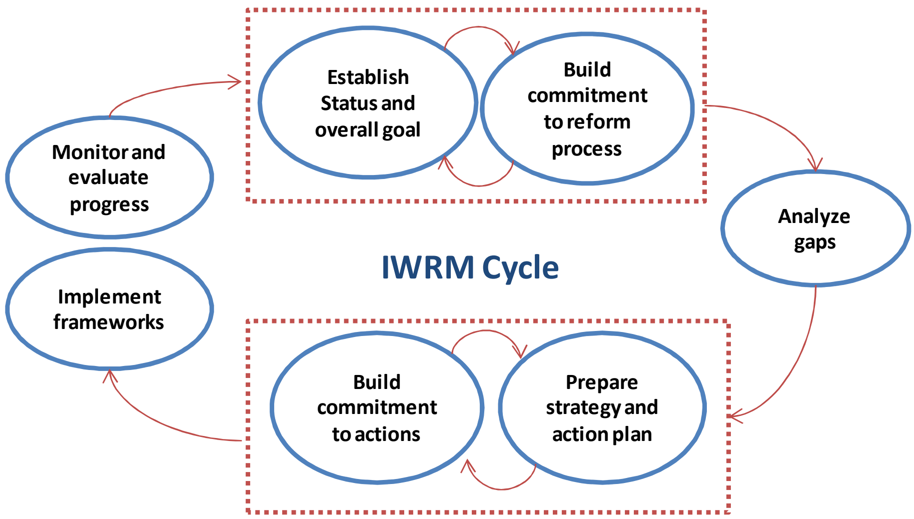
Fig. 1- The three basic pillars of the Integrated Water Resources Management (IWRM) concept.



Source: Jønch-Clausen (2004).

Updated information about the current status of the IWRM and its implementation can be found in the GWP, in its Technical Advisory Committee Background Paper Nº 1 (GWP 2004). In this paper, the IWRM is defined as a cyclical process, whose implementation takes places on a step-by-step basis following a feedback loop (see Fig. 2). This cyclical process is represented by an ongoing learning and development process in which stakeholders play a fundamental role in revising objectives and strategies as part of an iterative process.

Fig. 2- The Integrated Water Resources Management (IWRM) cycle.



Source: Own elaboration based on GWP (2004)

The incorporation of socio-human, institutional, economic and ecological factors, as well as the involvement of the stakeholders in water decision-making has proven to be effective for water management as well as for food production, nature conservation, and overall socio-economic development (Rosegrant et al., 2002; Varela-Ortega, 2007; Varela-Ortega et al., in press a). In addition, integrated water management strategies can provide more equitable water management decisions, and decreasing conflicts and tensions among competing users (Fischhendler and Heikkila, 2010; GWP, 2007).

Nevertheless, the implementation of the IWRM approach still remains controversial in real contexts. Many of the attempts made so far have either failed or resulted in excepted outcomes that were too low (Jeffery and Geary, 2006; Jonker, 2002). Biswas (2005) and Mazvimavi (2008) draw attention to the need of providing a more detailed look at the process of turning theoretical IWRM concepts into practice, whereas Molle (2008) warns about the impossibility of maximizing all of the different objectives (equity, economic efficiency, and environmental sustainability) simultaneously, identifying the IWRM concept as a 'nirvana concept'. In most cases, the implementation of the IWRM requires accomplishing significant institutional changes, which may become substantially complex due to heavy sectoral and organizational integrations (Biswas, 2004). Blomquist and Schlager (2005) indicate that physical integration in large-scale basins can make the agreement of the stakeholders difficult on what to adapt and how, as large basins usually comprise different regions, or even different countries, each with very different physical, economic, social, cultural, and legal conditions. The social learning process of different stakeholders groups can be hindered, obstructing the development of adaptive water management strategies (Pahl-Wostl, 2007; Saravanan et al., 2009).

1.3. Objectives and scope

As seen in the previous sections, water resources face increasing challenges, especially in semi-arid regions such as some regions in Spain. Growing scarcity and competition for water has become a major cause of disagreement among both different users and regions. At present, there is a growing consensus on the need to integrate socio-economic and environmental considerations into water decision-making. Why integration is needed and what should be integrated are issues that have been heavily addressed over the past few years. However, a number of questions still remain unanswered, and further investigation should be conducted to respond to issues such as the following: How the different domains in water resources management can be integrated; What processes should be used for integration; Which are the benefits of such integration; How the broad principles of IWRM can be put into practice.

The present study tries to fill some of these fundamental research gaps and challenges using a multidisciplinary approach for integrating the different environmental, hydrological, social, political, and institutional domains of complex water systems.

The **general objectives** of this PhD Thesis are:

- To develop a coherent and integrated methodological framework capable of capturing the multifaceted interactions between socio-economic and natural resources systems under risky situations in order to guide and support integrated water management processes.

- To apply the methodology developed in a real case study for testing its functionality and reducing the gap between IWRM theory and practice. With the aim of facilitating the transfer of empirical experiences, the modeling tools used in this research were applied to the Guadiana River Basin, but designed to be adaptable to the hydrology, economics, and institutions of other basins.

- To use the methodology developed to identify sustainable and cost-effectiveness water management strategies capable of effectively balancing the trade-offs between water for food production and water for nature conservation in the intensively-irrigated and large drought-prone region of the Guadiana Basin.

The **specific objectives** of the study can be summarized as follows:

- To analyze the site-specific regional and local conditions (agricultural, social, physical, ecological, institutional) of the Guadiana River Basin in order to identify relevant units of analysis and management for IWRM.

- To involve the stakeholders in the design, implementation, and validation of the models as well as in the process of scenario building to derive meaningful tools, identify socially accepted solutions, and facilitate the interpretation of results.

- To develop a hydro-economic modeling platform to study the interdependences between the agricultural and water sectors at different levels of analysis (field, groundwater bodies/catchments, sub-basins, and river basin) in detail, and provide relevant insights regarding farm income, public expenditure, water supply and demand, crop evapotranspiration and irrigation needs, instream flow requirements, and other hydrology parameters.

- To use integrated hydro-economic modeling to analyze the current status of irrigation systems in the Guadiana Basin and examine the potential implications of different water management instruments, applied to the context of the WFD, under diverse climate-related conditions and plausible development trends.

1.4. Choosing the case study

The Guadiana River Basin presents a paradigmatic case of a relatively large semi-arid region where many of the major issues in water management are represented: significant conflicts among competing water user sectors (agriculture, urban, industrial, environment), coexistence of surface and groundwater resources, degradation of wetlands and aquatic ecosystems, complex regulated river systems, intra and inter-basin water transfers, concurrence of public and private water management institutions, and challenging water governance (Coleto et al., 2003; Llamas et al., 2010). All of these aspects illustrate the complexity of water-related problems in the Guadiana basin and the need to adopt an integrated approach for promoting effective water use and sustainable water management. Therefore, the Guadiana Basin constitutes an emblematic case study where one can apply and learn from integrated watershed modeling.

Furthermore, the Guadiana Basin was chosen as an appropriate study area due to the availability of good climatic, hydrologic, and socio-economic data, and the extensive information collected from stakeholders during the participatory consultation process carried out by the Guadiana River Basin Authority for the development of the Guadiana River Basin Management Plan, and the several stakeholder meetings conducted in the study area within the framework of the EU projects NeWater and Scenes.

1.4.1. Study area specification

The Guadiana River Basin is a large trans-national basin situated in the south-western central plateau of the Iberian Peninsula (see Fig. 3). It spans an area of 67147 Km^2, of which 55527 Km^2 (83% of the basin) are within Spanish territory and 11620 Km^2 (17% of the basin) are in Portugal.

Fig. 3- Location of the study area.

In Spain, the Guadiana River runs westward over 592 km through three autonomous regions (Castilla-La Mancha, Extremadura, and Andalucía). Its drainage area covers 8 provinces (Albacete, Toledo, Cuenca, Ciudad Real, Badajoz, Cáceres, Córdoba and Huelva), 473 municipalities, and is home to 1.47 million people with a population density of 20.42 inhabitants per km^2. In distant regions from the Guadiana River, some areas are sparsely populated and present a high risk of desertification (CHG, 2008). As depicted in Fig. 1, the Guadiana Basin can be divided into three distinct areas based on river morphology: the Upper Guadiana (23004 km^2, mostly located in Ciudad Real), the Middle Guadiana (29402 km^2, almost completely lying within Badajoz), and the Lower Guadiana (3051 km^{2,} situated in Huelva).

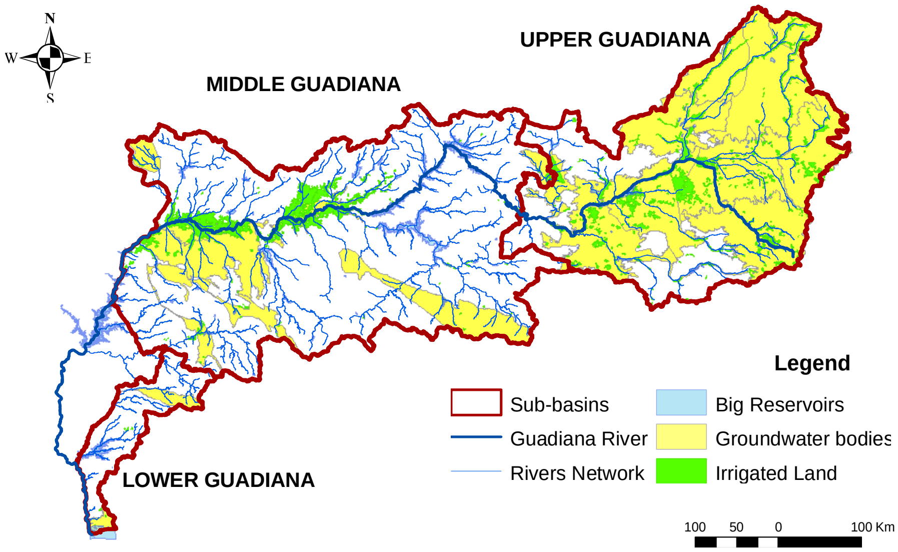
The region presents a Mediterranean-Continental semi-arid climate, where long dry periods alternate with short wet sequences, and hot dry summers follow short mild winters. Average rainfall is approximately 524 mm/year and the total annual evapotranspiration (according to the Thornthwaite index) is around 800-1000 mm/year. The mean temperature is 16°C, but may vary from 11°C in the upper part of the basin to 18°C at the mouth (CHG, 2007a).

Over the past century, the Guadiana Basin has experienced recurrent droughts of 4-5 years duration (e.g., in 1941-1945, 1979-1983, 1991-1995, 2004-2009). These drought periods have resulted in an annual precipitation and runoff decrease of 30% (on average), leading to water shortages for irrigation and urban use, crop failures, significant economic damages, environmental degradation, and conflicts among water users. (CHG, 2007a; Iglesias et al., 2007).

Mean natural runoff is around 4400 Mm^3/year, but it is also irregularly distributed, both in space and time. The frequent dry spells and the irregularities of the hydrologic regime of the Guadiana River have required the construction of a large number of reservoirs to increase the water resource availability and store water in wet years to be used in dry periods. Currently, the Guadiana is one of the most regulated rivers in Europe (Tockner et al., 2009). Among other river regulation infrastructures (dams, canals, irrigation channels, waste pipes, aqueducts), the Guadiana Basin comprises 86 reservoirs (> 1 Mm^3), which provides a total storage capacity of 9114 Mm^3. The Guadiana Basin comprises 137 rivers, those being the Gigüela (in the Upper Guadiana) and the Zújar (in the Middle Guadiana), which are the most important tributaries of the Guadiana River (CHG, 2010).

The region also has important groundwater reserves, which are mostly concentrated in the Upper part of the Guadiana Basin (see Fig. 4). In total, there are 20 groundwater bodies that cover an area of about 22484 km^2.

Fig. 4- Physical characterization of the study area.



The most important economic activity in the Guadiana River Basin is agriculture in terms of territory and employment, generating 81000 jobs and 1779 million € of gross added value. Agriculture is followed, in terms of economic relevance, by services and industrial activities, which have increased considerably in recent decades. Also, in terms of water consumption, agriculture is the main sector with 93% (3189 Mm^3/year) of total water consumption. Water demand for domestic supply is about 6% (including tourism) (233 Mm^3/year) and industrial water demand is around 1% (17 Mm^3) (CHG, 2006a).

Irrigated crops are distributed all along the river basin over an area of 350000 ha, featuring winter cereals, maize, vine, horticulture, fruits and olive trees. The most important cities of the Guadiana Basin (such as, Manzanares, Alcázar de San Juan, Mérida, and Badajoz) are located in the areas adjoining irrigated lands, especially in the Mancha region (in the Upper Guadiana basin in Ciudad Real) and in the fertile plains along the middle part of the Guadiana River called 'Vegas' (see Fig. 4).

Additionally, the Guadiana Basin holds important natural spaces of high ecological value classed in different environmental protection categories. The region includes valuable wetlands listed in the Ramsar Convention (107 Km^2), nationally protected Natural Spaces (3062 Km^2), habitats of Communitarian Interest (9262 Km^2), zones of Special Bird Protection (10433 Km^2), and UNESCO Biosphere Reserve areas (7274 Km^2) (CHG, 2010).

Environmental uses have been scarcely considered so far, and only recognized as a constraint upon the rest of water uses by the Spanish Water Law (Real Decreto Legislativo 1/2001). However, in recent years, policy makers have paid increasing attention to the need to allocate a share of water to maintain the functioning of freshwater-dependent ecosystems. At present, the establishment of minimum environmental flows is considered a key measure for restoring and managing river ecosystems in the Guadiana Basin, and ultimately, for achieving the environmental objectives of the WFD (Orden ARM/2656/2008). The required environmental flow regimes are currently being studied (CHG, 2009b). They will be specified in the new management plan of the Guadiana Basin.

1.4.2. Major issues and research problems

The key water-related problems and potential solutions vary in the different sub-regions of the Guadiana Basin. The specificities of each sub-region justify the need for downscaling and designing regional and local strategies targeted to specific areas, which makes the management at the basin level and the development of a unique River Basin Management Plan a difficult challenge (Krysanova et al., 2010).

The present PhD Thesis focuses on the Spanish part of the Guadiana Basin and specifically on the Upper and Middle parts of the Guadiana Basin, which represent 78% of the basin's total area and 94% of the basin area in Spain.

The Upper Guadiana Basin

This area is the driest region of the Guadiana Basin and one of the driest regions in Spain (precipitation is in the order of 400 mm/year) (CHG, 2007a). In the Upper Guadiana Basin, water is perceived as a very scarce resource and a basic input for farming activity and income gains (Zorrilla, 2009). Irrigation agriculture accounts for 95% of the total water use and covers around 200000 ha that are almost totally dependent on groundwater sources. The most important hydro-geological unit of the Upper Guadiana Basin is the Mancha Occidental aquifer, a large limestone aquifer of 5500 Km^2 and 20000 Mm^3 of storage capacity that is located in the center of the basin and connected to valuable surface wetlands (Coleto et al., 2003). It covers 300000 inhabitants as well as an important agricultural sector which boasts one of the most dynamic economies of the Castilla-La Mancha region. In this area, maize and other winter cereals (barley, wheat) cover 45% of the total irrigated surface. Other important crops in terms of surface, labor use and added value, are vineyards and vegetables (such as melon, potato, garlic, and pepper), which occupy around 40% and 15% of the total irrigated surface, respectively. In general, crops are irrigated with sprinkler and localized irrigation systems (CHG, 2007b).

The Mancha Occidental aquifer represents an interesting example of complex water-related conflicts derived from a mismanagement of groundwater resources (Hernández-Mora and Llamas, 2001; Llamas, 2003; Martínez-Santos, 2007). In this region, groundwater development started in the 1970s, mostly through the initiative of individual farmers featuring a 'silent revolution' (Llamas and Martínez-Santos, 2005) without proper control to ensure sustainable groundwater use. During the 1980s and 1990s, traditional irrigation was gradually displaced by intensive irrigation, in part encouraged by the establishment of direct payments based on crop production from the EU CAP, which favored the expansion of high water-intensive crops (Varela-Ortega, 2007). At the end of the 1980s, more than 125000 ha were under irrigation systems, using up to 600 Mm^3/year of groundwater (CHG, 2006b).

Irrigation induced a noteworthy socio-economic development in otherwise depressed rural areas. However, the poor control of groundwater pumping and the lack of trust and cooperative strategies among irrigators conducted to free-riding behaviors as well as to the over-exploitation of the Mancha Occidental aquifer, giving rise to significant water disputes and environmental problems (López-Gunn, 2003; López-Gunn and Hernández-Mora, 2001; Varela-Ortega, in press a). Excessive groundwater use for irrigation depleted the water table of the Mancha Occidental aquifer at an average rate of 1 m/year (IGME, 2004) and dramatically reduced the surface area of valuable groundwater-dependent wetlands in the 'Tablas de Daimiel' National Park and 'La Mancha Húmeda' UNESCO Biosphere Reserve (Castaño-Castaño et al., 2008; De la Hera, 1998; Iglesias, 2001; Martínez-Santos et al., 2008). Intensive agriculture also led to an excessive use of nitrate fertilizers. Currently, the Castilla-La Mancha region is the most polluted area by nitrates from agriculture in Spain (Varela-Ortega et al., in press b).

The Spanish government, having previously provided strong incentives for agricultural development in the region, implemented in 1991 a Water Abstraction Plan (WAP) to control and reduce groundwater use for irrigation. Alongside this, EU policies were also implemented to secure water conservation and wetland recovery through their Agri-Environmental Programs (AEP), which promoted water reduction by paying farmers for halting irrigation. The AEP programs were abandoned because of budgetary pressures and the WAP policies fell short in their objectives due to the strong opposition from the irrigators and the derived high transaction costs involved in the control and application of the law (Varela-Ortega, 2007; Varela-Ortega et al., in press a) .

At present, downward water table trends have not yet been reversed and the wetlands are being kept alive artificially by means of water transfers and planned abstractions. Recovering the wetlands requires new and effective policies that aim to promote environmental sustainability by eliminating excessive groundwater use for irrigation. In that context, the new Special Plan for the Upper Guadiana (SPUG) (CHG, 2007b), launched by the Guadiana River Basin Authority in 2007 within the framework of the EU WFD, attempts to achieve the aquifer's recharge by 2015 (or 2027 at the latest) by setting the maximum annual water volume diverted to the agricultural sector at 200 Mm^3. To achieve its goal, the SPUG includes different types of measures (such as purchasing water rights from the irrigators, the legalization and closing-up of un-licensed bores, a reforestation plan, the support of rain-fed agriculture) that still need to be implemented and tested. Thus, the revision of the current water policies and the application of new policy instruments and complementary measures for the rural populations which guarantee sustainable groundwater management is one of the major tasks that has to be addressed by water managers and policy makers in the area.

The Middle Guadiana Basin

This part of the Guadiana Basin is not absolutely water scarce (the average precipitation is about 590 mm/year). However, water usage is very large compared to natural resources, and reservoir storage is essential to satisfy the high existing consumptive water demands in the region, especially for irrigation (CHG, 2007a). In total, 762131 inhabitants live in the region. The most important cities are concentrated principally in the plains along the Guadiana River, in areas that adjoin irrigated lands (CHG, 2008).

In the Middle Guadiana Basin, like in the upper part of the Guadiana Basin, agriculture is the most important economic activity and water user. It provides an important part of the employment in some municipalities and is the base for many agro-related manufacturers and agribusinesses that have significant weight within the industrial sector (CHG, 2006a). The region includes around 145000 ha of irrigated land almost totally dependent on surface water, of which 57% is irrigated by gravity through irrigation canals, and 43% is irrigated under pressurized irrigation systems. In this area, crops grown with irrigation include cereals (especially water-intensive crops such as rice and maize) and tomatoes for processing, which occupy 84% of the total irrigated area. The remaining area is covered by fruit trees (7%), olive trees (7%), and vineyards (2%) (JE, 2007). In total, irrigated agriculture consumes over 1164 Mm^3/year, which accounts for 92% of the total water use (CHG, 2010).

In this part of the Guadiana Basin, the water volume delivered to farmers is large and highly subsidized. The expansion of irrigated land was developed with substantial public funds under state-managed irrigation development plans during the early 1960s and 1970s. The most important development plan in the region, known as 'The Plan Badajoz' (from 1952 to 1975), encouraged the construction of major hydraulic projects (dams and irrigation canals) along the Middle Guadiana River and its main tributaries (Zújar and Matachel), which allowed for the transformation of large irrigated areas and the settlement of the rural population (Medina, 2002). Under the Plan Badajoz, 135000 ha were converted into irrigation, and around 6000 peasant families ('colonists') were settled in the transformed irrigated land in small holdings of about 4-5 ha that included a dwelling house, farm implements, and livestock (Gimenez and Sánchez, 1994; Gómez-Pompa, 2002;).

The irrigation development plans implemented in the area increased agricultural production and raised the living standards of the population, promoting the socio-economic development of the region. In addition, the large development of water infrastructures highly enlarged the water storage capacity of the Middle Guadiana Basin (up to 7900 Mm^3, which represents 85% of the total storage capacity of the Guadiana Basin), leading to a higher resilience and lowering vulnerability to drought (Krysanova et al., 2010). The regulation provided by reservoirs increased the availability of water from a percentage of 1% of the mean annual flow in natural conditions (44 Mm^3/year) to 46% of the mean annual flow (1922 Mm^3/year) (Garrote et al., 2004).

However, most of the developed infrastructure for regulation, transportation and distribution of water resources is now deteriorating, and important water losses occur due to the poor state of the conveyance system. Recently, government plans for rehabilitation and modernization of irrigation systems have been put in place to improve the technical efficiency of old irrigation canals and encourage farmers to implement modern irrigation techniques for a better use of water at field level (Real Decreto 287/2006; MARM, 2010).

Additionally, the Middle Guadiana region has to deal with important policy challenges derived from the implementation of the EU WFD and the CAP. Complying with the requirements of the WFD, such as the cost-recovery of irrigation services and the restoration of the environmental flows, might considerably reduce water consumption for irrigation and produce serious impacts on farm income and land use (Esteve, 2009). On the other hand, achieving the CAP's objectives in the Middle Guadiana Basin requires the development of market-oriented crop productions, the modernization of agricultural systems, and the implementation of environmentally friendly farming practices. At the present, farms still tend to be fragmented and too small, which impedes crop diversification and working the holdings in a modern rational way.

Last but not least, the Guadiana Basin needs to tackle the common challenge of climate change. Future climate change projections for the Guadiana Basin foresee an increase in the frequency and intensity of droughts and a reduction by 11% of the availability of natural water resources by 2030 (the largest decrease in continental Spain), due to a temperature increase of 1ºC and a rainfall decrease of 5% (Brunet et al., 2009; CHG, 2007a; Moreno, 2005).

Integrating economic, social, environmental, climate-related and technological aspects into the Guadiana Basin is a major challenge for the adaptation to new forms of water management within the EU policy context.

1.5. Methodology

1.5.1. Brief review of methods and tools

The inherent complexity of water systems and the interdisciplinary nature of water problems require the development of new tools to integrate technical, economic, environmental, social, and institutional aspects into the coherent framework of IWRM (McKinney et al., 1999).

Several approaches, apart from the IWRM approach, seek the goal of 'holistic' water management: the ecosystems approach (EA) (Kay et al., 1999); the coupled human-natural systems approach (CHANS) (Liu et al., 2007); integrated assessments (IA) (Jakeman and Letcher, 2003); multi-criteria decision analysis (MCDA) (Romero and Rehman, 1987); among others. Liu et al. (2008) indicate that all of these approaches link aspects of natural systems and the human environment by integrating key components and relationships. A truly comprehensive integration is often impractical and very difficult to achieve through pure data collection or process studies. In recent years, integrated modeling has been found to be a useful strategy in tackling complex environmental problems, and has become widely applied in order to support water resources decision-making (Croke et al., 2007). Table 1 summarizes some of the models most commonly used in IWRM.

Table 1- Type of models used in IWRM.

Type of model	Characteristics	Examples
Agent-based Models	Focus on the interactions between the agents (individuals or collective decision-making entities, such as organizations or groups) in a system, where agents adapt to changes in their environment.	Becu et al. (2003); Schlüter and Pahl-Wostl (2007)
Bayesian Networks	Represent the essential components of a system and their interrelations using the Bayes' probability theory. They allow the active participation of relevant stakeholders and explicit consideration of uncertainty.	Carmona et al. (in press); Zorrilla et al. (2010)
Metamodels	Simplified models that are identified by data produced by the simulation of other complex, computational models. They can be used to run less time-consuming simulations.	Broad et al. (2010); Galelli et al. (2010)
Expert Systems Models	Programs that use expert knowledge and inference procedures to address non-algorithmic problems. They typically represent knowledge in a symbolic manner (production rules, frames, and semantic nets), and examine and explain their reasoning processes.	Bharwani (2006)
System Dynamics Models	Investigate and represent the key feedback structures of a system. They are well suited to the analysis of those problems whose behavior is governed by feedback relationships and that have a long-term time horizon.	Elmahdi et al. (2007); Stave (2003); Winz et al. (2009)
Theory-based Models	Also known as process-based models or hard-models, they represent the system through mathematical equations and aim to reproduce hydrological, operative, social, and economic processes based on physical theory and economic theory.	Merrit et al. (2004) ; Rosegrant et al. (2000); Varela-Ortega et al. (in press a)

In particular, theory-based models have proven to be outstanding tools in approaching different water-related problems, evaluating water management alternatives, and predicting how the system will respond to future natural conditions or managed actions. (GWP, 2000; Silva-Hidalgo et al., 2009). In the beginning, these models were based on hydrologic engineering models. However, the gradual incorporation of economic principles to support water decision-making throughout the last half century has given rise to the development of integrated hydrologic-economic models.

The use of hydro-economic models started in the early 1960s and 1970s in some semi-arid regions, such as Israel and the southwest of the US (Harou et al., 2009). Since then, numerous hydro-economic modeling applications have been developed worldwide to analyze issues such as the inter-sectoral allocation of water, expansion of water supply infrastructures, conjunctive use of groundwater and surface water, transboundary water management, water pricing, land use management, climate change, and water conflicts. Harou et al. (2009) track the application of 80 hydro-economic models over the past 43 years.

Experiences from the past have proven the potential of hydro-economic models as a tool to inform policy-makers and water managers on how to optimize the use of water for different purposes. In hydro-economic models, water resources are allocated and managed to maximize the economic value of water subject to physical and operational constraints on flows and capacities (Jenkins et al., 2004; Medellín-Azuara et al., 2009). These integrated tools can indicate the economic benefits and environmental consequences associated with specific planning practices and management endeavors, providing relevant insights in terms of integrated water management, and institutional and financial design (Pulido-Velázquez et al. 2008). Furthermore, when implemented with the collaboration of the stakeholders, hydro-economic models can help reach a better common understanding of water resources systems and problems, and more balanced and equitable negotiated solutions (Heinz et al., 2007).

Numerous software packages can be used to run hydro-economic models (see Harou et al., 2009). To date, few DSS have been developed to work specifically as hydro-economic models. Some examples are AQUARIUS (Díaz et al., 2000) and AQUAPLAN (Tilmant et al., 2008). Other well-known DSS for river basin simulation have been adapted to include economic components such as AQUATOOL (Andreu et al., 1996), OASIS (Randall et al., 1997), MODSIM (Labadie and Baldo, 2000), MIKE BASIN (Jha and Das Gupta,2003), CALSIM (Draper et al., 2004), WEAP (Yates et al., 2005), WSM DSS (Todini et al., 2006), and WaterWare (Cetinkaya et al.,2008). Additionally, optimization-based models for water management have been developed and applied in some specific regions such as WAS (Fisher et al., 2002) in Israel, CALVIN (Draper et al., 2003) in California, and SFWMM (South Florida Water Management

District, 1997) in Florida. Many other applications use generic modeling systems such as GAMS, AIMMS, AMPL, LINDO, etc., to develop custom (user-defined) model formulations.

Limitations in the implementation of hydro-economic models, as with the benefits, have been widely discussed in literature (McKinney et al., 1999; Brouwer and Hofkes, 2008; Cai, 2008). The integration of the hydrology and economic models creates a challenge, mainly due to the differences in scale (temporal and spatial) and modeling resolution techniques. In general, hydrology models are based on simulation techniques, while economic models are of the optimization type. Spatial boundaries in hydrology models usually refer to geo-hydrological limits (water bodies, catchments, and basins), which are different from the administrative boundaries that delimit economic models (municipalities, provinces, and regions). In addition, hydrology models are often run in daily or monthly time steps, whereas economic models are executed in annual time steps.

Different classifications of hydro-economic models are reported based on these mismatch characteristics. Among them, the most widely used classification refers to how different models are integrated. Braat and Lierop (1987) distinguish between 'holistic' hydro-economic models and 'departmental' or 'modular' hydro-economic models. Table 2 summarizes the main characteristics of these two types of approaches.

Table 2- Types of hydro-economic models.

Type	Description	Advantages	Disadvantages	Some examples
Holistic	One single model unit, where hydrologic and economic components are embedded	- Integrated analytical framework - Information is transferred endogenously - One single technique (easy to achieve an optimal solution)	- Sub-models are often simplified (unrealistic representation of reality) - Essential relations between the economic and hydrologic components are difficult to capture - Complex, difficult to solve	Cai (2008) Draper et al. (2003) Gürlük and Ward (2009 Rosegrant et al., (2000) Ward and Pulido-Velázquez (2008)
Modular	Independent modules, only input/output data are transferred between them	- Sub-models can be complex and well detailed - Sub-models can work on a stand-alone mode, and therefore be solved and updated externally - Simulation and optimization models can be combined	- Loose connection between the different economic and hydrologic components - Need for additional modeling (data-management interfaces) - Feedback loops or iterations may be needed - Difficult analysis	Ahrends et al. (2008) Maneta et al. (2009) Qureshi et al. (2008) Varela-Ortega et al. (in press a)

As seen in Table 2, in holistic models, all the components of the system are tightly connected to a consistent model. They permit a fluid transfer of information between the economic and hydrology modules, but need to be simplified in order to avoid complex and unfeasible model resolutions. On the other hand, compartmental models are organized into independent modules. Usually, the output data from one of the modules is entered as input data into the other module. The main problem is in providing communication and data exchange between the different subsystems, but they can definitely better match reality. Thus, although in practice, most hydro-economic models are based on a holistic approach, the use of compartmental models and generic software interfaces are becoming progressively more common (Harou et al., 2009). Table 3 collects some recent examples of modular hydro-economic models. At the end of the table and separated by a double line, the methodological approach developed and used in the present Thesis has been included.

Table 3- Some recent examples of modular hydro-economic models.

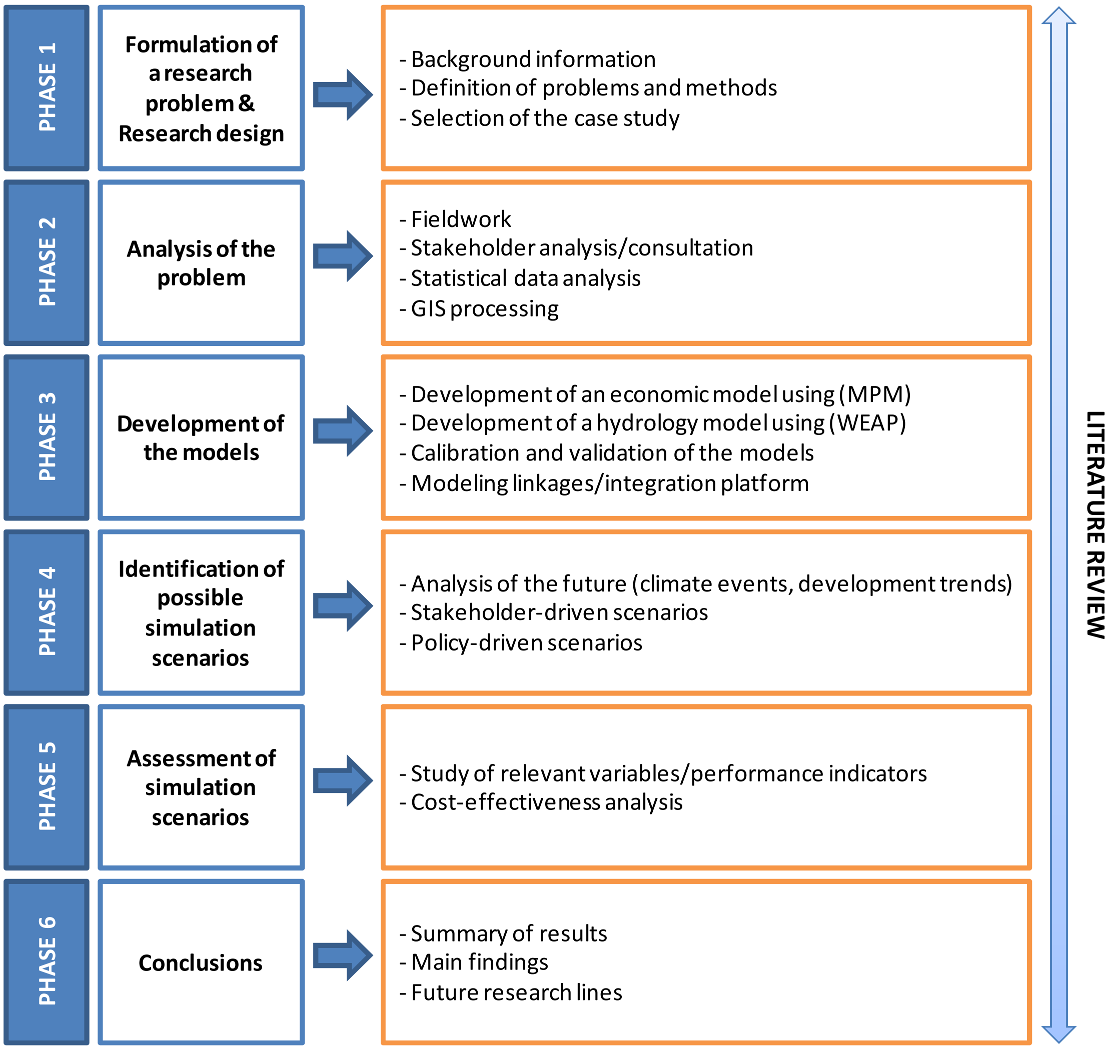
River basin	Methodological focus	Economic model	Hydrology model	Model integration	Examples
Volta Basin (Burkina Faso/Ghana)	Surface water/reservoir operations/land use	Net profit max.	WaSiM	Automated	Ahrends et al. (2008)
Volta Basin (Burkina Faso/Ghana)	Conjunctive use of groundwater and surface	Net profit max.	WaSiM	Manual	Bharati et al. (2008)
Burdekin delta (Australia)	Groundwater/ management/ seawater intrusion	Agro-economic model (regional net profit max.	MODFLOW	Manual	Qureshi et al. (2008)
San Joaquin basin (California, US)	Groundwater& surface water/climate change	Farm model (APSIDE)	CALSIM II	Semi-automated	Quinn et al. (2004)
Upper Ems River Basin (Germany)	Water pollution/ agric. management options/ cost-effectiveness	Farm model (BEMO)	SWAT	Semi-automated	Volk et al. (2008)
São Francisco RB (Brazil)	Groudwater&surface water/drought	Farm PMP model	MODHMS	Automated	Maneta et al. (2009)
Upper Guadiana RB (Spain)	Groundwater /w. management/drought	Risk-based farm model	WEAP (hard data entry)	Manual	Varela et al. (in press)
Middle Guadiana RB (Spain)	Surface water/w.policy/env. flows/drought	Risk-based farm model (multiscale)	WEAP (soil moisture method)	Automated	Blanco et al. (submitted)

As depicted in Table 3, the methodology used in this study offers an important extension of the existing literature concerning hydro-economic modeling in terms of model integration (with the development of automated links), the application of more detailed and sophisticated economic and hydrology models, and also by the novel methodological focus of the research (simulation of policy and climate scenarios). Kragt et al. (2010) indicate that there are few ecological-economic models capable of assessing the socio-economic impacts of environmental changes. As seen in Table 3, only Volk et al. (2008) analyze the impacts of water quality changes on land use. The novelty of the research also resides in the approach taken when starting the communication between the hydrology and the economic models. While most hydro-economic models are driven by variations in hydrological state variables (Brouwer and Hofkes, 2008), in this research (Blanco et al., submitted), as well as in Varela-Ortega et al. (in press a), the hydro-economic model is primarily driven by economic conditions. Furthermore, the work presented in this Thesis incorportes important methodological advances with respect to the modeling exercise developed by Varela-Ortega et al (in press a). First, the economic model used in the present research work was applied to the Middle, Guadiana Basin and constructed based on a multi-scale modeling approach. Second, unlike the hard data entry approach used in Varela-Ortega et al. (in press) to represent the hydrological components of the Upper Guadiana Basin, the hydrological modeling of the Middle Guadiana Basin was developed using the soil moisture method incorporated in WEAP ('Water And Planing' system). Third, the integration of the models was automated throught the development of data-management simulation engines. A more detailed description of the models is presented in the next section 1.5.2.

1.5.2. Applied methodological framework

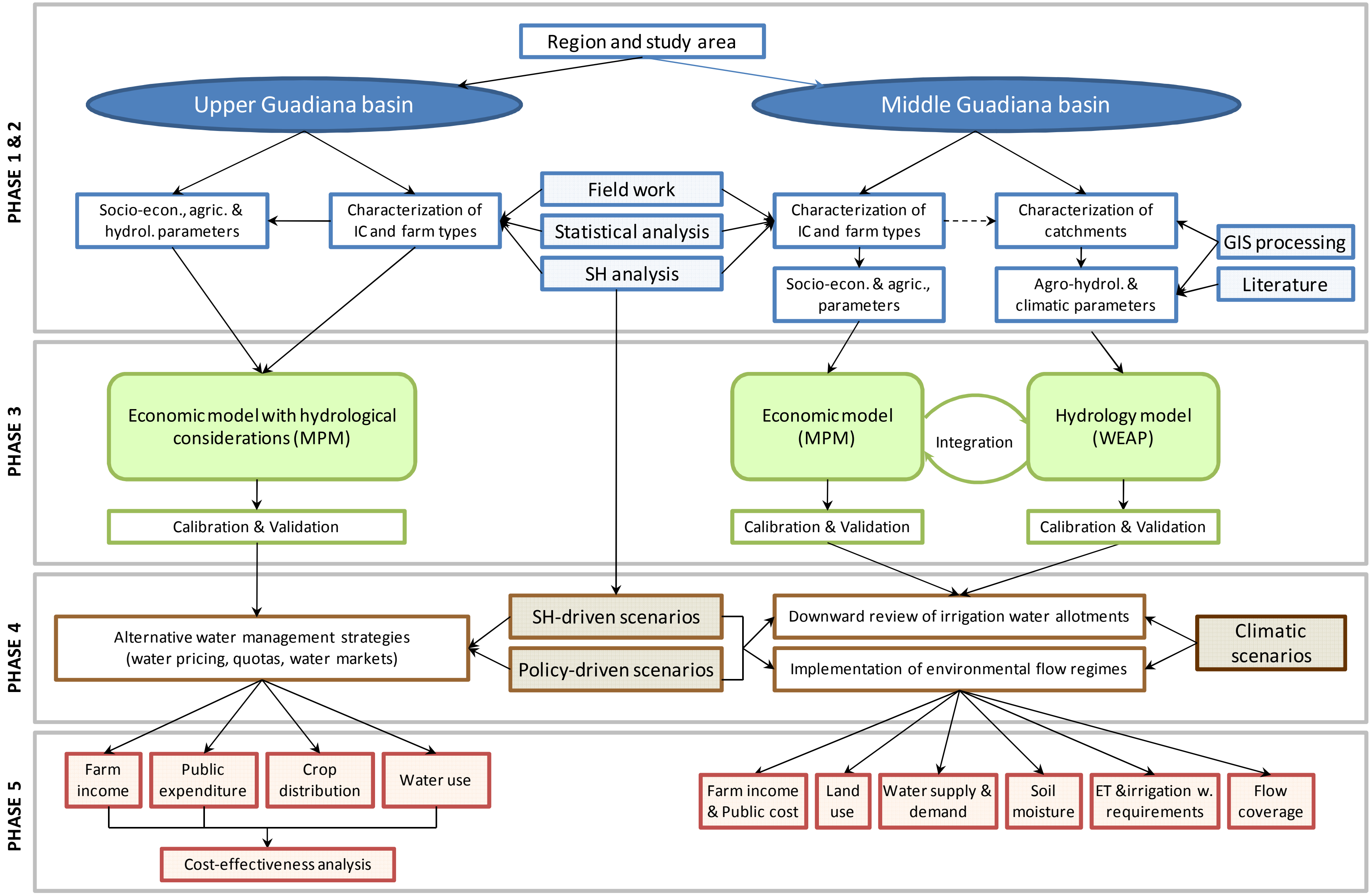
The present PhD Thesis has been carried out following a classic step-by-step approach. Fig. 5 illustrates the main stages of the research process implemented to complete this doctoral thesis.

Fig. 5- Main research phases followed to develop the PhD thesis.



A detailed representation of the analytical procedures used in each of the research phases is depicted schematically in Fig. 6.

Fig. 6- Detailed scheme of the methodology used in the PhD thesis.



- **Phase 1: Formulating the research problem and conceptualizing the research design.** The primary stage of any research project is selecting the topic of research and determining a research question. From the beginning, this study has focused on the concept of IWRM and how integrated tools can assist decision makers in the design and assessment of water management projects for semi-arid regions. Once the research idea was configured, extensive background information was compiled to ensure that the proposed research project included information about existing and previous studies, yet still be novel. A great number of papers and technical reports were consulted at this stage of the methodology, although an extensive review of the scientific literature was carried out throughout the research process. The compiled information helped to clarify the objectives of the thesis and devise an appropriate research hypothesis and methods. Finally, a pilot area was selected to test the research hypothesis and the designed methodology was applied.

- **Phase 2: Analysis of the problem.** This was one of the key stages in the development of the present doctoral thesis; it comprised the collection and processing of data.

  Data from a wide variety of sources (surveys, interviews, census collections, official reports, experiments, scientific publications, and web-catalogs) were collected to develop a reliable and comprehensive database. Collected data was processed and analyzed using statistical techniques and Geographic Information Systems (GIS). Extensive information about land use, climatic conditions, stream flows, water infrastructures, management practices, irrigation systems, prices, yields, etc., was used to characterize the different catchments, Irrigation Communities, and farm types as well as to determine the technical coefficients and parameters for the development of the economic and hydrology models.

  Ample fieldwork and stakeholder consultations were carried out from 2005 to 2010 in the context of the EU projects NeWater and Scenes. Personal interviews and field surveys addressed to individual farmers, irrigation community representatives, water managers, and technical experts, were carried out both in the Upper and Middle Guadiana Basins. In the Upper Guadiana Basin and within the context of the NeWater project, 30 targeted surveys were conducted during 2006 and 2007, in the five main Irrigation Communities of the Mancha Occidental aquifer (Alcazar de San Juan, Daimiel, Herencia, Manzanares, and Tomelloso), covering an area of 4587 ha (Varela-Ortega et al., 2006c). Similarly, in the context of the Scenes project, 107 surveys were carried out from 2008 to 2010 in the five main Irrigation Communities of the Middle Guadiana Basin (Mérida, Montijo-Canal de Montijo, Orellana, Tomas Directas del Guadiana, and Zújar) over an area of 4,655 ha.

In parallel, several stakeholder meetings were organized as part of the research activities of the projects NeWater and Scenes, and were attended by representatives of the main stakeholder groups of the Guadiana Basin (farmers, irrigation communities, river basin managers, regional government officials, environmental NGO's, farmers unions, private law firms, and scientifics). Two general preparatory meetings and three thematic meetings were held in Madrid from April 2005 to January 2007, specifically with the stakeholders of the Upper Guadiana Basin and within the framework of the NeWater project, in order to discuss agro-economic, legal-institutional, and hydrological aspects of water management in the upper part of the Guadiana Basin (Hernández-Mora, 2007; Llamas et al., 2006; Martínez-Santos and Llamas, 2007; Varela-Ortega et al., 2006a). Subsequently, from May 2008 to February 2010 and this time within the context of the Scenes project, stakeholders from the entire Guadiana Basin were involved in three stakeholders meetings to develop and analyze different future scenarios for the Guadiana's freshwater up to 2025/2050 (Blanco, 2010; Varela-Ortega et al., 2008; Varela-Ortega et al., 2009; Varela-Ortega et al., 2010). Additional information was obtained from the stakeholder meetings organized by the Guadiana River Basin authority as part of the participatory process carried out for the development of the new River Basin Management Plan, in which the NeWater and Scenes projects were also engaged (see CHG, 2009a).

Stakeholder knowledge of local social, economic, political, and environmental conditions helped to identify the site-specific characteristics of the Upper and Middle Guadiana Basin, enrich the development and validation of the quantitative models, and select the simulation scenarios. Most of the results obtained were presented back to the different stakeholders. A stakeholder meeting to disseminate the results of the research carried out in the Upper Guadiana Basin was held in Ciudad Real (November 2008) within the framework of the NeWater project. A second stakeholder meeting is planned to be held in Badajoz (January 2011), within the context of the Scenes project, to disseminate the results obtained from the research carried out in the Middle Guadiana Basin.

- **Phase 3: Development of the models.** Different models were developed and applied to the Upper and Middle Guadiana Basins with the aim of adapting the modeling exercise to the specific bio-geophysical conditions of the Guadiana Basin. The development of economic and hydrology models were explicitly requested by the stakeholders during meetings and discussions along the mentioned research projects in which this thesis has been framed. This permitted to have the stakeholders directly involved in the field-based data gathering, scenario selection and model validations which added a significant social component to the modeling exercise.

  A detailed economic model with relevant hydrological components was designed and applied to the Upper Guadiana Basin, and more specifically, to the Mancha Occidental aquifer, the most significant management unit of the Upper Guadiana Basin characterized in the present study by four representative farm types. The model, written in GAMS, can be considered a simplified holistic hydro-economic model as it includes economic and hydrological functions within a single process unit. It is a non-lineal static Mathematical Programming Model (MPM) of constrained optimization that tries to maximize the regional utility subjected to specific agronomic, environmental, and policy constraints. The model constraints can operate both at the regional scale (aquifer level) and at the local scale (farm level), providing a multi-scale modeling approach. Functions linking legal and illegal groundwater uses, groundwater levels and economic pumping costs, and groundwater exchanges were explicitly specified in the model.

  However, in spite of the hydrology-based economic model, it was felt along the research development that the hydrologic system in the Upper Guadiana had to be further specified. For this reason a modular hydro-economic modeling platform was constructed that coupled a farm-based economic model (MPM) with a GIS-based hydrology water management simulation model WEAP ('Water Evaluation and Planning' system) defined at the sub-basin's level (see Varela-Ortega et al., in press). This first modular model integration was used for analyzing the water and agricultural policy interactions in the Upper Guadiana basin and their joint impacts on the hydrology and socio-economic systems. Models were defined along a short and long time horizons (2006 and 2007-2027, respectively) consistent with the region's policy developments. This first model-coupling research initiative (not included explicitly in this Thesis, being the author of the present

Thesis a second author in the related publication, as shown in section 1.6) opened the pathways for the subsequent modeling excercises.

Following the research path into another area of the basin, the irrigation systems of the Middle Guadiana Basin, almost totally dependent on surface water, were modeled using a compartmental hydro-economic model. In this part of the basin, it was necessary to develop a more detailed physical model to capture the complex dynamic of surface water bodies. The GIS-based hydrology model WEAP (‘Water Evaluation and Planning’ system) was used to simulate the watershed hydrologic processes and represent the large-scale water-related infrastructure of the Middle Guadiana Basin. In total, 24 catchments were modeled, of which 13 were irrigated. The economic model, in essence similar to the model developed for the Upper Guadiana Basin, was applied to seven main Irrigation Communities of the Middle Guadiana Basin, each of them represented by one to up to three representative farm types. The economic model was linked to the WEAP model through a data management interface developed using Visual Basic for Applications and other complementary simulation engines.

All the models were duly calibrated and validated.

- **Phase 4: Identification of possible simulation scenarios.** The scenarios simulated in the present study stem mainly from public policies currently in force (water and agricultural policies) and from the stakeholders’ own opinions.

  In the Upper Guadiana Basin, current water policies were contrasted with other types of policy-relevant instruments derived from the literature and from the stakeholder discussions (mechanisms for legalized illegal abstractions, water pricing schemes, water quotas, and water right’s markets).

  In the Middle Guadiana, the development of a detailed hydrology model also permitted the simulation of climate-driven scenarios. In this area, the full implementation of current water policies and agricultural policies was evaluated under normal and dry climate conditions in the short and long term. The scenarios selected were relevant issues that had arisen during the stakeholder meetings and discussions.

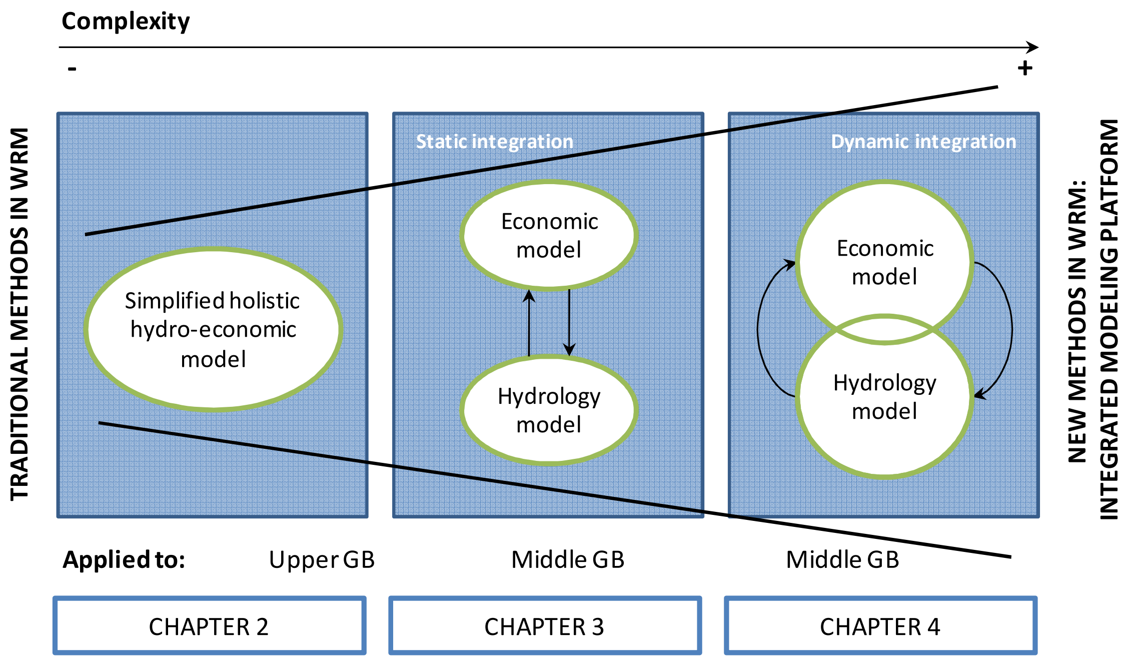
- **Phase 5: Assessment of simulation scenarios.** The developed models were used to assess the effects of the selected scenarios on the environmental and social systems of the Guadiana Basin. A set of significant indicators was selected to measure the impacts regarding farm income, public expenditure, crop distribution, water consumption, water supply, evapotranspiration requirements, crop irrigation requirements, runoff, flow regimes, etc. Additionally, in the case of the Upper Guadiana Basin, a cost-effectiveness analysis was carried out to identify the least costly option for achieving the goal of the Mancha Occidental aquifer's sustainability.

- **Phase 6: Conclusions.** Ultimately, the main findings of the study were summarized and the limitations of some aspects of the research work were discussed. Future lines of research for integrated water management were also suggested.

1.6. Structure of the Thesis

The uniqueness of this PhD thesis lies in the integrated methodological approach adopted to balance water for food production and water for nature protection in irrigated dependent semi-arid regions. Thus, the structure of the Thesis has been specifically designed to illustrate the progressive integration of the economic and hydrology models that highlights the value of the developed methodology. Each of the chapters of the present Thesis elaborates on a specific stage towards the development of an integrated tool for water resource management. Fig. 7 shows the connection between the applied methodology and the structure of the PhD thesis.

Fig. 7- Links between the applied methodology and the structure of the PhD thesis.



- **Chapter 1. General introduction.**

This section summarizes the context of the research and shows a glimpse of the issues to be address in the subsequent sections. It also includes a literature summary of the IWRM concept, tools for implementing IWRM, and main empirical experiences. It illustrates the main research questions, objectives of the thesis, characteristics of the case study, and proposed methods and tools.

- **Chapter 2. Cost-effectiveness of groundwater conservation measures: A multi-level analysis with policy implications.**

This section relates the development of a simplified holistic hydro-economic model (that is, a mathematical economic optimization model with hydrological-related parameters), and its application to the Upper Guadiana Basin (region characterized by the expansion of groundwater irrigation, the over-exploitation of the Mancha Occidental aquifer, and the degradation of the important wetlands in the National Park of ‘Tablas de Daimiel’) to study the effects of water conservation measures at the local scale (farm level) and at the regional scale (aquifer level). It analyzes the environmental and socio-economic impacts of alternative water conservation measures to help policy makers identify the least costly policy option for achieving the goal of the Mancha Occidental aquifer's sustainability, which corresponds to the good ecological status objective of the WFD in this area.

This chapter is based on:

- ✓ Blanco, I., Varela-Ortega, C., Flichman, G. Cost-effectiveness of groundwater conservation measures: A multi-level analysis with policy implications. Agricultural Water Management, in press (doi: 10.1016/j.agwat.2010.10.013).

And,

- ✓ Blanco, I., 2007. Analyse économique de politiques publiques pour la gestion durable des eaux souterraines: le cas de l'aquifère de la Mancha Occidentale (Bassin du Guadiana-Espagne). In: Master of Science Series, MSc Thesis No. 86, Montpellier, France, 155 pp. ISBN: 2-85352-369-1.

- ✓ Blanco, I., Varela-Ortega, C., 2008. Cost-effectiveness of groundwater conservation measures: A multi-level analysis with policy implications. Poster presented at the International Final NeWater Conference on Adaptive Integrated Water Resources Management under Uncertainty, Seville, Spain, November, 2008.

- ✓ Blanco, I., Varela-Ortega, C., Flichman, G., 2007. Cost-effectiveness of water policy options for sustainable groundwater management: a case study in Spain. Paper presented at the International Conference on Adaptive & Integrated Water Management: Coping with complexity and uncertainty (CAIWA), Basel, Switzerland, November 2007.

- ✓ Blanco, I., Varela-Ortega, C., Flichman, G., 2008. Cost-effectiveness of groundwater conservation measures: a multi-level analysis with policy implications. Poster presented at the XII Congress of the European Association of Agricultural Economist (EAAE) on People, Food and Environments: Global Trends and European Strategies, Ghent, Belgium, August 2008.

- ✓ Blanco, I., Varela-Ortega, C., Flichman, G., 2008. Groundwater development and wetlands preservation: assessing the impact of water conservation policies. Paper presented at the XXIII World Water Congress of the International Water Resources Association (IWRA) on Global changes and water resources: Confronting the expanding and diversifying pressures, Montpellier, France, September 2008.

- ✓ Llamas, M.R., Varela-Ortega, C., De La Hera, A., Aldaya, M.M., Villarroya, F., Martínez-Santos, P., Blanco-Gutiérrez, I., Carmona-García, G., Esteve-Bengoechea, P., De Stefano, L., Hernández Mora, N. Zorrilla, P., 2010. The Guadiana Basin. In: Mysiak, J., Henrikson, H.J., Sullivan, C., Bromley, J., Pahl-Wostl, C., (Eds.), The adaptive water resource management handbook. Earthscan, London, pp. 103-114. ISBN: 978-1-84407-792-2.

- ✓ Varela-Ortega, C., Blanco, I. Water conservation policies and stakeholder participation: coping with water scarcity? Ecological Economics, under revision (ref. No. ECOLEC-D-09-00213).

- ✓ Varela-Ortega, C., Blanco, I., 2008. Adaptive capacity and stakeholders' participation facing water policies and agricultural policies. Paper presented at the XII Congress of the European Association of Agricultural Economist (EAAE) on People, Food and Environments: Global Trends and European Strategies, Ghent, Belgium, August 2008.

- ✓ Varela-Ortega, C., Blanco, I., Esteve, P., 2008. The interaction of water policies and agricultural policies on land use and the rural economy: an integrated modeling framework. Paper presented at the International Conference on Impact Assessment of Land Use Changes. SENSOR, EFORWOOD, PLUREL, and SEAMLESS projects, Berlin, Germany, April 2008.

- **Chapter 3. Hydro-economic modeling for promoting integrated water resource management: understanding the interactions between water and the economy.**

As shown in Fig. 7, this section focuses on the development and specification of an economic model (MPM) and a hydrology model (WEAP), and explores methods for an effective integration of these two types of models. The integrated model was applied to the Middle Guadiana Basin, characterized by the expansion of surface water irrigation, a great number of reservoirs holding a large storage capacity, and deteriorated surface water bodies where the implementation of minimum environmental flows is required. It illustrates a 'trial-run' carried out to test the functionality of the models for a reference year (2007) and to explore the local and regional interdependences between socio-economic processes and natural systems, both at farm and sub-basin level.

This chapter is based on:

- ✓ Blanco, I., Varela-Ortega, C., Purkey, D. Hydro-economic modeling for promoting integrated water resource management: understanding the interactions between water and the economy. Environmental Modeling & Software, submitted.

And,

- ✓ Varela-Ortega, C., Blanco, I., 2008. Integrating stakeholder participation in agroeconomic and hydrology modeling for assessing nature conservation policies. Paper presented at the International Conference on Impact Assessment of Land Use Changes. SENSOR, EFORWOOD, PLUREL, and SEAMLESS projects, Berlin, Germany, April 2008.

- ✓ Varela-Ortega, C., Blanco, I., Swartz, C., Downing, T.E., 2009. Dealing with the tradeoff between water for nature and water for rural livelihoods under climate uncertainties: lessons for water management. Paper presented at the XXVII International Conference of Agricultural Economists (IAAE) on The New Landscape of Global Agriculture, Beijing, China, August 2009.

- ✓ Varela-Ortega, C., Blanco, I., Swartz, C., Downing, T.E. Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: a hydro-economic modeling framework. Global Environmental Change: human and policy dimensions, in press (accepted on July 2010, ref. No. GEC-D-08-00216R1).

- ✓ Varela-Ortega, C., Swartz, C., Downing, T.E., Blanco, I., 2008. Water policies and agricultural polices: an integration challenge for agricultural development and nature conservation. Paper presented at the XXIII World Water Congress on Global changes and water resources: Confronting the expanding and diversifying pressures, Montpellier, France, September 2008.

- **Chapter 4. A dynamic economic-hydrologic analysis of ecologically sustainable water policies under diverse climate conditions and plausible development scenarios.**

This section demonstrates the improved integration of the economic and hydrology models (here linked in space and time) and reveals the potential of the developed integrated methodology. The integrated modeling platform was also applied to the Middle Guadiana Basin. The research focuses, firstly, on a short-term analysis of the agricultural and water policies currently in force in some selected Irrigation Communities of the Middle Guadiana Basin. Secondly, in a mid-term perspective, this section analyzes the effects of future water conservation measures (a downward revision of surface irrigation water allotments and the implementation of environmental flow regimes) under different climate scenarios and development trends, along the time span set by the EU to accomplish the WFD's ecological objectives (2015).

This chapter is based on:

- ✓ Blanco, I., Varela-Ortega, C., Purkey, D. A dynamic economic-hydrologic analysis of ecologically sustainable water policies under diverse climate conditions and plausible development scenarios. Water Resources Research, submitted.

And,

- ✓ Krysanova, V., Dickens, C., Timmerman, J., Varela-Ortega, C., Schlüter, M., Roest, K., Huntjens, P., Jaspers, F., Buiteveld, H., Moreno, E., De Pedraza-Carrera, J., Slámová, R., Martinkova, M., Blanco, I., Esteve, P., Pringle, K., Pahl-Wostl, C., Kabat, P., 2010. Cross-Comparison of climate change adaptation strategies across large river basins in Europe, Africa and Asia. Water Resources Management 24, 4121-4160.

- ✓ Varela-Ortega, C., Blanco, I., Swartz, C., Downing, T.E., 2009. Dealing with the tradeoff between water for nature and water for rural livelihoods under climate uncertainties: lessons for water management. Paper presented at the XXVII International Conference of Agricultural Economists (IAAE) on The New Landscape of Global Agriculture, Beijing, China, August 2009.

- ✓ Varela-Ortega, C., Blanco, I., Swartz, C., Downing, T.E. Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: a hydro-economic modeling framework. Global Environmental Change: human and policy dimensions, in press (accepted on July 2010, ref. No. GEC-D-08-00216R1).

- **Chapter 5. Final conclusions.**

This section summarizes the main findings of the research, original contributions, and limitations of the study. Ultimately, it includes some recommendations and suggestions for further research.

- **Chapter 6. References.**

This section includes all the sources used in the development of the present doctoral Thesis.

- **Chapter 7. Annexes.**

This section comprises three thematic annexes:

Annex A: 'Data collection' refers to the data collected throughout the development of the present study. It includes an example of the survey questions addressed to farmers of the Upper Guadiana Basin during 2006 and 2007, and a data collection matrix where all the sources used in the development of the economic model and the hydrology model in the Middle Guadiana Basin are indicated.

Annex B: 'Methodology' elaborates on the methodology developed to integrate the economic and hydrology models. This annex is based on:

- ✓ Blanco, I. Exploring the interactions between the general algebraic modeling system (GAMS) and the Water Evaluation And Planning system (WEAP). SEI Working paper, Davis, USA, under revision.

Annex C: 'Results' show some of the results obtained from the application of the models in the Upper and Middle Guadiana Basin, but not included in the chapters of the Thesis.

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2. Cost-effectiveness of groundwater conservation measures: A multi-level analysis with policy implications

2.1. Abstract

Groundwater in Spain, as in other arid and semiarid countries worldwide, has been widely used in the expansion of irrigated agriculture. In the Spanish Mancha Occidental aquifer, the excessive, and sometimes illegal, water abstraction for irrigation has promoted outstanding socioeconomic development in the area, but it has also resulted in exploitation of the aquifer and degradation of valuable wetlands. Water policies implemented in the region have not yet managed to restore the aquifer and face strong social opposition. This paper uses a multi-scale modeling approach to explore the environmental and socio-economic impacts of alternative water conservation measures at the farm and basin levels. It also analyzes their comparative cost-effectiveness to help policy makers identify the least costly policy option for achieving the goal of the Mancha Occidental aquifer's sustainability. To conduct this analysis, a Mathematical Programming Model has been developed to simulate: the closing-up and taxed-legalization of unlicensed wells, uniform volumetric and block-rate water prices, water quotas, and water markets. Aggregate results show that net social costs are not substantially different across policy option, so none of the considered policy options will be clearly more cost-effective than the others. However, there are significant differences between private and public costs (at the farm and sub-basin levels), which will be critical for determining the application in practice of these policies. Results show that controlling illegal water mining (through the legalization of unlicensed wells) is necessary, but is not sufficient to recover the aquifer. Rather, effective water management in this area will require the implementation of other water management policies as well. Among them, uniform volumetric and block-rate water pricing policies will entail the lowest net social cost, but will produce important income losses in the smallest and most water-intensive farms, which might put at risk the viability of these farms and the social acceptance of the policies. Further investigations on social costs,

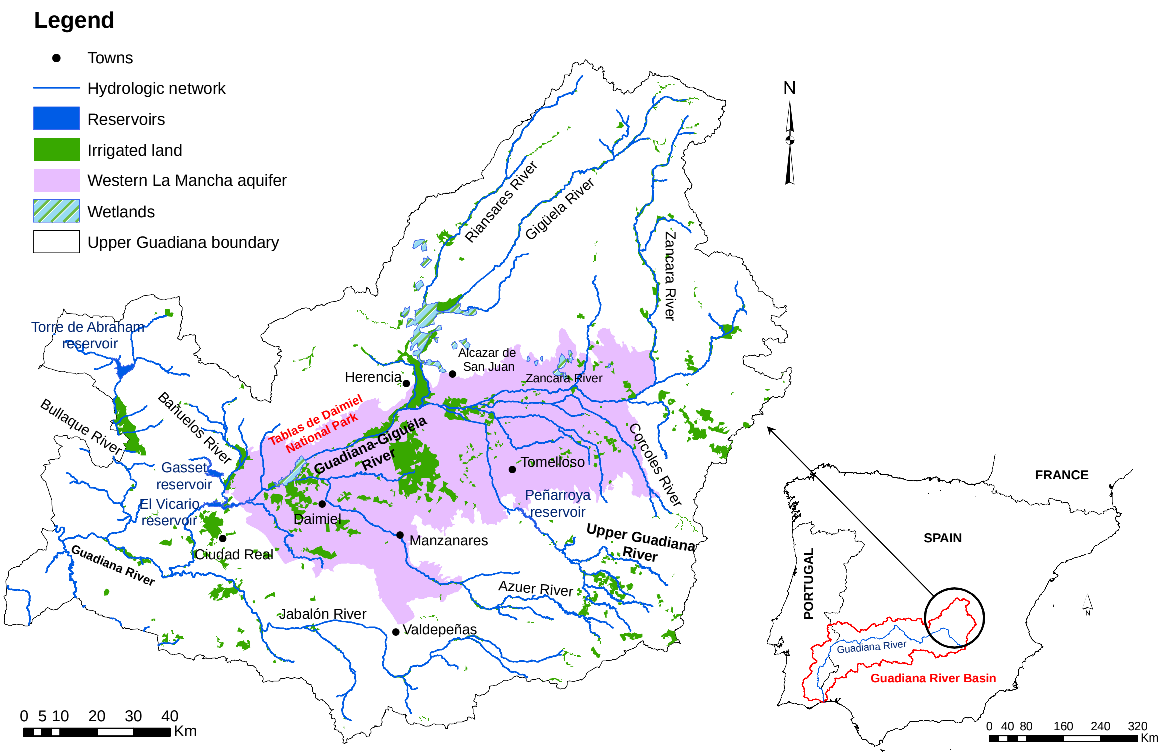
policy enforcement capacity and public participation in water management are highly recommended.

Keywords: Groundwater resources; Irrigation; Wetlands conservation; Multi-scale economic modeling; Water policies; Cost-effectiveness analysis.

2.2. The problem: groundwater development and wetlands preservation

Groundwater in Spain, as in other arid or semiarid countries worldwide, has been widely used in the expansion of irrigated agriculture (Giordano and Villholth, 2007; Llamas and Martínez-Santos, 2005; Shah et al., 2007). This phenomenon has helped to stimulate the socioeconomic development in rural communities (Foster and Chilton, 2003; Varela-Ortega, 2007). However, in many cases, the largely uncontrolled agricultural groundwater use has produced far-reaching environmental and social problems (water table depletion, groundwater quality degradation, destruction of associated water ecosystem, proliferation of free-riding behaviors) (Schuyt, 2005). This is a clear fact in several Spanish aquifers, in which groundwater is the primary water source for all uses (Garrido et al., 2006), but it is especially remarkable in the Mancha Occidental aquifer, a large, over-drafted aquifer extending over 5000 km^2 situated in the inland central region of Castilla-La Mancha in the Upper Guadiana river basin (see Fig. 8). The area presents a continental semiarid climate, with an average annual rainfall of 415 mm, an average annual temperature of 15ºC, and potential evapotranspiration rates on the order of 1000 mm/year.

Fig. 8- Geographical setting of the Upper Guadiana basin.



Source: Varela-Ortega et al. (in press)

As a consequence of the legal declaration of overexploitation of the Mancha Occidental Aquifer in 1987, water authorities pursued the constitution of groundwater user associations and the Water Abstraction Plans (WAP). Typically, these were imposed using a top-down approach. The WAP forbade drilling new wells or deepening the existing ones, and limited annual water abstractions by means of a quota system based on farm size, with no compensation (see Table 4).

Table 4- Water Abstraction Plan (2007).

Farm size (ha)	Water quotas (m^3/ha)
0-30	2640
30-80	2000
> 80	1200
vineyard	1000

Source: (CHG, 2006)

This program was implemented without the agreement of the farmers, who are the main water users, and has faced strong social opposition ever since (Schlager and López-Gunn, 2006; Varela-Ortega and Blanco, 2008). The nearly non-existent institutional arrangements between the regional government, water authorities and water users themselves, and the high enforcement cost of controlling water abstractions for agricultural irrigation have led to the continued exploitation of the aquifer, proliferation of numerous unlicensed wells, and generation of environmental externalities derived from degradation of the valuable wetlands ecosystems associated with the aquifer in 'Tablas de Daimiel' National Park (Martínez-Santos et al., 2008). Official sources estimate that presently, nearly 50% of the wells in the Mancha Occidental aquifer are unlicensed (approximately 20000 wells) and total water abstractions greatly exceed the Natural Recharge Rate (NRR) of the aquifer, estimated to be around 230-240 Mm^3/year (CHG, 2007). The intensive pumping for irrigated agriculture caused noteworthy water table drawdowns (of about 1m/year), resulting in a reduction of the flooded wetland area from 1800 ha to 200 ha over the past 30 years.

This situation is not sustainable and contradicts the European Water Framework Directive (WFD) (EC, 2000), which proclaims the protection of water resources and aims at achieving 'good ecological status' for all water bodies by 2015. The Directive requires the elaboration, including public consultation, of a basin management plan and a program measures for each River Basin district by the end of 2009. Thereafter, they will be updated every six years (articles 11, 13, and 14). A program of measures must include the implementation of water-pricing policies by 2010 to provide adequate incentives to use water more efficiently and contribute to the recovery of the cost of all water services, including environmental and resources costs (article 9). Moreover, the WFD suggests that a cost-effectiveness analysis (CEA) should be performed in order to achieve the Directive's goals at lowest cost (Annex III, WATECO, 2002). This analysis is key when selecting alternative measures and identifying excessive costs that could justify lower objectives as well as the postponement of the fulfillment of the Directive's objectives (article 4 of the WFD). Nevertheless, the Directive hardly describes how to proceed with the CEA and only a few Northern European countries have developed consistent evaluation methods so far. Most of the reviewed cost-effectiveness methods have a strong focus on water quality issues and consider the river basin scale as an indivisible and unique unit for analysis (see for instance, Interwies et al., 2004, for the Germany context, and Postle et al., 2004, for the UK context).

The WFD principles and instruments have already been partially contemplated in the Special Plan for the Upper Guadiana (SPUG), recently approved by the Spanish parliament (CHG, 2007), and they will be reflected in the new Guadiana river basin water management plan by 2010. The SPUG aims at establishing sustainable water use in the Upper Guadiana Basin by 2027, strengthens the participation of the stakeholders in water management and introduces innovative conservation measures for recovering the Mancha Occidental aquifer. These measures include campaigns for purchasing irrigation water rights (although some of the recovered water volume will be subsequently returned to irrigators for legalizing some un-licensed wells); strict regulations to control groundwater overdrafts and close up unlicensed wells; a reforestation plan; and complementary measures for promoting rainfed agriculture and the cultivation of less water-intensive crops in the area (CHG, 2007).

In conclusion, the revision of the current water policies and application of new cost-effective and environmentally sensitive policy instruments which guarantee efficient public participation in water management processes is one of the major tasks that must be addressed by water managers and policy makers in Spain, and especially in the Upper Guadiana Basin. This paper contributes to this debate, evaluating the cost-effectiveness of alternative water conservation policies that may reduce water consumption in the Mancha Occidental aquifer and, ultimately, promote sustainable groundwater management in the Upper Guadiana basin.

In section 2.3, we revise numerous studies that have investigated alternative groundwater management instruments, their advantages and disadvantages. However, little attention has been focused on the comparative assessment of the cost and effectiveness of different instruments, and rarely has this analysis been made on water quantity issues at different spatial scales. One of the key aspects of our methodology is the development of a reproducible multi-scale economic optimization model able to assess environmental and socio-economic policy impacts at different spatial scales (at farm and sub-basin level).

2.3. Theoretical background: policy instruments for groundwater management

Groundwater is considered a ‘common pool resource’ (rival and non-excludable good) and its overexploitation is often explained by the model of the Tragedy of the Commons set forth by

Garret Hardin (Hardin, 1968). Following his model, individual users tend to maximize their water consumption, ignoring the impact of their extractions on future water levels. The incentive for any individual is to free-ride on the benefits from conservative behavior by the others (Olson, 1965). Consequently, the extraction rate reached is higher than the optimum social rate, resulting in collective inefficiencies and groundwater overexploitation (Feinerman, 1988; Gordon, 1954). In most cases, this disparity is due to lack of regulation or insufficient dynamism of the existing institutional arrangements (Millimam, 1956; Schlager and López-Gunn, 2006).

Numerous studies have investigated the use of policy instruments to regulate groundwater withdrawals and promote more efficient groundwater use. Since agriculture constitutes the main use of water in arid and semi-arid countries, most of these studies focus on the potential of water conservation instruments in irrigation water management. Water use quota systems are likely the most widely employed regulatory instruments in controlling groundwater pumping and water consumption for irrigation (Koundouri, 2004). These mechanisms allow equity issues to be taken into consideration and promote transparent reallocation of water (Johansson et al., 2002; Wichelns, 1999). Nevertheless, some authors (such as Dinar et al., 1997; Molle, 2009; Rogers et al., 2002; among others) cast doubts on the establishment of quota allotments or water use rights as being too inflexible to adapt to changing conditions. They furthermore warn of the high costs of monitoring processes and measurement controls which would be incurred if water quotas are not socially accepted following a bottom-up design approach.

Administered pricing policies are also policy instruments commonly analyzed in the literature for their water-saving potential and their reputation as appropriate cost-recovery mechanisms (Bazzani et al., 2005; Gómez-Limón and Riesgo, 2004; Molle and Berkoff, 2007; Tsur et al., 2004; Varela-Ortega et al., 1998; among others). Rogers et al. (2002) argue that, when water scarcity becomes a leading issue, pricing policies may increase efficiency in water management as well as improve water reallocation, equity and sustainability. However, in spite of their popularity, their application remains controversial, especially in developing countries. Many studies (see e.g. Cornish et al., 2004; De Fraiture and Perry, 2007; Molle et al., 2008) indicate that substantial price increases are required to induce water saving, which might increase farmers' financial vulnerability and endanger the social acceptability and political feasibility of water pricing policies. Thus, Chohin-Kuper et al. (2003) and Molle (2009) state that centralized water prices are actually more often used to recover water costs than to reduce water consumption, even when water scarcity is high.

The last two decades witnessed the resurgence of decentralized water management schemes to improve water efficiency and confront increasing conflicts among water users (Dinar and Subramanian, 1997; Johansson et al., 2002; Zekri and Easter, 2005). Easter et al. (1998) discuss the potential of water markets in a wide variety of contexts and argue that, when transaction costs are low, these instruments may provide better water allocation efficiency and higher economic benefits than other regulatory approaches. Nevertheless, there are numerous conditions necessary to hold down transaction costs, and several studies show that in real-world contexts the apparent superiority of water markets is limited (see Garrido and Calatrava, 2010; Johansson et al., 2002; Kemper, 2001; Koundouri, 2004; Rosegrant and Schleyer, 1996; among others).

Feinerman (1988) claims that in terms of water use efficiency no single groundwater management tool is clearly superior to another. Feinerman's study also states that equity aspects (i.e. wealth distribution among individual users) are as important as efficiency issues. Past experiences show that the most efficient tool, in economic terms, may not be the most suitable solution. Dinar et al. (1997) conclude that no single economic instrument can work in all situations.

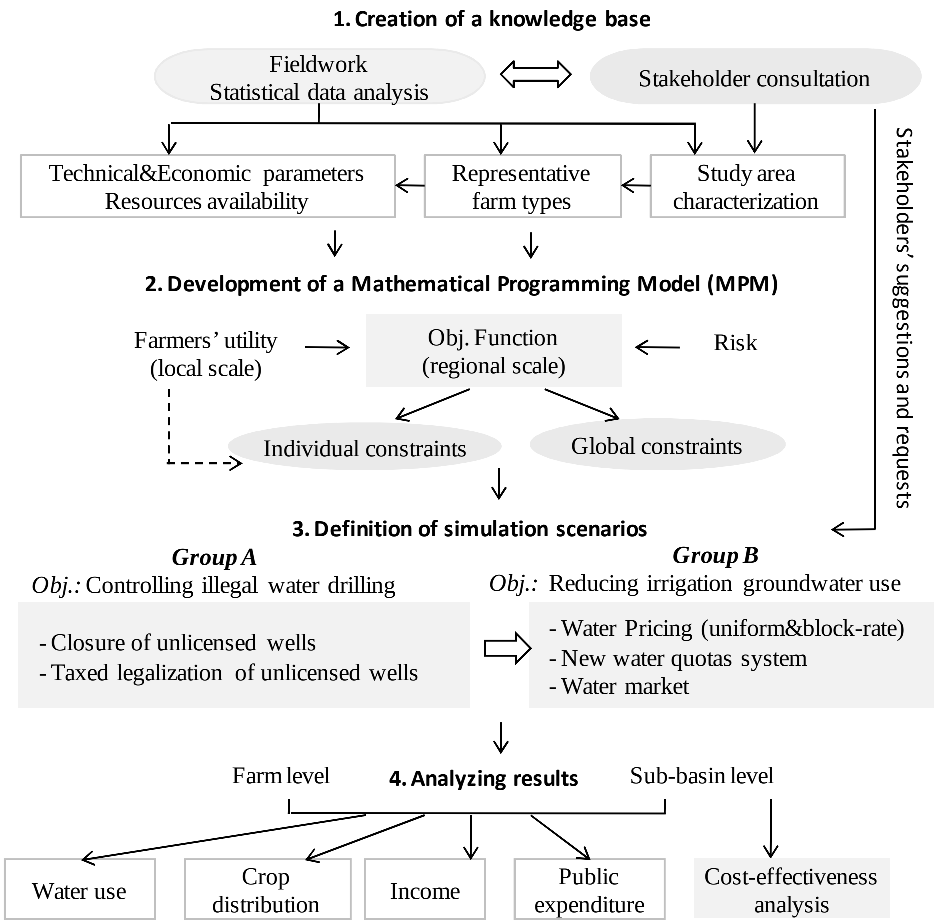
There are still many uncertainties about the potential of water quotas, water pricing and water markets for groundwater demand management. The existing studies about the use of economic instruments in irrigation water management are limited to specific local conditions, both physically and institutionally (Bjornlund et al., 2007). Therefore, more investigations are needed to provide new insights and transferable empirical experiences.

2.4. Analytical framework

2.4.1. Methodological overview

The methodology adopted for this research is represented schematically in Fig. 9. A detailed step-by-step description of the analytical procedures is presented after this figure.

Fig. 9- Methodological overview.



- Step 1: Creation of a knowledge base. This step comprises the site-specific characterization of the study area, selection of the representative farms and estimation of the MPM model's input coefficients and parameters. It is based on fieldwork, statistical data collection, and stakeholder consultation.

- Step 2: Development of a non-linear Mathematical Programming Model (MPM) of constrained optimization to simulate farmers' behavior under different policy scenarios and risk situations.

- Step 3: Definition of simulation scenarios, based on literature review and stakeholders' suggestions. They include policies devised to control illegal water drilling in the aquifer of study (Group A), and water management policies designed to reduce groundwater consumption for irrigation (Group B).

- Step 4: Results and cost-effectiveness analysis. A set of multi-level indicators was used to represent the economic, social and environmental performances of the Mancha Occidental's agricultural systems at the farm level and sub-basin levels (Upper Guadiana basin).

2.4.2. Creation of a knowledge base

Farms are considered the basic unit of analysis in agriculture. However, modeling agricultural systems confronted with environmental issues usually requires integrating farm-scales with regional-scales. In this research, the zone of study has been characterized using typologies of farms aggregated at regional scale. Typologies have been widely used for representing the complexity of farmers' systems in different Spanish irrigation communities (Arriaza et al., 2002; Bjornlund et al., 2007; Gómez-Limón and Riesgo, 2004; Iglesias and Blanco 2008; Varela-Ortega et al., 1998). Maton et al. (2005) and Poussin et al. (2008) review different methods to build typologies. Based on their findings, the 'positivist method' was selected and applied to this study. First, a statistical analysis of official data was performed to study the characteristics of the regional agricultural production in the area overlying the Mancha Occidental aquifer and to determine the structural characteristics of the representative farm types. This information was collected from regional and national Government sources as well as from the Guadiana River Basin publications. Subsequently, farm typologies were completed by targeted fieldwork surveys (30 in total) and personal interviews with the stakeholders (mainly local experts and irrigation communities). Finally, farm typologies were clustered according to structural criteria in order to obtain homogeneous groups with similar production systems.

As shown in Table 5 below, the study region (the Mancha Occidental aquifer) has been identified as a weighted (by surface) sum of four representative farm types (F1, F2, F3 and F4). Each 'farm type' is considered an aggregation of homogeneous types of agricultural production systems in terms of growing surface, type of wells, water use, soil quality, and crop distribution.

Table 5- Representative farm types in the Mancha Occidental aquifer.

Characteristics	Representative farms				Aquifer
	F1	**F2**	**F3**	**F4**	
Total growing surface (ha)	56667	55254	38838	76741	227500
Average farm size	10 (very small)	35 (medium)	75 (big)	265 (very big)	23
Irrigated surface (%)	100	100	80	50	80
Water use (m^3/ha)					
Water quotas [(a)]	2220	1500	1600	1000	1527
Actual water consumption[(b)]	3390	1906	2371	2371	2514
Number of wells[(c)]	12401	18266	3824	4723	39214
Licensed/Unlicensed (%)	61/39	13/87	100/0	100/0	40/60
Irrigated hectares per well	4	3	8	8	5
Soil type (Bad/Good soil)	39/61	20/80	58/42	80/20	51/49
Crop distribution (%)					
Cereals (barley, wheat)	30.0	18.0	45	63.7	41.0
Maize	0.0	0.0	2.0	0.3	0.4
Vegetables	30.0	5.0	14.0	10.0	14.5
Vineyard	30.0	75.0	28.0	10.0	33.8
Set-aside	10.0	2.0	11.0	16.0	10.3
Total area (%)	100	100	100	100	100
Surface weight (%)	25	24	17	34	100

([a]) Water quotas established by the WAP (CHG, 2006)
[(b)] Actual water consumption is calculated based on the prevailing crop distribution and corresponding crop water requirements.
[(c)] This is an estimate of the total number of wells. The number of wells actually in use is known (around 8,000).
Source: Own elaboration based on official statistics (CHG, 2007; IES, 2006) and farmers' surveys (2005&2006)

The Mancha Occidental aquifer covers about 400000 cultivated ha. Irrigated surface spans an area of 182000 ha (46% of the total cultivated area), from which almost 60000 are allegedly being irrigated form unlicensed wells. The farm types F1 and F2 represent fully irrigated agricultural systems in which licensed and unlicensed wells coexist and water consumption rates exceed the water abstraction quotas imposed by the Guadiana River Basin Authority. These production systems are concentrated in small-medium holdings with good soil qualities and high value-added crops, such us vegetables and irrigated vineyards which, being difficult to map using satellite imagery, are often illegally irrigated. On the other hand, the average size of farms F3 and F4 is larger. These farms have more diversified crops (barley, wheat, maize, vegetables and vineyards) than the farm F2, and combine rainfed and irrigated agricultural productions in different soil qualities. Only licensed wells are used to pump water for irrigation, though they also use more water than that allowed by the WAP. As we are considering the cost of compliance with the WFD, which includes the environmental costs related to the aquifer's degradation, we have not selected any completely 'legal' representative farm (that is, a farm that complies with the WAP and has no unlicensed wells), although they also exist in the region.

2.4.3. Development of a Mathematical Programming Model

The model used to perform this analysis is a non-linear single-year static MPM of constraint optimization defined at regional scale (sub-basin aggregation). It complements previous modeling work developed by Iglesias (2002), Varela-Ortega et al. (1998), and Varela-Ortega (2007) at plot scale in the same area of study.

According to the expected utility theory of Von Neuman and Morgenstern (1944), farmers are considered rational and self-interested individuals with well ordered preferences that try to maximize their utility choosing among alternative farm plans. In the present study, the model maximizes a utility function subject to land, labor, water, and policy constraints. The utility function is defined by a profit function and a risk vector that takes into account climate as well as market prices variations (see Appendix for detailed specifications). Several studies (such as Ellis, 1993; Huirne, 2000; Hardake, 2004) provide empirical evidence that risk and uncertainty situations generate income instability, affecting farmer decision-making. In that regard, Friedman and Savage (1948) demonstrate that farmers are usually 'risk averse' (do not wish to take risks) and, therefore, they tend to choose less-risky alternatives even if that requires renouncing part of their potential income.

In particular, the economic model developed to undertake this analysis optimize the regional expected utility, as an aggregation of the expected utilities of the four farm types, while keeping the specificity of individual constraints. This twofold characteristic of the model facilitates the mobility of water resources among the different farm types, permits the up-scaling of farm-based results at the sub-basin aquifer level, and allows analyzing the complex social, physical and economic interactions between legal and illegal groundwater uses in a more integrated way. Similar multi-scale programming models have been recently developed by Alary and Deybe (2005), Flichman et al. (2006), Henseler et al. (2009), Medellín-Azuara et al. (in press), Rounsevell et al. (2003), for integrated regional analysis. These studies indicate that different farms can be aggregated at regional level and represented by a unique MPM under conditions of homogeneity. Day (1963) and Buckwell and Hazell (1972) demonstrate that technologically homogeneous and pecuniously and institutionally proportional farms (i.e., farms with the same possibilities of production, agroclimatic conditions, levels of technology, availability of resources, management capacity, etc.) can be grouped together with relatively small problems of aggregation bias. In addition, Gómez-Limón and Riesgo (2004), indicate that, when decisions are based on the same decision-making criteria (in our case, the utility's maximization), farm types can be modeled by means of a unique MPM.

The model was calibrated with the risk-aversion coefficient[2] and validated using the Percentage Absolute Deviation[3] (PAD) parameter to verify the actual crop distribution (main decision-making variable in the model) in each farm type. PAD values ranged from 3.5% in farm F2 to 16% in farm F4, which are below the threshold value of 20% that determines the rejection of a model (Hazell and Norton, 1986, pp.271).

2.4.4. Simulation scenarios

Tuinhof et al. (2003) and Foster and Chilton (2003) identified different hydraulic stress stages of groundwater resource development analyzing the impacts of abstraction rates and proliferation of wells over time. The critical situation of the Mancha Occidental aquifer could be associated with a stage of 'unstable groundwater development' in which inaction might lead to an irreversible degradation of the aquifer and severe social conflicts among stakeholders. To avoid this undesirable outcome, the combination of an adequate regulatory framework with water demand management policies has been highly recommended by water experts (e.g. Dinar et al., 1997; Kemper, 2007; Tuinhof et al., 2003). Following these recommendations, different policy options were combined to, first, control illegal water consumption (as a base of an appropriate regulatory framework) (group of policy scenarios A),

[2] The risk aversion parameter selected was 1.65. It indicates that the probability to have an income higher or equal to Z is 95% with an error of the hypotheses test lower to 5%.

[3] $PAD(\%) = \sum_{c-n}^{n} \left| \overline{X_c} - X_c \right| \cdot 100 / \sum_{c-n}^{n} \overline{X_c}$; $\overline{X_c}$: observed surface; X_c: simulated surface.

and second, reduce groundwater demand for irrigation to comply with the WFD's environmental objectives (group of policy scenarios B)[4]. Table 6 briefly summarizes the simulated policy scenarios.

Table 6- Simulated policy scenarios.

Group of scenarios	**Objective**	**Simulated policy scenarios** — Policy options for managing… Unlicensed water use[a]	**Simulated policy scenarios** — Policy options for managing… Licensed water use[a]	**Description of simulated policy scenarios**
A	**Regulatory objective:** Controlling illegal groundwater consumption[b]	Closure of unlicensed wells	Prevailing water quota system (WAP)	Fierce control of groundwater over-drafts: - licensed extractions respect the WAP - all unlicensed wells are closed-up
		Taxed legalization of unlicensed wells		Moderate control of groundwater over-drafts: - licensed extractions respect the WAP - unlicensed wells are legalized by paying an entry right fee of 6000 € per irrigated hectare[c].
B	**Environmental objective:** Reducing irrigation groundwater consumption to assure the aquifer's recharge	Taxed legalization of unlicensed wells	Uniform water pricing	Gradual increase of 0.02 €/m^3 in water price for forty price levels (P1, …P40)
			Block-rate water pricing	Set of prices (t-t'' €/m^3) and quantities delivered (% of water allotment right): (i) t=0.07 €/m^3, 0-33%; (ii) t'=0.014 €/m^3, 33-66% (t'>t); (iii) t''=0.021 €/m^3, 66-100% (t''>t')
			New water quota system	Non-tradable groundwater extraction rights (equally distributed per hectare of irrigated surface). Total water abstractions are limited to the NRR of the aquifer.
			Water rights market	Previous administered water use rights are exchanged. The market equilibrium price is set using the dual values of the preceding simulation results (new water quota system scenario). Transaction costs of 5% are considered.

[a] From now on, 'unlicensed water use' refers to the water extracted from unlicensed wells and 'licensed water use' refers to the water extracted from licensed wells
[b] 'Illegal groundwater consumption' comprises the water pumped from unlicensed wells and the water consumed over the quotas established by the WAP.
[c] This policy option is contemplated in the recently approved SPUG (CHG, 2007).

[4] All wells are equipped with groundwater metering devices. Although some of them have been broken or altered in the past intentionally, water authorities are currently revising the good functioning of these instruments, as established by the SPUG. We assume that water consumption can be fully metered.

To accomplish the first objective, the authors evaluate alternative policy options for eliminating 'unlicensed water use' (primary cause of 'illegal groundwater consumption') under the assumption that the current WAP is still in place. To reach the second objective, the cost and effectiveness of alternative water demand management policies are analyzed, assuming that all unlicensed wells have been previously legalized.

The different policy and management options were selected based on a review of the literature (see section 2.3) and stakeholders' requests. Several stakeholder meetings were held as part of a participatory process conducted from 2005 to 2008 within the framework of the NeWater project[5]. In particular, three stakeholder meetings, thematically oriented around economic, hydrological and institutional aspects of irrigation groundwater management, served as basis for scenario building[6]. Each meeting was attended by roughly 25 stakeholders from different groups: farmers, irrigation communities, environmental conservation groups, regional departments (of environment and agriculture), Guadiana basin authority, etc.

Throughout the consultation process, stakeholders were encouraged to suggest, explicitly for the study area, alternative water management policies which might potentially reach the goal of aquifer sustainability. Stakeholders' suggestions basically stressed the reform of the on-going water policies and the implementation of new water management options (Varela-Ortega, in review). The current WAP is highly criticized by farmers for restricting their historical water rights (4280 m^3/ha) and establishing differentiated water quotas according to the cropping distribution and farms' surface, which created unpleasant frictions between small and large landowners-irrigators. Thus, stakeholders were very interested in exploring the cost and effectiveness of a more equitable water quota system and new decentralized water policies, such as the establishment of water pricing schemes or a water rights market. It is worth mentioning that discrepancies arose among stakeholders when discussing the best option for eliminating unlicensed groundwater use (Martínez-Santos et al., 2010). While the

[5] NeWater (New Approaches to Adaptive Water Management under Uncertainty) is a four-year (2005-2009) Integrated Project funded by the European Union's 6th Framework Research Program (nº: FP6-2003-GLOBAL-2-SUSTDEV-6.3.2 – 511179-2) (www.newater.info)

[6] Detailed information about the development and main results of the stakeholder consultation process are provided by Martínez-Santos et al., 2008; Martínez-Santos et al. 2010; Varela-Ortega, under revision; and Zorrilla et al., 2010.

environmental conservation groups request a strict application of the law and ask for fining of illegal pumpers as well as closing up all unlicensed wells, the irrigators suggested a 'second chance' and advocate for finding an agreement with the government that will allow them to register their unlicensed wells. In between these disparate view points, the Guadiana water authority, which is the agency responsible for water management in the basin, is urged to enforce the law and close-up unlicensed wells, but has no means by which to do so and prefers to avoid such an unpopular and costly task.

2.5. Simulation results

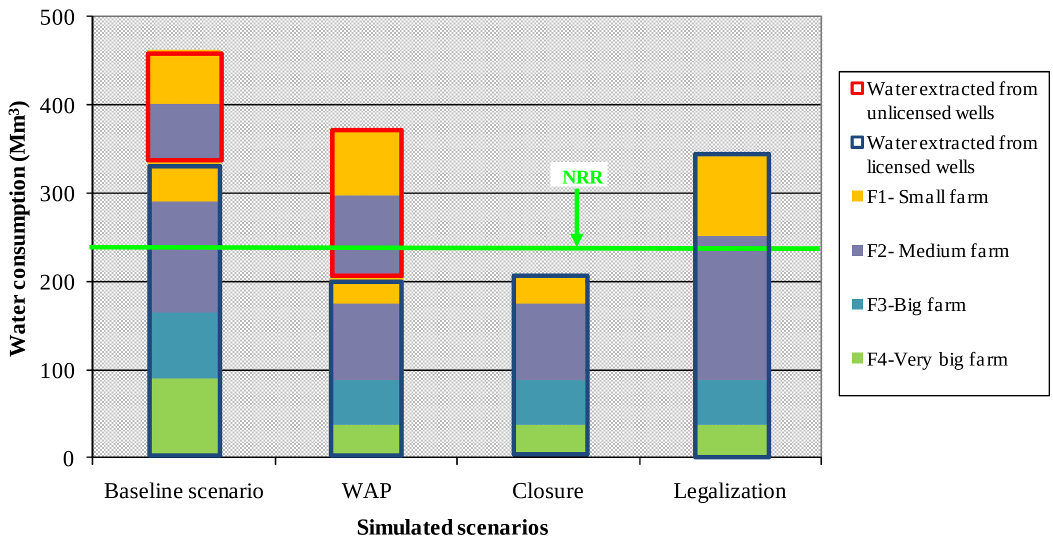
2.5.1. The open access problem: strengthening of groundwater regulatory framework

The baseline scenario[7] represents the current situation of the Mancha Occidental aquifer, in which total groundwater abstractions (460 Mm^3) largely exceeds the NRR of the aquifer (240 Mm^3). Irrigators do not comply with the existing water quota regime (WAP)[8] imposed by the Guadiana River Basin Authority to recover the exhausted aquifer (335 Mm^3 of water for agriculture is extracted from licensed wells), neither respect the prohibition to extract water from unlicensed wells (approximately, 127 Mm^3 of water is illicitly extracted). Fig. 10 shows the impact on total groundwater consumption of the application of different policy options for eliminating groundwater overdrafts in the Mancha Occidental aquifer.

[7] The prevailing situation of the Mancha Occidental aquifer in 2007 is considered the baseline scenario or reference situation.

[8] The WAP establishes a maximum water volume of 200 million m^3 to be yearly diverted to the agricultural sector (CHG, 2006). The structure of the WAP water quotas is shown in Table 1.Table 2 includes the WAP water quotas by representative farm.

Fig. 10- Water consumption for irrigation in the Mancha Occidental Aquifer under different policy scenarios for eliminating groundwater overdraft.



The simulation results indicate that any attempt to restrain ‘licensed water abstractions’ (water extracted from licensed wells), e.g. through a strict enforcement of the current WAP, would be ineffective unless ‘unlicensed water abstractions’ (water extracted from unlicensed wells) are previously controlled. As evidenced in Fig. 10 (WAP scenario), farms in which legal and illegal wells coexist (such as, the small and medium farms F1 and F2) would try to intensify their water abstractions from unlicensed wells to compensate their losses for complying with the WAP. Consequently, total water consumption in the aquifer would be only slightly reduced (from 460 Mm^3 to 370 Mm^3). Experiences from the past suggest that this situation might provoke a heavy clash between ‘legal’ and ‘illegal’ irrigators, increasing the already existing social tensions and free-riding behaviors in the region (Martínez-Santos et al., 2008; Varela-Ortega, 2007). Thus, overcoming groundwater overdrafting would require an effective combination of measures addressed to control water consumption and halting illegal drilling at the same time. Table 7 shows the model results of the WAP scenario and the application of alternative policy options (closure and legalization of unlicensed wells) for controlling ‘unlicensed water abstractions’, assuming that all irrigators comply with the current WAP. Disaggregated results on water consumption farm income, public revenue collection and expenditure, and crop distribution are displayed in Table 7. In the present study, the net public expenditure is calculated as the gross public expenditure minus the public collection. Public collection refers to water fees and charges collected by the water authority (basically, water use tariffs, taxes per well and taxes paid for registering the unlicensed wells), whereas the gross public expenditure comprises the CAP subsidy payments for crops and land paid by the government and will mainly depend on the cropping distribution of the farms.

Table 7- Effects of different policy options for eliminating groundwater overdrafts in the Mancha Occidental aquifer.

POLICY SCENARIOS	POLICY INDICATORS							
	Water use (m^3/ha)	Farm income (€/ha)	Public collection (€/ha)	Public expenditure (€/ha)	Crop distribution (%)			
					Rainfed	Viney.	Cereals	Veg.
Baseline scenario								
F1- Small farm	3390	1063	3.1	117	5	30	34	31
F2- Medium farm	1906	604	1.6	56	3	75	17	5
F3- Big farm	2371	534	3.6	153	20	28	38	14
F4- Very big farm	2372	391	2.4	185	50	10	30	10
WAP scenario								
F1- Small farm	3195	1053	3.1	113	18	30	21	31
F2- Medium farm	1828	597	1.6	55	7	75	13	5
F3- Big farm	1600	517	3.6	142	58	28	0	14
F4- Very big farm	1000	337	2.4	179	84	10	0	6
Closure of unlicensed wells								
F1- Small farm	1539	811	3.1	109	55	22	0	23
F2- Medium farm	525	23	1.6	51	77	20	0	3
F3- Big farm	1600	517	3.6	142	58	28	0	14
F4- Very big farm	1000	337	2.4	179	84	10	0	6
Taxed leg. of unlicensed wells								
F1- Small farm	2878	920	133	106	39	30	0	31
F2- Medium farm	1633	285	312	51	20	75	0	5
F3- Big farm	1600	517	3.6	142	58	28	0	14
F4- Very big farm	1000	337	2.4	179	84	10	0	6

Percentage of surface occupied by rainfed crops in a representative farm, by policy scenario
Percentage of surface occupied by irrigated vineyard in a representative farm, by policy scenario
Percentage of surface occupied by irrigated cereals in a representative farm, by policy scenario
Percentage of surface occupied by vegetables in a representative farm, by policy scenario

Closing up unlicensed wells would, in fact, reduce irrigation groundwater consumption to a volume compatible with the sustainable management of the aquifer (approximately 200 Mm^3) (see Fig. 10). However, the enforcement of such policy seems problematic due on one hand, to the high income losses inflicted upon some farmers and to the other hand, to the large transaction costs in which public authorities would incur to close the large number of unlicensed wells, as demonstrated by past experiences. As we can see in Table 7, the medium farm F2 would see its income gains reduced by 96% (from 604 to 23 €/ha), as a consequence of a major shift from irrigated to rainfed agriculture with less economic profitability (74% of the total irrigated surface, mainly vineyard, would be transformed into rainfed cropland). Two main reasons can explain this switch in land use: first, obviously, is the strong reduction in water consumption (from 1906 to 525 m^3/ha, see Table 7) caused by the closure of wells (almost 60% of the water used by the farm F2 is pumped from unlicensed wells); and second is the low crop diversification potential of the farm in question. Irrigated vineyard spans over 75% of the farm's growing surface, limiting the possibility of adjusting the cropping pattern within the farm to reduce water consumption in the short-term. In that regard, Martinez-Santos et al. (2008) indicate that there are not many other lucrative and water-efficient crops to be used as alternatives to irrigated vineyards in the area.

On the other hand, Table 7 shows that the legalization of unlicensed wells would entail milder income losses to farms F1 and F2 (15% and 47%, respectively) and would preserve irrigated vineyards and vegetables. From the public point of view, the model results indicate that public expenditure is almost equivalent in all simulated scenarios. However, public collection would greatly increase in the legalization scenario (from 2.5 to 110 €/ha on average) because of the taxes collected by the water authority for registering unlicensed wells (see Table 6), offsetting gross public expenditure in farms F1 and F2. Notwithstanding the positive aspects of the legalization of unlicensed wells in comparison to the closing up scenario, this policy option would trim down groundwater use for irrigation to 340 Mm^3, but would not guarantee the sustainability of the Mancha Occidental aquifer (see Fig. 10). For accomplishing the environmental objective the prevailing WAP, which constrained only the 'licensed groundwater use', should now be transformed in such a way that the water quotas also include the water extracted from the new legalized wells. In the next sub-section 2.5.2., a new water quota system is analyzed, as well as other alternative groundwater demand instruments for reducing water consumption.

2.5.2. The role of water management policies to achieve conservation goals

This section shows a selection of the results obtained in the simulation of policy scenarios aiming at reducing irrigation groundwater consumption (to 240 Mm^3) to assure the aquifer's sustainability. Table 8 shows the model results of the application of alternative water management policies, under the assumption that all unlicensed wells have been previously legalized. Disaggregated results on the environment (water consumption and crop distribution), private sector (farm income), and public sector (government revenue collection and expenditure) are displayed in Table 8.

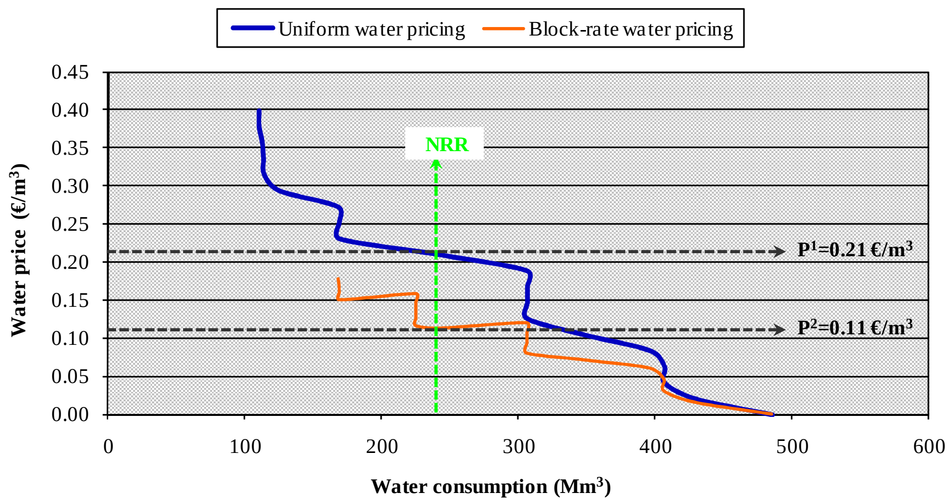
Table 8- Effects of water management policies for promoting sustainable groundwater use in the Mancha Occidental aquifer.

POLICY SCENARIOS	POLICY INDICATORS					
	Water consumption (m3/ha)	Farm income (€/ha)	Public collection (€/ha)	Public expenditure (€/ha)	Crop distribution (%)	
					Rainfed	Irrigated
Baseline scenario						
F1- Small farm	3390	1063	3.1	117	5	95
F2- Medium farm	1906	604	1.6	56	3	97
F3- Big farm	2371	534	3.6	153	20	80
F4- Very big farm	2372	391	2.4	185	50	50
Uniform w. pricing (P^1=0.21€/m^3)						
F1- Small farm	1079	496	273	113	59	41
F2- Medium farm	1592	- 43	637	51	20	80
F3- Big farm	1469	255	250	142	59	41
F4- Very big farm	1242	232	133	178	81	19
Block w. pricing (P^2=0.11€/m^3)						
F1- Small farm	1079	612	156	113	59	41
F2- Medium farm	1592	87	507	50	20	80
F3- Big farm	1469	386	120	142	59	41
F4- Very big farm	1242	294	71	178	81	19
Water use quota						
F1- Small farm	1337	775	46	111	54	46
F2- Medium farm	1337	235	299	52	26	74
F3- Big farm	1337	480	3.6	142	61	39
F4- Very big farm	1337	372	2.2	178	80	20
Water markets (P^3=0.24€/m^3)						
F1- Small farm	1337	775	46	111	54	46
F2- Medium farm	1351	236	303	52	25	75
F3- Big farm	1337	480	4.5	142	61	39
F4- Very big farm	1315	373	4.5	178	81	19

2.5.2.1 Water pricing

Groundwater irrigation farmers usually pay the full financial cost of groundwater use (capital costs and maintenance and operation costs), however seldom assume the environmental and resource costs of groundwater abstractions (Garrido et al., 2006; Llamas and Martínez-Santos, 2005; Shah et al., 2007). The national report from the Spanish Ministry of the Environment and Rural and Marine Affairs on water pricing and cost recovery in Spain (MMA, 2007) points out that in the Guadiana basin, the average financial cost of groundwater services is 0.10 €/m^3 with a cost recovery level among agricultural users of 90-100%. Garrido and Calatrava (2010) state that water tariffs should be doubled if environmental costs are included in the water services costs. In the Mancha Occidental aquifer, irrigators already pay the full economic cost of groundwater abstractions, estimated to be 0.08 €/m^3. Fig. 11 shows water demand responses to water prices.

Fig. 11- Water demand curves under uniform volumetric and block-rate water prices in the Mancha Occidental aquifer.

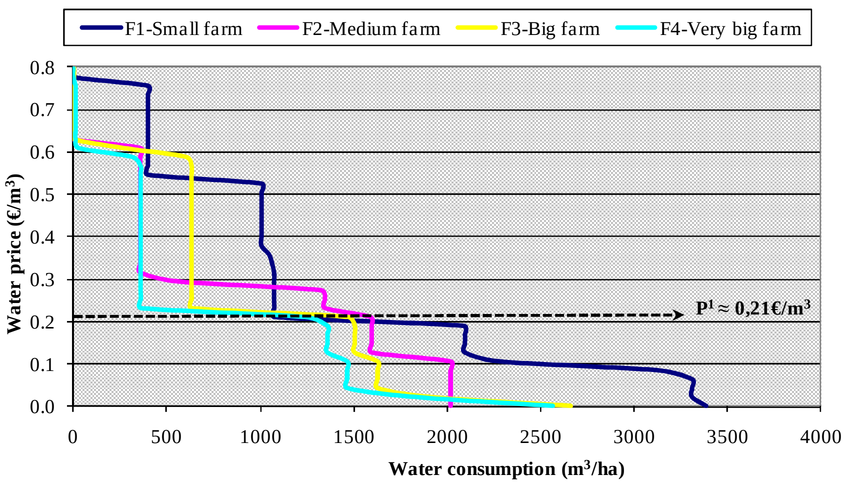


As evidenced in Fig. 11, our findings indicate that additional water tariffs, ranging between 0.11-0.21 €/m^3, should be implemented in the Mancha Occidental aquifer for fully recovering the environmental costs associated to the aquifer's degradation. These levels of water tariffs reduce groundwater consumption to 240 Mm^3 (equivalent to the NRR of the aquifer) and therefore, they promote the recovery of the aquifer, which is essential for the restoration of the valuable groundwater-dependent wetland ecosystems of the Tablas de Daimiel National Park. Based on the 'replacement cost method' (Turner et al., 2004), the water prices needed to achieve the environmental target of the aquifer's conservation were used to measure the environmental costs associated with the use of groundwater for irrigation. The aggregate water demand response for the two types of selected price schemes (uniform volumetric and block-rate water pricing) is shown in Fig. 11.

The model results indicate that block-rate tariffs are more water saving than uniform tariffs. In other words, higher water prices would be needed with a uniform volumetric water pricing system to reduce groundwater consumption to 240 Mm^3. As we can see in Fig. 11, it would be necessary to apply a uniform tariff of 0.21 €/m^3 to achieve the desired reduction in groundwater consumption, whereas a lower block-rate tariff of 0.11 €/m^3 would be enough to accomplish the same objective.

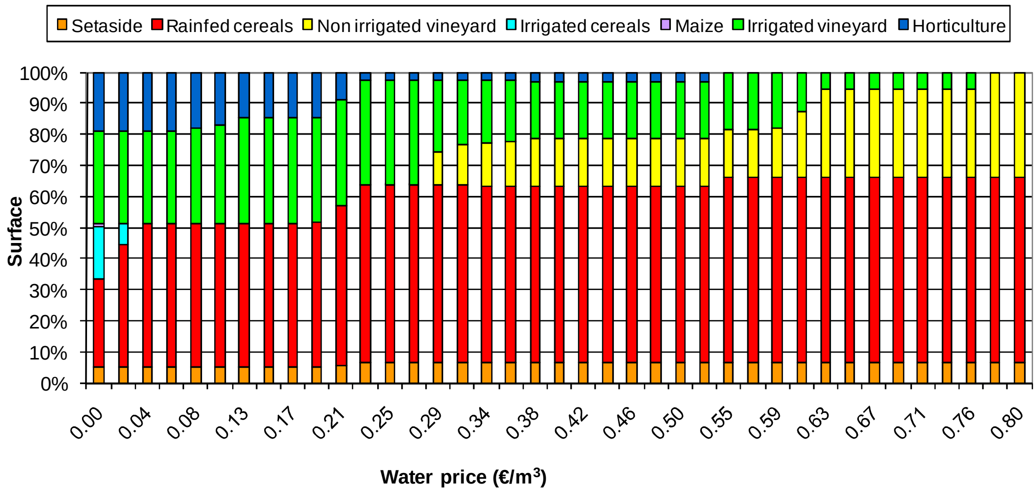
On the whole, Fig. 11 shows that movements along the demand curve result in significant water savings. However, a disaggregated analysis reveals that water demand responses are not uniform across farm types due to their diverse structural parameters (basically, crop distribution and farm size). Similar results have been obtained by Bazzani et al., (2005), Gómez-Limón and Riesgo (2004), and Varela-Ortega et al., (1998), among others. Fig. 12 shows the results of the application of uniform volumetric water prices on the selected farm types of the Mancha Occidental aquifer.

Fig. 12- Water demand curves under uniform volumetric water prices.



The simulation results indicate that water demand is less elastic at low prices in small and medium farms F1 and F2. In the medium farm F2, in particular, water demand is completely inelastic bellow 0.11€/m^3, which means that water prices should be incremented 5 times before they will induce significant water savings. The inelasticity of water demand at low water price ranges may induce important farmers' income losses, limiting the applicability of water pricing schemes in real-world contexts (see e.g. Cornish et al., 2004; De Fraiture and Perry, 2007; Molle et al., 2008). At the same water price level (0.11€/m^3), bigger farms F3 and F4 would save larger amounts of water, evidence of the presence of regional economies of scale. However, farm size is not the only factor that determines water demand responses. Water savings are clearly conditioned by potential land use changes. Crop diversified farms, such as F3 and F4, can adopt more flexible adaptive strategies and easily adjust their crop mix to decrease water consumption. These farm types combine rainfed and irrigated agricultural productions in different soil qualities and are capable of substituting irrigated cereal crops (such as barley, wheat, and maize) by rainfed crops (mainly, barley) for reducing water consumption without sacrificing a large part of their income. On the other hand, the representative farm F2 has a very rigid cropping pattern (based on irrigated vineyard crops) and therefore, it presents a very low price-responsive water demand. Similarly, the representative farm F1, with very low diversification potential and high value-added crops (such as vegetables and to a lesser extent, vineyards), substitutes water intensive crops (pepper) by less water demanding crops (melon or vineyard) at low prices, but it is constrained to replace vegetable crops with rainfed crops when water prices are high, reducing water consumption and farm income substantially. As evidenced by the data in Fig. 12, a water price level of 0.21€/m^3, would induce a reduction in water consumption of 68, 21, 45 and 52%, in farms F1, F2, F3 and F4, respectively. Fig. 13 illustrates the cropping strategies adopted by farmers facing increasing uniform volumetric water prices in the Mancha Occidental aquifer.

Fig. 13- Farmers' cropping strategies under uniform volumetric water prices.



The simulation results also indicate that the establishment of water prices as a mechanism to reduce groundwater consumption and assure the regeneration of the Mancha Occidental aquifer would have adverse effects on farmers' income in the region. Fig. 14 shows farmers' income under uniform volumetric and block-rate water prices.

Fig. 14- Farmers' income under uniform volumetric and block-rate water prices in the Mancha Occidental aquifer.

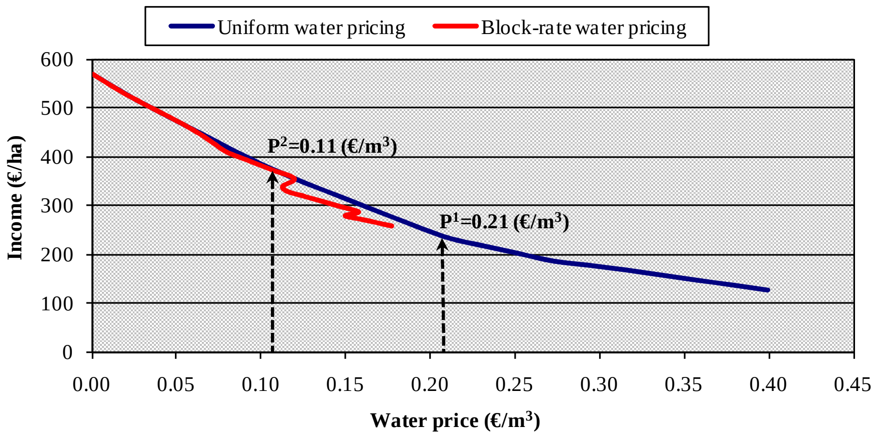


Fig. 11 and 14 point out that, when uniform volumetric and block-rate water prices reach 0.21 €/m^3 and 0.11 €/m^3 respectively, farmers' would sacrifice 58% and 40% of their income gains for reducing 50% their water consumption, which may be neither politically nor socially acceptable. Disaggregated results displayed in Table 8 show that, at that uniform water price level (0.21 €/m^3), the medium farm F2, specialized in growing irrigated vineyard, would even go out of farming (negative income). Irrigated vineyards as well as horticultural crops play a substantial role as a source of employment and income generation. Thus, alternative choices should be considered to reduce water use in vineyard intensive farms, because putting at risk the viability of these farms might severely curtail the economy of the region.

2.5.2.2. Water quotas

As an alternative to the prevailing WAP, a new water use quota system was devised to limit total groundwater abstractions for irrigation to 240 Mm^3 per year (water volume compatible with the Mancha Occidental aquifer's recharge rate). Unlike the current WAP, this global quota was equally distributed across types of farms in such a way that each farm was assigned a non-tradable groundwater use right of 1337 m^3/ha[9]. The simulation results in Table 8 show that this water allotment reallocation would favor larger farms F3 and F4 more than small and medium farms F1 and F2. In comparison with the baseline scenario (see Table 8), big farms F3 and F4 would see their income gain reduced only by 10% and 5% respectively, whereas the smaller farms F1 and F2 would lose 27% and 61% of their income.

Regarding the public sector, it is worth mentioning that public collection would substantially increase in farms F1 and F2, especially in the latter (299 €/ha, in Table 8), as it comprises the legalization fees paid by irrigators for registering unlicensed wells to enter in the new water quota system. Besides that, public expenditure will slightly decrease in all farms due to expansion of rainfed crops in the cultivated area (rainfed crops received lower direct CAP subsidies than irrigated crops). Rainfed surface would increase from 5%, 3%, 20% and 50% (for farms F1, F2, F3 and F4, respectively, under the baseline scenario) to 54%, 26%, 21% and 80% under the quota system scenario.

[9] These individual water quotas were obtained by dividing the global water quota (240 million m^3) by the total number of irrigation hectares in the area (on the order of 180,000 has).

2.5.2.3. Water market

In this section we take a further step, simulating a water market. The water market simulated in this study can be defined as an irrigation spot market implemented at sub-basin level. Thus, groundwater can be voluntarily and directly traded among irrigators within the Mancha Occidental aquifer, but it cannot be transferred to other irrigation systems outside the aquifer's boundaries, nor exchanged with water users belonging to other production sectors (e.g. residential and commercial sectors). In order to guarantee the aquifer's annual recharge rate, total water exchanges are limited to a maximum of 240 Mm^3 per year. The initial allocation of groundwater rights for each farm corresponds with the established water use quotas of the previous simulation scenario (1337 m^3/ha, that is, 75, 73, 42 and 50 Mm^3 for F1, F2, F3 and F4 respectively), in such a way that the sum of initial water rights equals the maximum exchangeable amount of water in the Mancha Occidental aquifer. Simulation results from the previous water use quota scenario have also been used to define the range of potential water market prices that provide a win-win situation (from 0.20 to 0.26 €/m^3). These price levels were identified within the range of prices delimited by the lowest and highest dual water values of the water availability restrictions in the simulated water use quota scenario. Among the possible market prices, the equilibrium market price was set at 0.24 €/m^3; the level at which the expected regional utility is maximized. Since even the most efficient water market entails establishment and operation costs, it has been considered that water sellers have to pay for the transaction costs incurred in the trading (around 5% of the total receipts). This assumption has been based on literature review from existing water markets (Hearne and Easter, 1997; McCann et al., 2005)

Results indicate that the medium farm F2 buys 0.8 Mm^3 from the largest farm F4, because of the higher marginal utility or opportunity cost of water of small and medium holdings. Once the transaction has been completed, total water consumption is 74.6 Mm^3 (1351 m^3/ha) for farm F2 and 50.5 Mm^3 (1315 m^3/ha) for farm F4 (see Table 8). Gomez-Limón et al. (2007) demonstrate that, for most market price levels, farmers' willingness to buy water is higher in small and medium farms than in large farms. In comparison with the previous non-market situation (water use quota scenario), water trading results in small income gains (farm income is only increased in 1 €/ha in farms F2 and F4), and slightly higher public collections (303 and 4.5 €/ha in farms F2 and F4 respectively).

2.5.3. Cost-effectiveness analysis of alternative water management policies

To conclude our research, a CEA analysis was performed to identify the most cost-effective policy option to meet the WFD objective of water resources conservation in the Mancha Occidental aquifer. According to theory in environmental-economic evaluation, the purpose of the CEA is to find out how preset environmental objectives (in our case, reducing total groundwater consumption for irrigation in the aquifer to reach its sustainable recharge rate, set at 240 Mm^3) can be attained at least social cost. Following Brouwer and De Blois (2008), Semaan et al. (2007), Turner et al. (2004), Zanou et al. (2003), and this analysis was developed comparing the net social cost of the different simulated water management policies with respect to the baseline situation. The most-effective water management policy will be that with the lowest net social cost.

Net social costs are calculated as the algebraic sum of private and social costs related to each policy measure (Mejías et al., 2004; Semaan et al., 2007; Varela-Ortega and Blanco, 2008; Varela-Ortega and Sumpsi, 1999). Private costs refer to farmers' income losses and public costs express the government net public expenditure (see section 2.5.1). Table 9 shows the private and public costs of each water management policy (with respect to the baseline situation) in the Mancha Occidental aquifer.

Table 9- Costs and effectiveness of water management policies in the Mancha Occidental aquifer.

<table>
<tr><th colspan="2" rowspan="2">Index</th><th colspan="4">Water management policy</th></tr>
<tr><th>Uniform .w.p (P= 0.21 €/m^3)</th><th>Block-rate w.p (P= 0.11 €/m^3)</th><th>Water use quotas</th><th>Water market (P= 0.24 €/m^3)</th></tr>
<tr><td rowspan="2">Private cost</td><td>€/ha</td><td>399.8</td><td>295.8</td><td>176.6</td><td>176.5</td></tr>
<tr><td>%[(a)]</td><td>-63</td><td>-47</td><td>-28</td><td>-28</td></tr>
<tr><td rowspan="2">Public cost</td><td>€/ha</td><td>-314.5</td><td>-210.5</td><td>-89.8</td><td>-90.7</td></tr>
<tr><td>% [(a)]</td><td>+244</td><td>+163</td><td>+69</td><td>+70</td></tr>
<tr><td colspan="2">Net social cost (€/ha)</td><td>85.3</td><td>85.3</td><td>86.9</td><td>85.8</td></tr>
<tr><td colspan="2">Ranked cost-effectiveness[(b)]</td><td colspan="2">1</td><td>3</td><td>2</td></tr>
</table>

[(a)] Percentage of private and public cost with respect to the baseline scenario
[(b)] Simulated management instruments have been ranked from 1 to 3, having the #1 the highest cost-effectiveness

Results leads to the conclusion that the most cost-effective water management policy would be the establishment of a water pricing system, ranked #1 with the lowest net social cost (85.3 €/ha). Table 9 shows that uniform volumetric and block-rate water pricing schemes have the lowest public costs (-314.5 and -210.5 €/ha respectively), but entail the highest private costs (399.8 and 295.8 €/ha respectively). On the other hand, the water use quota system is the most costly water management policy and it is ranked #3. This water management policy has the highest net social cost (86.9 €/ha), and presents the highest public cost (-89.8 €/ha). In between, the water market policy instrument is ranked #2. It has a net social cost of 85.8 €/ha, but entails the lowest private cost (176.5 €/ha). It is worth mentioning that public costs are negative in all cases (government collections are higher than government expenditures because of the taxes collected by legalizing the unlicensed wells), so public costs should be understood as public revenues in Table 9.

2.6. Discussion of the results

The results show that attaining the target of the aquifer's sustainability would require an effective simultaneous combination of measures addressed to control water consumption and halting illegal drilling.

Closing up unlicensed wells would reach the environmental objective of the aquifer's conservation, but it would be opposed by small and medium-size farmers who will undergo acute income losses. Taking into consideration that the current WAP is highly contested by the farmers and that the water Administration has not been capable of enforcing this policy due to the large costs incurred in monitoring and metering water consumption, it seems unlikely that 20000 wells (almost the 50% of the wells in the Mancha Occidental aquifer) can be closed. Kemper (2007) and Koundori (2004) warn about the high transaction costs of monitoring individual wells, and Molle et al. (2008) inform about the risk of farmers' uprisings when imposing extremely costly fines on unlicensed wells. In addition, historical evidence shows that any attempts to prosecute illegal pumping in the study area ended up in numerous lawsuits, still pending to be settled by the Spanish court (CHG, 2007; Llamas and Martínez-Santos, 2005). On the other hand, the results show that the taxed legalization of unlicensed wells would entail milder income losses to farmers and lower enforcement costs to the public authorities than the closing-up scenario. In Jordan, a similar experiment also proved effective with the legalization in 2005 of numerous unlicensed wells. Irrigators were given the opportunity to obtain an abstraction license for free, but were encouraged to change the legal status of their wells by paying higher tariffs for the water abstracted from unlicensed wells (Haddadin, 2006). The taxed legalization of unlicensed wells can control illegal groundwater pumping, but it is not sufficient to recovery the aquifer. Rather, effective water management in this area will require the implementation of other water management policies as well.

The establishment of water pricing policies can reduce groundwater consumption and promote the recovery of the aquifer. The results show that water tariffs would induce substantial water savings, especially in large crop-diversified farms. Recent studies on water prices (e.g., Schoengold et al., 2006; Wheeler et al., 2008) suggest that irrigation water demand is more elastic than highlighted in other studies (e.g., Cornish et al., 2004; De Fraiture and Perry, 2007; Varela et al., 1998;) and that water prices can encourage water savings even at low rates. Shiferaw et al. (2008) demonstrate that well-defined and implemented groundwater prices in India would induce changes in land allocation and the implementation of water saving technologies, inflicting moderate income losses upon the farmers. Our findings indicate that groundwater prices promote water saving, but they inflict substantial income losses upon small farms with rigid cropping patterns. A comparative policy analysis between the two selected water pricing schemes leads to the conclusion that block-rate water prices would provide fewer revenue collections to the water authority, but would mean lower income losses for farmers. Several authors (such as Bar-Shira et al., 2006; Dinar and Subramanian, 1997; Liu et al., 2003; Olmstead et al., 2007), highlight the benefits of using block-rate water pricing systems for combining efficiency and equity considerations and indicate that block-rate pricing, although usually applied to the urban water sector, is being progressively introduced to regulate agriculture water uses.

Equally distributed water quotas can also achieve the environmental objective of the aquifer’s conservation by reducing groundwater consumption and inequity among farmers. Molle (2009) and Wichelns (1999) state that quantity-based restrictions may induce land use changes in the same way as explicit water prices do. In addition, Shiferaw et al. (2008) demonstrate that the use of water quotas increase the feeling of equity among farmers and encourage groundwater users to cooperate and to act in the interest of the collective.

The results obtained indicate that, when the previously established water use quotas are traded on a market-based mechanism, only small amounts of water are actually exchanged, providing small income gains. Shiferaw et al. (2008) also prove that groundwater markets in semi-arid areas are usually not completely developed as a consequence of the low profits obtained. Along the same lines lines, Gómez-Limón et al. (2007) and Zekri and Easter (2005) state that intra-sectoral water markets for irrigation result in small water trades and minor increases in farmers' income, proving fewer benefits than the mainstream neo-classical theory would advocate for market mechanisms. However, considerable volumes of water are traded from farmers to urban users, increasing welfare gains. The potential of inter-sectoral markets to promote aquifer stability in the area should be analyzed in future works. In the present study, a win-win trading situation will occur when market prices varies from 0.20 to 0.26 €/m^3. These results match with other studies on hypothetical water markets in irrigation districts of southern Spain (see for instance Arriaza et al., 2002; Calatrava and Garrido, 2005), which document equilibrium prices as being around 0.15-0.30 €/m^3 (for 1000 and 2000 water allotments respectively, in years of normal supply). Albiac et al. (2006) also analyze real informal water markets for irrigation in a South-eastern basin of Spain, and report exchange prices in the range of 0.1 to 0.4 €/m^3.

The cost-effective analysis concludes that any of the water management instruments considered in this research has a clear advantage, in terms of social costs, over the others. Similarly, Dinar et al. (1997) state that no single economic instrument can work in all situations. Alauddin and Quiggin (2008) also confirm that no single policy can solve the complex problems related to irrigation water management, and recommend a combination of market and non-market measures. However, the differences obtained in the present study between private and public costs at farm and at sub-basin level will be decisive for putting water conservation policies into practice since they may condition the acceptance and involvement of the end-users in the policies' enforcement. Accordingly, Zanou et al. (2003) emphasizes that encouraging the cooperation and co-ordination among the stakeholders will be the least costly way to improve watershed quality in a river basin.

2.7. Conclusions and policy implications

Complying with WFD principles presents a significant challenge for most European basins in terms of management and methodology. Particularly, fulfilling the ‘polluter pays’ principle and the cost recovery objective requires the development of novel methodologies to evaluate their potential impacts and costs. Some studies and guidance documents exist, but they need to be further elaborated to incorporate water quantity issues, different spatial scales and transferable empirical experiences. The methodology developed in this paper attempted to shed light on these questions, analyzing the cost and effectiveness of alternative water conservation policies to reduce groundwater consumption and assure the sustainability of the Mancha Occidental aquifer.

In agreement with other authors (Bazzani et al., 2005; Gómez-Limón and Riesgo, 2004; Medellín-Azuara et al., in press; Varela-Ortega et al., 1998), our results confirm that the application of water management policies would produce differential effects across farm types. Most of the studies about CEA are exclusively specified at river basin level, missing important differences at local scale (in terms of soil, agrarian structure, farmers’ behavior, technological conditions, and site-specific institutional factors) as well as important interactions among the different levels of analysis. Our findings demonstrate that a multi-scale modeling approach is more realistic and highly recommended.

The study also shows that various alternative mechanisms can be used to attain the target of the aquifer’s sustainability. Results indicate that the best policy option for establishing an efficient regulatory framework to control unlicensed drilling is the taxed legalization of unlicensed wells. However, this policy option will not be capable of dealing on its own with groundwater overdrafts and it will be necessary to apply other water conservation policies to attain the aquifer’s sustainability target. From this study we can infer that none of the considered alternative water conservation policies (water pricing, water quota, water market) is clearly more cost-effective than the others.

Aggregate results show that net social costs are not substantially different across policy options. However, there are important differences between private and public costs (at farm and sub-basin level), which may influence the political viability of the various options. From an overall perspective, uniform volumetric and block-rate water pricing policies are the most cost-effective instruments to reach the goal of aquifer's sustainability. However, both pricing schemes (especially, uniform volumetric water prices) will entail important income losses to medium farms with more rigid cropping patterns (such as vineyards) and could therefore put their viability at risk. The quota system inflicts lower income losses upon the farmers, but is the most costly option for the government and the least cost-effective instrument to recover the aquifer. The water market has the lowest private cost, but does not provide as much profit gains as the mainstream neo-classical theory would suggest. Thus, our results confirm the findings of Alauddin and Quiggin (2008) and Dinar et al. (1997), among others, who state that no single policy can solve the complex problems related to irrigation water management, and recommend a combination of market and non-market measures.

Additional studies on net social costs are highly recommended to include long term recurrent costs, as well as policy implementation and operation costs. Other criteria not considered in this research, such as the policy enforcement capacity and level of social acceptance, should also be taken into consideration. Experiences from the past indicate that water quotas are likely opposed by the farmers and entail high costs of monitoring and enforcement. Increasing the direct participation and involvement of stakeholders in water management decisions is highly necessary for the acceptance of the policies. Notwithstanding the research's limitations, we would like to stress the potential of this methodology for environmental-economic modeling and policy analysis. Even though no clear cost-effective solutions were found, this methodology improves the ability to predict policy impact at multiple scales and provide valuable results for the stakeholders with regards to the potential impacts and costs of the WFD in a wide variety of contexts and water policy scenarios.

2.8. Acknowledgments

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2.9. Appendix: Specification of the economic model

This appendix presents the essential elements of the economic model described in the text. While this model was developed for application to the Upper Guadiana basin, it was designed to be easily adaptable to a variety of situations.

Objective function

Based on the mean-standard deviation analysis, the objective function of the model is:

$$MaxU = \sum_f \left(Z_f - \phi \cdot \sigma_f \right)$$

where *U* is the regional expected utility, Z_f the average net income by farm type *(f)*, ϕ the risk aversion coefficient and σ_f the standard deviation of the income distribution by farm type *(f)*. Average farm income is calculated as follows:

$$\begin{aligned} Z_f = {} & \sum_c \sum_k \sum_r \sum_i gm_{c,k,r} \cdot X_{c,k,r,i,f} + sfp_f \cdot md \cdot numf_f - oc \cdot \sum_p fla_{p,f} - hlp \cdot \sum_p hl_{p,f} \\ & - \sum_i nvin_{i,f} \cdot invc - \sum_i vin_{i,f} \cdot pullc - \sum_i wpc_{i,f} - \sum_i sirrg_{i,f} \cdot wtarif_i - \sum_i well_{i,f} \cdot wellt_i \end{aligned}$$

where $X_{c,k,r,i,f}$ are the decision-making variables representing the growing area by crop type *(c)*, soil type *(k)*, irrigation technique *(r)*, legal status of the water used *(i)* and farm type *(f)*; $gm_{c,k,r}$ gross margin (including the coupled subsidies of the Common Agricultural Policy (CAP)); sfp_f single farm payment (decoupled subsidies of the CAP); *md* modulation rate; $numf_f$ number of farms; *oc* family labor opportunity cost; $fla_{p,f}$ family labor; *hlp* wage for hired labor; $hl_{p,f}$ hired labor; $nvin_{i,f}$ new vineyard surface; *invc* annual payment of the investment costs incurred in planting new vineyards; $vin_{i,f}$ surface of vineyard pulled up; *pullc* annual payment of the costs incurred in pulling up vineyards; $wpc_{i,f}$ water pumping costs; $sirrg_{i,f}$ irrigated surface; $wtarif_i$ water use tariff; $well_{i,f}$ number of wells; $wellt_i$ tax paid by well (not applicable to unlicensed wells).

The standard deviation is generated by a set of states of nature defined by climate variability (crop yields) and market variability (crop prices) 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 the different states of nature (*N=100*).

Constraints

- Land constraints:

- Availability of land resources. They indicate that the cultivated area cannot surpass the potential arable land ($surf_{k,f}$) and limit the area under irrigation to the total area of potentially irrigable land ($sirrg_{i,f}$).

$$\sum_c \sum_r \sum_i X_{c,k,r,i,f} \leq surf_{k,f}$$

$$\sum_c \sum_k \sum_{ri} X_{c,k,ri,i,f} \leq sirrg_{i,f}$$

- Vineyard land acquisitions. They state that the cultivated vineyard surface is determined by the current 'plantation rights' ($svin_{i,f}$), surface of vineyard pulled up ($vin_{i,f}$) and the new vineyard plantations ($nvin_{i,f}$). According to the vineyard restructuring programs in Castilla-La Mancha, as part of the CAP, vine growers are allowed to create new vineyard plantations (up to max *nvin*). This is a single-period MPM, so we assume that vineyards are in full production.

$$\sum_{vi} \sum_k \sum_r X_{vi,k,r,i,f} = svin_{i,f} + nvin_{i,f} - vin_{i,f}; \qquad where \qquad \sum_i \sum_f vii_{i,f} \leq \max nvin$$

- Labor constraints. They indicate that the seasonal labor requirements must to be covered by total available agricultural labor (family, $lafa_{p,f}$, and hired labor, $lhi_{p,f}$).

$$\sum_c \sum_k \sum_r \sum_i lr_{c,r,p} \cdot X_{c,k,r,i,f} \leq lafa_{p,f} + lhi_{p,f}$$

- Water constraints (and some other relevant hydrology equations):

- Water availability at the farm level. It illustrates that the crop water needs ($wr_{ck,r}$) cannot exceed the amount of water available at the farm level ($watera_f$).

$$\sum_{c}\sum_{k}\sum_{r}\sum_{i} wr_{c,k,r} \cdot X_{c,k,r,i,f} \leq watera_{i,f}$$

- Water availability at the sub-basin level. It limits the total water consumption in the aquifer ($wc_{i,f}$) to the amount of water available at the sub-basin level (twc_i) (usually subjected to Natural Recharge Rate of the Mancha Occidental aquifer).

$$\sum_{f} wc_{i,f} \leq twc_{i}$$

- Estimation of water pumping costs. It shows how pumping costs increase as water levels in the aquifer decline. In the present study, water consumption was used as a proxy for measuring changes in groundwater levels. σ_i, β_i, δ_i, are the coefficients of the polynomial function of groundwater pumping costs, obtained using statistical analysis from experimental field data collection.

$$\alpha_{i} \cdot \left(wc_{i,f}\right)^{2} + \beta_{i} \cdot wc_{i,f} + \delta_{i} = wpc_{i,f}$$

- Policy constraints. They depict the EU CAP requirement for farmers to set-aside a ($X_{sa,k,r,i,f}$) a given fraction (bound by a minimum, *smin,* and a maximum, *smax*) of the COP (cereals, oilseeds and proteins) growing area ($X_{cop,r,d,f}$).

$$s\min \cdot \sum_{cop}\sum_{k}\sum_{r}\sum_{i} X_{cop,k,r,i,f} \leq \sum_{k}\sum_{r}\sum_{i} X_{sa,k,r,i,f} \leq s\max \cdot \sum_{cop}\sum_{k}\sum_{r}\sum_{i} X_{cop,k,r,i,f}$$

- *S*ubsequently, other parameters and constraints are added into the model for simulating different water policies (e.g. legalization fees, administered water prices, water market prices, transaction costs, water trading, etc.).

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3. Hydro-economic modeling for promoting integrated water resource management: Understanding the interactions between water and the economy

3.1. Abstract

Increasing water scarcity and competition for water is an issue of major concern, especially in arid and semi-arid areas affected by droughts and characterized by broad climate variability. Balancing the trade-offs among the different uses and users of water requires an inter-sectoral and multi-disciplinary approach to water resource management. Hydro-economic models constitute useful tools to improve water management. They allow one to capture the multifaceted relationships between socio-economic processes and natural systems and provide relevant insights for water planning, water allocation, policy design and implementation. This paper offers an important extension of the available hydro-economics modeling tools. It explores the development of a prototype model based on the integration of an integrated water resources simulation model using WEAP ('Water Evaluation And Planning' system) and a multi-scale farm-decision economic optimization model. The economic model was encoded in GAMS (General Algebraic Modeling System) and prepared using modeling interfaces programmed with VBA (Visual Basic for Applications) to facilitate its interaction with the WEAP platform. The model was applied to a large-scale, drought-prone catchment situated on the southwestern plateau of the Iberian Peninsula in Spain (the Middle Guadiana basin) to test its functionality and to analyze the local and regional interdependence between agriculture and other water use sectors. The results obtained from the modeling exercise showed that the developed hydro-economic model was capable of capturing the structural diversity of agricultural systems in the region of study, as well as the temporal and spatial variability of water resources systems. This type of model may contribute valuable information concerning farm and regional incomes, optimal crop mixes, public expenditures, ecosystem functions, water consumption, demand coverage, etc., and thus offer sound guidance for water management decision making in the study area.

Keywords: irrigation; water management; economic model; hydrology model; integrated modeling; semi-arid region.

3.2. Integrated water modeling

Water scarcity is a significant and growing problem in many areas of the world. The demands for freshwater resources are rising rapidly, while the development of new water supplies to overcome water deficits is becoming increasingly difficult and costly (Comprehensive Assessment of Water Management in Agriculture, 2007; Gleick et al., 2009). Water stress situations are provoking considerable water quality problems and a mounting competition for water resources among sectors (environment, agriculture, tourism, industry) and social groups (De Fraiture and Wichelns, 2010). To make matters worse, climate change projections foresee an increase in the intensity and frequency of droughts that might reduce the availability of water resources even further in areas with arid and semi-arid climates, such as the Mediterranean region (Iglesias et al., 2007; Krysanova et al., 2010).

In this context, a comprehensive vision is required to balance the trade-offs among all of the uses and users of water (Postel et al., 1996; Varela-Ortega, 2007). This type of vision leads to an integrated and multidisciplinary water resources management approach that aims to ensure a more sustainable use of water resources and, ultimately, more sustainable economic and social development (Osann et al., in press). According to this approach, the objective of this study is to develop an integrated methodology that can contribute to a better understanding of the complex ecological, hydrological and socio-economic interactions within water systems from local to basin-wide levels.

Thus far, different methods have been developed for Integrated Water Resources Management (IWRM) (see Croke et al., 2007): mental models and system dynamics approaches (e.g., Pahl-Wostl, 2007), Bayesian networks (e.g., Carmona et al., in press), hydro-economic models (e.g., Brouwer and Hofkes, 2008), metamodels (e.g., Broad et al., 2010), risk-assessment approaches (e.g., Kammen and Hassenzahl, 1999), agent-based models (e.g., Becu et al., 2003), and expert systems or knowledge elicitation tools (e.g., Bharwani, 2006), among many others.

In particular, the application of integrated hydro-economic models and the incorporation of economic principles, concepts and instruments into watershed management are steadily gaining attention (Harou et al., 2009). The combination of economic insights with hydrology and engineering processes in water modeling provides a more realistic and coherent framework to analyze the economic and environmental consequences of water management for households, farms, and business firms and for aquatic ecosystems (Brouwer and Hofkes, 2008). Hydro-economic models can better inform policy-makers regarding to the more efficient use of water resources and the optimization of water allocation among competing uses and users (Jenkins et al., 2004; Medellín-Azuara et al., 2009), which will undoubtedly lead to more rational decisions on water planning, investment and financial operations, policy design and implementation (Ward and Pulido-Velázquez, 2008).

Hydro-economic models have been applied to many water systems worldwide (see Harou et al., 2009). Some of these models adopt a 'holistic' approach using a single integrated model, whereas others follow a 'modular or compartmental' approach, which implies that the hydrology and economic models are independent and that only the input/output data are exchanged between them (Braat and Lierop, 1987). Holistic models (often based on optimization techniques) avoid the need for model interfaces and data exchanges, and allow a more efficient representation of the interdependences between the models; however, they usually represent the socio-economic and hydrologic processes in a very simplified way (McKinney et al., 1999). Some recent examples of holistic models are those presented by Draper et al. (2003) and Jenkins et al. (2004) in California, Cai (2008) and Rosegrant et al. (2000) in the Maipo basin in Chile, Pulido-Velázquez et al. (2008) in the Adra river system in Spain, Gürlük and Ward (2009) in the Nilüfer river basin in Turkey, Ward and Pulido-Velázquez (2008) in the Rio Grande in the US, Medellín-Azuara et al. (2009) in Baja California in Mexico, Letcher et al. (2007) in the Yass river catchment in Australia.

On the other hand, hydro-economic models with a modular approach may result in a loss of information during communication between the models, but provide a higher probability of converging on a realistic solution. Furthermore, they present more detailed sub-models, which can be easily developed and updated in the future (Harou et al., 2009). Usually, this type of approach combines hydrology simulation models and economic optimization models. Among others, Ahrends et al. (2008) and Bharati et al. (2008)coupled the hydrology model WaSIM with a non-linear economic model in the Volta Basin (West Africa); Quinn et al. (2004) integrated the hydrology model CALSIM II with the economic model APSIDE in the San Joaquin basin (California); Maneta et al. (2009b) coupled the hydrology model MODHMS with a positive mathematical programming model in the São Francisco River in Brazil; Qureshi et al. (2008) integrated the hydrology model MODFLOW with a liner mathematical programming model in the Burdekin delta in Australia; Volk et al. (2008) coupled the hydrology model SWAT with a linear economic model, BEMO, in the Upper Ems River Basin in Germany.

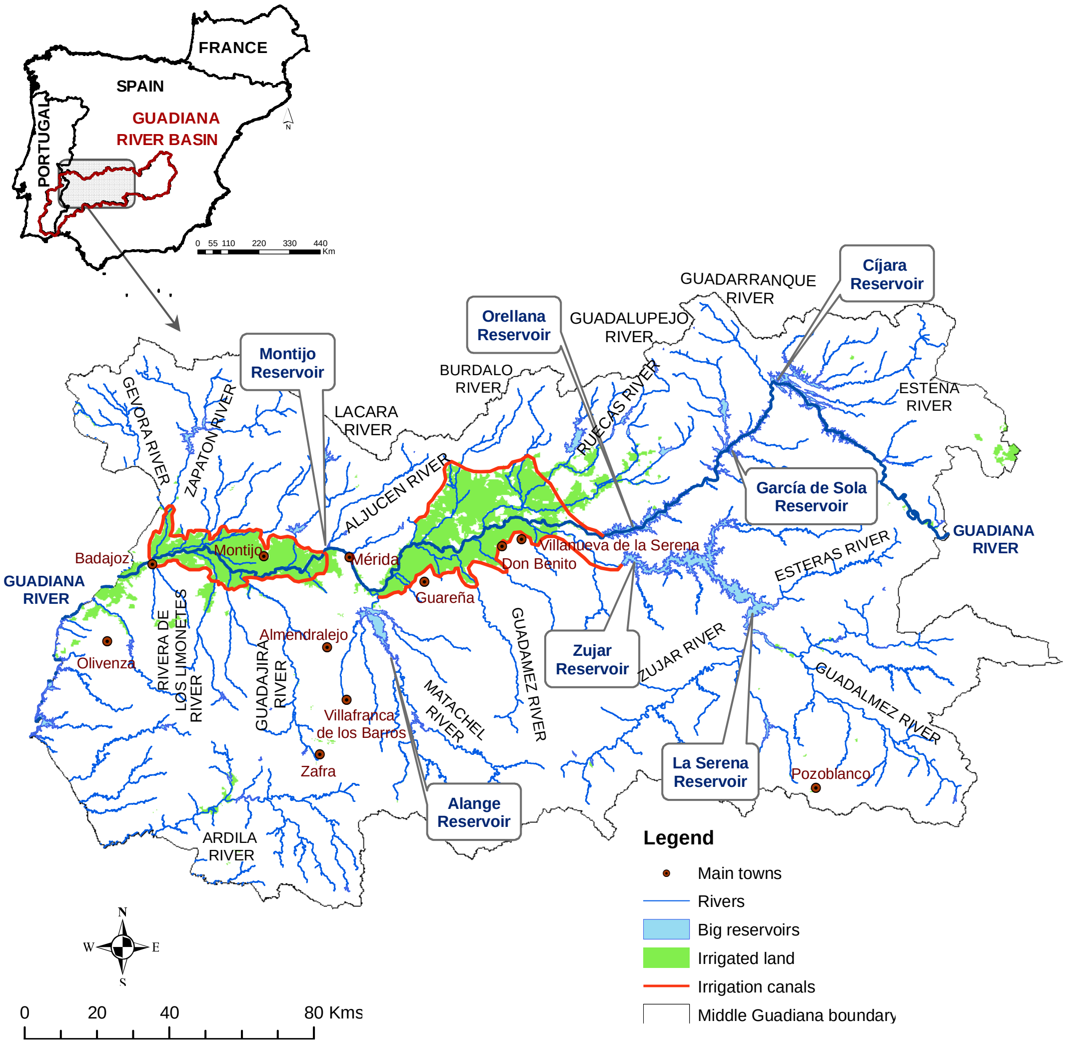
This paper offers an important methodological extension of the existing literature concerning hydro-economic modeling by developing an innovative hydro-economic model based on the integration of a hydrology simulation model using WEAP ('Water Evaluation And Planning' system) and a multi-scale non-linear optimization model using GAMS (General Algebraic Modeling System). Recently, Varela-Ortega et al. (in press) illustrate how the WEAP model can be linked with a farm-based non-linear optimization model and applied to a groundwater-based irrigation area of Spain (the Upper Guadiana basin) using a rigid-demand approach. The present research goes a step further by simulating rainfall/runoff processes in the WEAP model and the behavior of farmers at different levels of analysis (farm level and regional level) in the economic model, which provides a more comprehensive vision of water systems. In addition, this paper shows how the hydrology and economic models can be automatically linked through simulation engines. The prototype hydro-economic model was applied to a large-scale, drought-prone, surface-irrigated area in Spain (the Middle Guadiana basin) to test its capabilities and to investigate the local and regional interactions between the environment and the economy in a recent year (2007).

3.3. Characterization of the study area

3.3.1. Physical environment and historical context

The Middle Guadiana basin is located on the southwestern plateau of the Iberian Peninsula in Spain, and its left boundary acts as a natural border between Portugal and Spain (see Fig. 15).

Fig. 15- Geographical setting of the Middle Guadiana basin.



The basin extends over an area of 29402 km^2 within Spanish territory and spans two different Autonomous Communities (Castilla-La Mancha and Extremadura), five regional provinces and 249 municipalities. The study region is home to 762131 people. The most important and fast-growing cities in the region are distributed principally along the length of the Guadiana River and its tributaries in areas that adjoin irrigated lands (CHG, 2008).

The natural vegetation in the Middle Guadiana basin is characterized by a small amount of forest habitat (mostly pines and cork oak trees growing in acid and humid soils) and large extents of grassland, natural prairies and shrubs. However, the land is occupied mainly by agriculture (CHG, 2008). The cultivated land covers nearly 12000 km^2 (40% of the total surface of the basin), of which 1450 km^2 are irrigated. As shown in Fig. 15, irrigated cropland is concentrated in the plains along the Guadiana River called 'Vegas', which are low-lying fertile soil mantles of Quaternary clays.

The Middle Guadiana basin is considered one of the driest regions of Spain (Abanades et al., 2007). It exhibits a semi-arid Mediterranean climate characterized by a low and irregular rainfall and by high evapotranspiration rates, especially during the summer when the hot and dry season occurs. The average annual precipitation is 590 mm/year, the mean annual temperature varies between 11-18 ºC, and the total annual potential evapotranspiration estimated by Thornthwaites' formula is approximately 800-1000 mm/year (CHG, 2008).

The Middle Guadiana basin, as well as other river basins in Spain, has experienced several severe drought spells during the past century (e.g., in 1941-1945, 1979-1983, 1991-1995, 2004-2009) that caused water shortages for irrigation and urban use, crop failures, considerable economic damage, environmental degradation and conflicts among water-using sectors and social groups (CHG, 2008; Iglesias et al., 2007). Moreover, drought episodes and drought-related effects are likely to be aggravated in the future, since Spain is situated in one of the world's climate change hotspots (Giorgi, 2006; López-Gunn, 2009).

In the Middle Guadiana basin, where there is a predominance of surface water sources, drought periods have generally coincided with a considerable development of major hydraulic infrastructures and large-scale irrigation transformations, mostly by state government agencies under publicly funded development plans (e.g. the 'Plan Badajoz' in 1952) (Brandão and Rodrigues, 2000; Varela-Ortega, 2007). Over the past half century, the construction of a large number of reservoirs and dams has greatly increased the storage capacity of the Middle Guadiana basin up to 8000 Mm^3 (nearly, 15% of the total reservoir capacity in Spain) (CHG, 2008), which has helped to partially mitigate the vulnerability of water resources to the climate variability of the region (Krysanova et al., 2010).

As in many other parts of the world where massive water-supply infrastructure has been developed for agricultural water uses (see e.g., Kingsford, 2000, in Australia; Kyei-Baffour and Ofori, 2006, in Ghana), the extension of irrigation in the Middle Guadiana basin has undoubtedly contributed to solving long-lasting human and economic problems in rural areas, but it has been accompanied by an increase in the diffusion of nitrogen pollution, the loss of riparian vegetation, and the degradation of important natural spaces of high ecological value that are listed in numerous environmental protection catalogues (such as the Ramsar List Convention, Protected Natural Spaces, Habitats of Communitarian Interest, and Zones of Special Bird Protection) (Tockner et al., 2009).

At present, the irrigated agricultural sector still plays a fundamental role in supporting the socio-economic development of the basin, but it faces important political, economic and technical challenges. Irrigated agriculture, which accounts for approximately 93% (1164 Mm^3/year) of the total water usage in the basin (CHG, 2006), has to adapt to the new European policies (agricultural policies and water policies) that call for a more sustainable use of water resources. Additionally, new water pricing schemes and water-saving irrigation technologies need to be put in place to encourage water conservation and improve water use efficiency. In this context, it seems likely that current water uses for irrigation may not be maintained in the future because of the increasing water demands for environmental and industrial uses and the expected decline in the natural water resource availability caused by climate change.

3.3.2. Water management institutions: the role of irrigation communities

In Spain, River Basin Authorities, belonging to the Ministry of Environment and Rural and Marine Affairs, are responsible for all water management at the river basin scale. However, the Irrigation Communities (ICs) are the predominant institutional arrangements governing irrigation systems at the local level. The ICs are independent public administration bodies comprised of all the landowner irrigators that share a common water concession, which collectively regulate the distribution and control of water for irrigation, and share the use and maintenance of the hydraulic networks (Varela-Ortega and Hernández-Mora, 2010).

In the Middle Guadiana basin, there are a total of 21 ICs. Among them, the most important ICs are situated along the middle Guadiana River occupying a surface of 136000 ha (90% of the total irrigated area). Table 10 summarizes the main characteristics of the 12 ICs situated along the Guadiana River in the Middle Guadiana basin.

Table 10- Characteristics of the main Irrigation Communities in the Middle Guadiana basin.

IC code	Year of creation	Irrigated area (ha)	Nº of irrigators	Water source	Water allotments (m^3/ha)	Irrigation technology
BCL	1960	1400	160	Lobón canal	7500	Sprinkler, drip, gravity
BCM	1962	10500	1653	Montijo canal	7500	Gravity
CDO	1976	40400	5080	Orellana canal	10900	Gravity
GDC	1962	3363	380	Montijo canal	7500	Sprinkler, drip
MCM	1962	10600	2500	Montijo canal	7500[a]	Gravity
MER	1959	5215	1300	Lobón canal	7500	Sprinkler, gravity
TDG	1993	21852	666	Guadiana River	6600	Drip, sprinkler, gravity
TLR	1959	7176	600	Lobón canal	7500	Gravity, sprinkler
VA1	1976	3757	536	Dehesas canal-García Sola dam	10900	Gravity
VA2	1976	5751	663	Orellana canal	10900	Gravity
VA3	1976	4925	216	Orellana canal	10900	Gravity
ZUJ	1990	21140	6000	Zújar canal	7000	Drip, sprinkler

[a] In the process of consolidating its administrative water allotment.

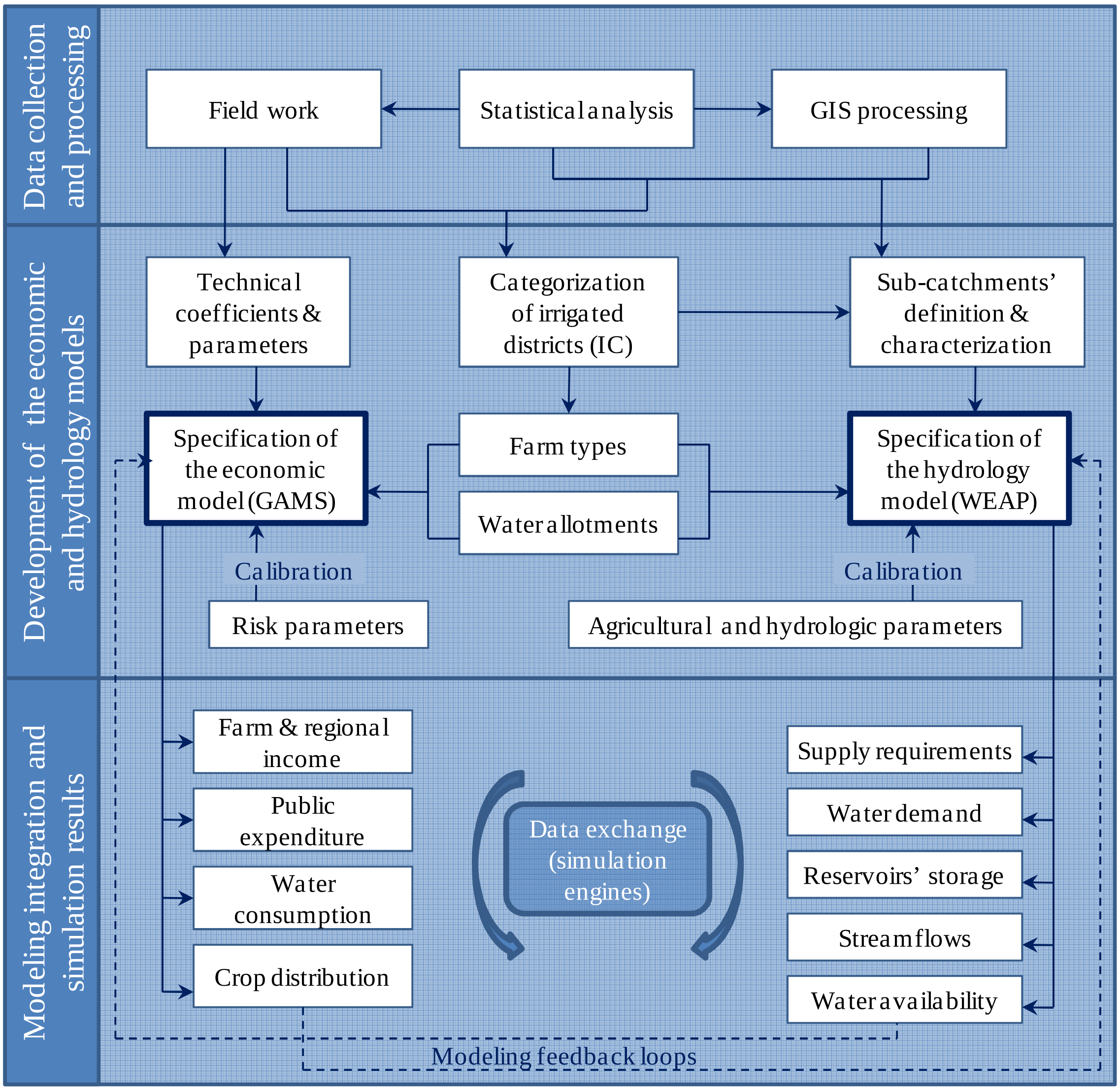
The largest IC of the Middle Guadiana basin, the Canal de Orellana IC (CDO), extends over an area of approximately 40000 ha in the upper part of the Middle Guadiana basin. CDO farms, mainly including rice producers, are irrigated with traditional furrow-gravity systems. This IC has experienced severe water shortages during drought periods, which has justified the establishment of large administrative water allotments (10900 m^3/ha). Rice growers can obtain even higher water allotments (up to 15000 m^3/ha). The ICs of Vegas Altas (VA_1, VA_2, and VA_3), which were once part of the previously described IC, presents similar characteristics to those of the CDO IC. On the opposite bank of the Guadiana River, the Zújar IC (ZUJ) represents a modern automated system of pressurized irrigation. This IC manages the operation of the Zújar irrigation canal and provides highly efficient on-demand irrigation services to farmers. The water allotments are relatively low (7000 m^3/ha), and the IC penalizes farmers who exceed their permits with a 10% surcharge over the volumetric fee (0.026 €/m^3). The ICs of Talavera La Real (TLT), Mérida (MER), Guadiana del Caudillo (GDC), Montijo Canal de Montijo (MCM), Badajoz-Canal de Lobón (BCL), and Badajoz-Canal de Montijo (BCM) are located downstream of the basin (in Vegas Bajas) and are fed by the Montijo and Lobón irrigation canals. Created in the 1950s and 1960s, these small ICs are experiencing considerable problems concerning the state of their conveyance systems. Modernization projects have been established to repair the water infrastructure and to promote the use of pressurized irrigation systems. However, gravity irrigation still predominates, especially in MCM where water is usually priced per irrigated hectare or per hours of irrigation. The IC of Tomas Directas del Guadiana (TDG) presents a very different situation. This modern IC includes all of the irrigators that carry water directly from the rivers and, therefore, it is spatially widespread along the banks of the Guadiana River and its major tributaries. Irrigators are exempt from paying any water use tariffs to the River Basin Authority (RBA), but they are required to pump water from the river; thus, they assume a significant cost on their own. Water allotments are the lowest (6600 m^3/ha) in this IC, although they can be increased by request in some specific individual cases.

As seen in this section, the Guadiana basin faces complex challenges with environmental, technical, social, economic and political characteristics, which make it an illustrative case study in which integrated watershed modeling can be both applied and used for learning purposes. Integrated hydro-economic modeling of the Guadiana catchment will improve our understanding of the multifaceted characteristics of water resources systems and will contribute to ensuring a more sustainable use of water resources in the basin.

3.4. Modeling framework: an integrated economic-hydrology model

A schematic representation of the integrated methodology developed in this study to analyze the complexity of the interactions between the economy and water resources systems is shown in Fig. 16.

Fig. 16- Diagram of the methodology sequence.



As depicted in Fig. 16, the steps followed to perform this analysis can be grouped into three common analytical procedures:

(a) Data collection and processing. First, extensive research and analyses of the available data were carried out to generate a sound comprehensive database. Information was obtained from different statistics, publications, official spatial data catalogs, fieldwork, etc., and it was processed using statistical techniques and geographical information tools. This part of the methodology will be explained in the description of the model development.

(b) Development of the economic and hydrology models. A non-linear, farm-based mathematical programming model (MPM) formulated in GAMS was developed to optimize land use decisions and to replicate the behavior of different farm types, which were aggregated at the regional level (Irrigation Community scale). Concurrently, a hydrology simulation model, configured as a contiguous set of sub-catchments using WEAP, was developed to simulate watershed hydrologic processes, infrastructure operation, and to provide basin-scale insights about water management and planning.

(c) Modeling integration and simulation results. Finally, the economic and the hydrology model were coupled using different simulation engines to facilitate the input/output exchange of data on an annual basis. The economic model generates yearly predictions regarding farm income, public expenditures, the use of irrigation technology, crop mixes, water consumption, etc., whereas the hydrology model provides monthly information about water demand, supply, runoff, evapotranspiration requirements, streamflows, water storage, and other hydrological parameters.

3.4.1. The economic model

The economic model developed in this research is a multi-scale, farm-decision, static (single-year) model that is formulated, in mathematical terms, as a non-linear MPM of constraint optimization. Based on Von Neuman and Morgenstern's theory (1944), we assume that farmers are rational, self-interested individuals who possess a unique order of preferences and who try to maximize their 'expected' utility subject to one or more constraints. During this process, the decisions of farmers (e.g., crop selection) are affected by risk and uncertainty situations, which are mainly provoked by natural hazards and market fluctuations (Ellis, 1993). These conditions lead to instability in farmers' income and cause farmers to be cautious in their decision making, which results in 'risk-averse' decision outcomes (Friedman and Savage, 1948; Mendola, 2007; Walker and Jodha, 1986). In the present study, the objective function corresponds to the farm income minus a variation of that income because of the multiple risks faced by the farmers. The objective function is subjected to land, labor, water and policy constraints. For a detailed specification of the economic model, see Appendix.

Empirical application of the model was carried out in different ICs of the Middle Guadiana basin to allow regional and structural comparisons. In total, 7 ICs (CDO, MCM, MER, TDG, TLR,

VA_1, and ZUJ) were selected for economic modeling. As it can be observed in Table 10, the selected ICs extend over an area of 110140 ha (80% of the total irrigated surface) and represent a wide array of different situations.

Each IC was characterized by one or more types of farms. First, a statistically representative set of farms in terms of the irrigated area, number of farms, soil quality and crop distribution was obtained by analyzing the official data gathered from the Spanish National Statistics Institute (INE, 1999; INE, 2007) and the Regional Department of Agriculture of Extremadura (JE, 2007). Next, this information was complemented with empirical data obtained from a considerable amount of fieldwork conducted from 2008 to 2010 in the study area within the framework of the SCENES[10] project. The fieldwork consisted of targeted surveys addressed to IC managers and individual farmers. In total, 4 ICs (MCM, MER, TDG and ZUJ) and 107 farms (4655 ha) comprising 21 different municipalities were surveyed. Information obtained from the ICs served to complete the characterization of the irrigation units, while data collected from the farm surveys were mainly used to enrich the characterization of representative farms. The real farms were clustered into homogeneous groups using their geographical location, total irrigable surface and crop mix as discriminant variables. This clustering technique, which is widely used to represent the system diversity of the farmers in a given region (see Bazzani et al., 2005; Gómez-Limón and Riesgo, 2004; Köbrich et al., 2003; Maton et al., 2005; Poussin et al., 2008), allowed us to define different types of farms and to obtain a broader realistic picture of the agricultural practices and techniques followed by each type of farm. Finally, 14 representative farms covering 11 municipalities and 3 agricultural regions of varying characteristics were selected. A detailed description of these farms is presented in Table 11.

[10] 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 11- Representative farm types in the Middle Guadiana basin.

Farm type code	IC code	Location (municipality)	Average farm size (ha)	Surface weight in the IC (%) & Representative are within IC (ha)	Agricultural region/Soil quality	Crops (% of the total farm surface)[a]					
F_1	CDO	Don Benito	35 (Medium)	54% (21643)	Don Benito/ Standard quality	Rice 42	Maize 25.5	Tomato 20	Peach 10	Set-aside 2.5	-
F_2		Villar de Rena	25 (Small)	25% (10100)		Rice 100	-	-	-	-	-
F_3		Santa Amalia	15 (Small)	21% (8657)		Maize 45.5	Rice 25	Tomato 25	Set-aside 4.5	-	-
F_4	MCM	Montijo	30 (Medium)	76% (8056)	Mérida/Good quality	Maize 41	Tomato 25	Peach 20	Olive 5	Wheat 4.5	Set-aside 4.5
F_5		Puebla de la Calzada	10 (Very Small)	24% (2544)		Tomato 60	Maize 36.4	Set-aside 3.6	-	-	-
F_6	MER	Mérida	100 (Very Big)	100% (5215)	Mérida/Good quality	Peach 30	Maize 27.3	Tomato 20	Olive 20	Set-aside 2.7	-
F_7	TDG	Badajoz	90 (Very Big)	53% (8101)	Badajoz/ High q.	Maize 40	Tomato 20	Peach 15	Olive 10	Melon 10	Set-aside 5
F_8		Guareña	20 (Small)	47% (7126)	D.Benito/ Standard q.	Maize 54	Rice 25	Tomato 10	Set-aside 6	Peach 5	-
F_9	TLR	Badajoz	75 (Big)	49% (3516)	Badajoz/ High quality	Maize 53	Wheat 15	Tomato 10	Plum 10	Set-aside 7	Vineyard 5
F_{10}		Talavera La real	25 (Small)	51% (3660)		Maize 50	Wheat 22	Tomato 10	Set-aside 8	-	-
F_{11}	VA_1	Acedera	40 (Medium)	100% (3757)	Don Benito/ Standard q.	Rice 50	Wheat 24	Maize 16	Set-aside 10	-	-
F_{12}	ZUJ	Don Benito	60 (Big)	49% (10371)	Don Benito/ Standard quality	Maize 49	Tomato 23	Olive 15	Rice 7	Set-aside 6	-
F_{13}		Villanueva de la Serena	35 (Medium)	19% (3989)		Peach 40	Plum 20	Maize 15	Maize 15	Tomato 5	Set-aside 2
F_{14}		Guareña	25 (Small)	32% (6781)		Maize 40	Tomato 35	Olive 20	Set-aside 5	-	-

[a] Set-aside represents set-aside land (CAP requirement)

Thus, 7 MPMs were developed, one for each of the selected ICs represented as a weighted (by surface) sum of one or more representative farms. Each of the developed MPMs maximizes the regional expected utility at the IC scale, while keeping the specificities of individual constraints. This modeling approach has been adopted in similar studies on integrated economic and environmental analyses of agricultural systems (Blanco et al., in press; Flichman et al., 2006; Henseler et al., 2009; Rounsevell et al., 2003), where it was found very useful to study the potential policy and climate impacts at different level of analysis (at the farm and regional levels).

The technical coefficients of the model (yields, variable costs, prices, subsidies, water and labor requirements, etc.) were obtained from fieldwork data, a local agricultural consultancy firm (TEPRO, www.tepro.es), and different official statistics and reports (see CHG, 2006; MAPA, 2005a; MAPA, 2007; among others).

The model was written in GAMS (General Algebraic Modeling System, www.gams.com, Rosenthal, 2008) and employs the non-linear solver CONOPT3 to compute the optimal solution by obtaining the values of the decision-making variables (optimal cropping mix) that satisfy all of the constraints and maximize the value of the objective function. The model was calibrated with the risk-aversion coefficient within a range of values varying from 0.9 (F4) to 1.5 (F9 and F11). As predicted by the economic theory, a more pronounced risk-averse attitude was observed among small landholders than among large landholders (Hazell and Norton, 1986; Lipton, 1968; Mendola, 2007). Likewise, the model was validated using the percentage absolute deviation (PAD)[11] parameter to compare the crop mix simulated by the model with the actual crop distribution determined for 2007. The PAD values obtained from the model ranged from 3 (F1) to 15.6 (F12), and all of them were below the threshold level of 20% proposed by Hazell and Norton (1986, pp. 271), which determines the rejection of an MPM for economic analysis.

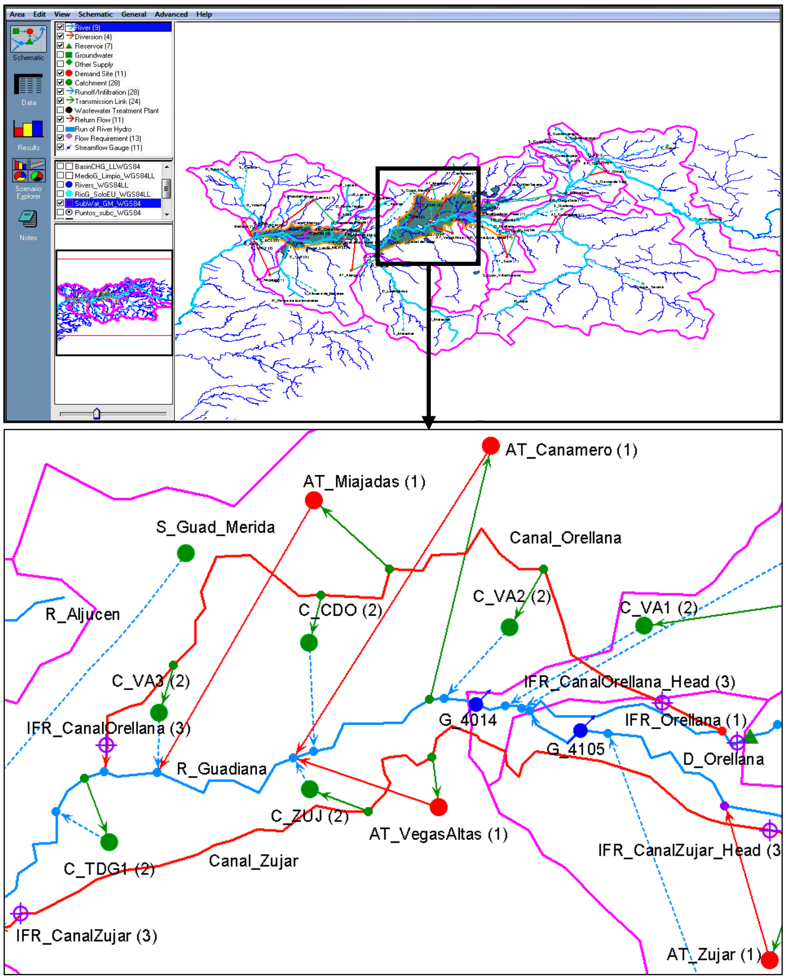
[11] $PAD(\%) = \sum_{c-n}^{n} \left| \overline{X_c} - X_c \right| \cdot 100 / \sum_{c-n}^{n} \overline{X_c}$; $\overline{X_c}$: observed surface; X_c: simulated surface.

3.4.2. The hydrology model

The Water Evaluation And Planning (WEAP) model is a Decision Support System (DSS) software platform developed by the Stockholm Environment Institute (SEI) to support integrated water resources management and planning (Raskin et al., 1992) (http://www.weap21.org/). The WEAP model is unique compared to other water resource tools because it integrates the watershed-scale physical hydrologic processes with the simulated management of the water resources infrastructure and water allocation mechanisms into a common modeling platform (Groves et al., 2008). Based on the 'water-balance' accounting principle (inflows equal outflows), WEAP simulates catchment processes such as evapotranspiration, runoff and deep percolation on a user-defined time interval, typically a month. Subsequently, the model allocates the residual water among the competing demands using a priority-based linear optimization algorithm that takes into account different demand priorities and water supply preferences (Yates et al., 2005a; Yates et al., 2005b). The WEAP software is programmed in Delphi Studio® language (Borland Software Corporation) and uses the MapObjects® software libraries from the Environmental Systems Research Institute (ESRI) to provide geographic information system (GIS) functionalities to the model (Vogel et al., 2007). Thus, the WEAP platform offers a user-friendly, GIS-based graphical interface that allows the user to easily create, view and modify the representation and data associated with a particular water system; it also facilitates the interactions and involvement of stakeholders in the development and application of the model (Purkey et al., 2007). The inputs and outcomes of the model can be presented in a wide variety of formats (maps, charts, tables) and imported from/exported to other software. WEAP provides a practical yet robust framework for water assessment and policy analysis, as previously demonstrated by a wide variety of WEAP applications worldwide (see e.g., Assaf and Saadeh, 2008, in Lebanon; Höllerman et al., 2010, in Benin; Levité et al., 2003, in South Africa; Rosenzweig et al., 2004, in some parts of South America, Europe and China; Vicuña et al., 2010, in Chile; Young et al., 2009, in USA; among many others).

In the present study, the WEAP model has been specified, calibrated and validated for the Middle Guadiana basin. Fig. 17 shows the WEAP interface and a schematic of the Middle Guadiana basin, i.e. the main hydrologic elements and their linkages within the basin as depicted in the WEAP platform.

Fig. 17- The WEAP interface and zoomed WEAP layout of the Middle Guadiana basin.



As shown in Fig. 17, the management of the system has been represented by rivers (blue lines), water diversion systems (orange lines) and reservoirs (green triangles). Rivers include the Guadiana River (headflow) and eight major tributaries (labeled R_). Water diversions refer to the four main irrigation canals (Orellana, Zújar, Montijo, Lobón) that supply water to the different ICs (labeled Canal_). The reservoirs (labeled D_) correspond to big seven dams, which hold 90% of the total storage capacity in the Middle Guadiana basin (7000 Mm^3). The GIS spatial hydrology data (river networks, reservoirs locations, basin boundaries, etc.), monthly time series of river and canal flow rates (1915-2000), evolution of storage levels (1946-1998), reservoir evaporation rates and elevation-capacity curves, operations rules, etc., were obtained mainly from the Guadiana RBA (www.chguadiana.es) and complemented using a wide variety of national and European sources, such as the National Geographic Institute of

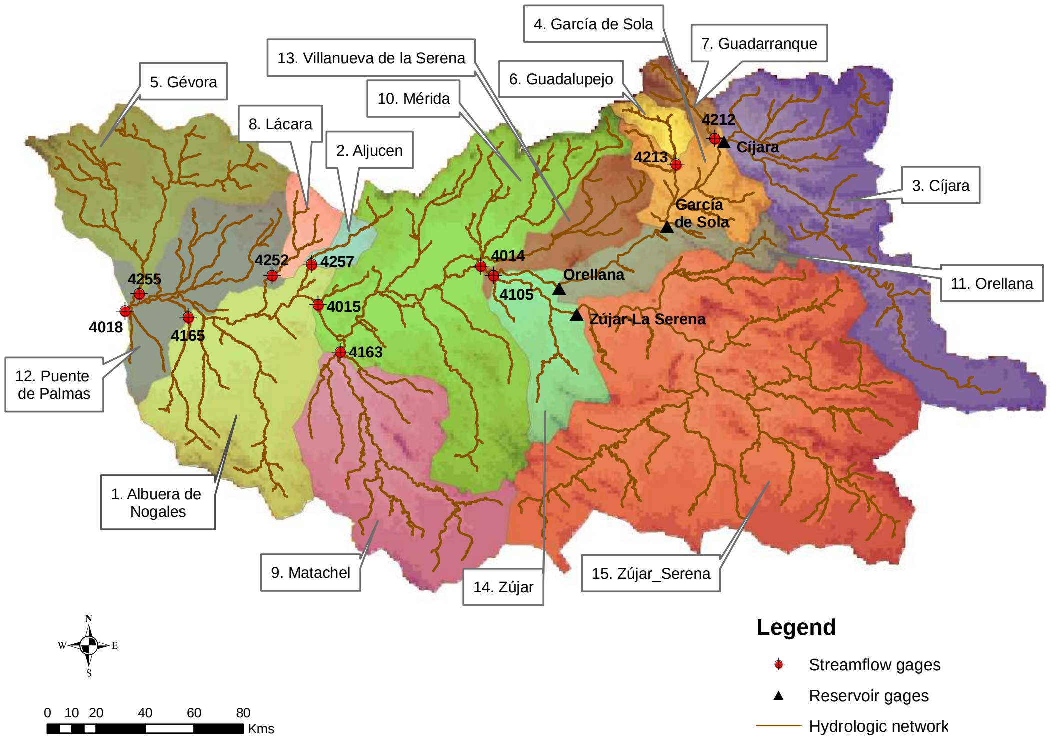
Spain (IGN) (www.ign.es), the Integrated Water Information System (SIA) of the Spanish Ministry of Environment and Rural and Marine Affairs (MARM) (www.marm.es), the Environmental European Agency (www.eea.europa.eu/), and the Joint Research Center of the European Commission (www.ec.europa.eu/dgs/jrc/index.cfm).

The WEAP representation of water demand nodes is symbolized by red dots (see Fig. 17). Tags starting with AT_ indicate an 'association of towns' and represent the domestic water use of 11 groups of municipalities/towns that share the same mechanisms for water supply and waste water disposal. Population data and trends from 1971 to 2008 were collected from different municipal censuses developed by the Spanish National Statistics Institute (INE, 1991; INE, 2001; INE, 2008). Annual domestic water consumption rates and monthly variations were obtained from studies and data provided by the Guadiana RBA and the MARM (CHG, 1998; CHG, 2006). For the present study, it has been assumed that domestic demands use 20% of the inflow received from rivers or canals (i.e. 20% is lost from the system), and the remainder is returned to the system through return flow connections (red arrows).

Other elements included in the WEAP representation of the Middle Guadiana basin are the stream-flow gauges (labeled G_ and characterized by dark blue dots with diagonal lines, see Fig. 17) and the in-stream flow requirement objects (tagged IFR_ and symbolized by purple cross circles), which are set to mimic river basin management rules. The green dots (catchments) with blue dotted arrows (runoff/infiltration links) in Fig. 17 represent the spatial watershed elements that direct inflows to the rivers. The objects labeled S_ refer to the catchments dominated by natural vegetation or non-irrigated arable land (their boundaries are indicated by pink colored lines), whereas C_ symbolizes the catchments that contain some percentage of permanently irrigated land. The numbers in brackets, which are associated with demand nodes and irrigated catchment objects, specify the demand priorities for water use as established by the Spanish Water Law and the Guadiana Special Drought Management Plan (CHG, 2007): first, water for domestic use; and second, water for agriculture.

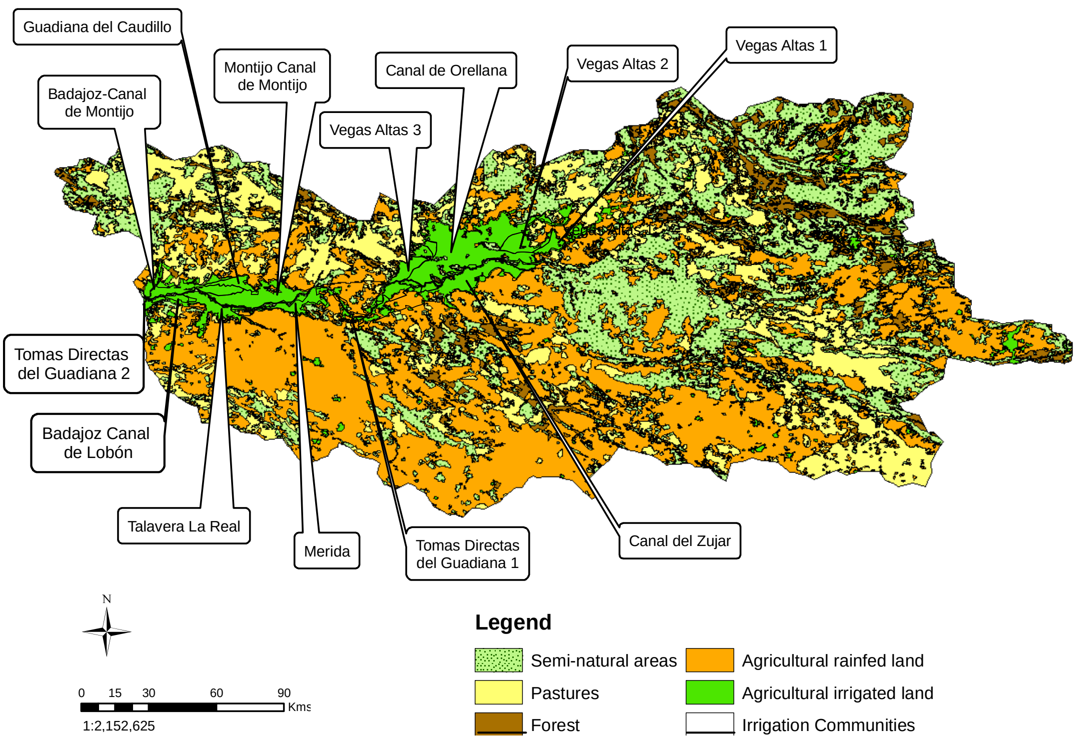
To delineate the catchments, first, 11 streamflow gauges and 4 reservoirs with a good record of the data for the calibration period (1970-1990) were selected as watershed pour points or watershed outlets. Next, using some of the hydrologic functions of the GIS software ArcEditor and a Digital Elevation Model (DEM) with a resolution of 90 m obtained from the US Geological Survey (USGS) (http://www.seamless.usgs.gov/), the flow directions, streams, and catchment boundaries were calculated. Fig. 18 shows the selected pour points and the spatial distribution of the 15 catchments created.

Fig. 18- Pour points and watersheds of the Middle Guadiana basin.



Each of the catchments was associated with spatially interpolated climate data with a resolution of 0.5 degrees. The CRU TS 2.1 Global Climate Database from the Consultative Group on International Agriculture Research (CGIAR) (Mitchell and Jones, 2005) was used to obtain monthly time series of mean temperature and precipitation for the period 1901-2002. Other climatic data related to relative humidity and wind speed were gathered from the Irrigation Advisory Service of the Extremadura Autonomous Community (REDAREX, http://aym.juntaex.es/) and the Spanish State Meteorological Agency (AEMET, 2004). Additionally, within each catchment, the area was subsequently divided into five categories of land use classes (seminatural area, forest, pasture, non-irrigated agricultural land and irrigated agricultural land), which totaled 100% of the total catchment area. Land cover spatial information was obtained from digital maps at a scale of 1/50000 from the MARM (MAPA, 2005b) and from the CORINE Land Cover database of the IGN, which contains digital maps at a scale of 1/100000, with up to 85 classes of land use types for 1990 and 2000 (IGN, 2004). Based on the similarities in agronomic and hydrological properties and with the aim of simplifying the study, the different land use classes obtained from official data were aggregated into the five land categories described in this study. Because the hydro-economic modeling exercise presented herein focuses on the study of agriculture-water links, the irrigated areas defined in the new stylized land use classification were considered as independent catchments and identified with the 12 ICs selected for the economic modeling to facilitate the integration of the hydrology and the economic models. The IC of Tomas Directas del Guadiana (TDG), which is dispersed all along the Guadiana River, was represented by two irrigated catchments: C_TDG_1, situated in the upper part of the basin, and C_TDG_2, located downstream on the Guadiana River. Fig. 19 shows the land use distribution of the Middle Guadiana basin and the selected irrigated catchments.

Fig. 19- Land cover and main irrigation communities in the Middle Guadiana basin.



To satisfy the irrigation requirements, irrigated catchments carry water from several sources (rivers, reservoirs, and mainly irrigation canals) that are subjected to specific government-determined water allotments (as established in Table 10). Catchment inflows (or water allotments) are considered *key assumptions* in WEAP and are represented by the flow rates associated with the water transmission links (green arrows, see Fig. 17). A percentage of the flow that passes through the links was assumed to be lost to reflect the evaporative and leakage losses of the conveyance systems and the technical efficiency of the different irrigation canals.

The hydrological processes that operate within a catchment were simulated using the 'Rainfall-Runoff Model' in WEAP. This model considers a one-dimensional, two-compartment soil moisture scheme to calculate evapotranspiration, surface runoff, sub-surface runoff (interflow) and baseflow for each fractional area (land class) of a watershed unit or catchment (SEI, 2010). For a detailed description of the algorithms and the function of the model, see Yates (2005a) and Yates (2005b). Specification of the rainfall-runoff method was performed by estimating the value of a set of hydrologic parameters for each land class: crop coefficients (k_c); runoff-resistance factor (*Rrf*); preferred flow direction (*fd*); effective water-holding capacity of the upper and deep soil layers (*swc* and *dwc*); hydraulic conductivity rates of the upper and deep soil layers (K_1 and K_2); storage capacity of the upper and deep soil layers (Z_1 and Z_2). The range of possible values and the initial value estimates were obtained from different sources, in particular from the FAO reports (Allen et al., 1998), the REDAREX, http://aym.juntaex.es/), the Agroclimatic Information System of the MARM (www.mapa.es/siar/), and similar WEAP (CCU-SEI, 2009; Vicuña et al., 2010; Young et al., 2009). During the process of model calibration, the initial values assigned to the most sensitive hydrologic parameters (*Rrf, fd, swc,* K_1 and K_2) were adjusted to improve the hydrologic and water resource simulation. The calibration was performed manually using the Bias and the Nash-Sutcliffe statistical parameters[12] (Nash and Sutcliffe, 1970) to compare simulated and observed monthly river flow rates at different watershed pour points situated along the basin, preferably in the outlets of natural watersheds, which are only slightly altered by human actions. The calibration interval was set from 1974 to 1990 based on the quality of the available river flow data and the variations

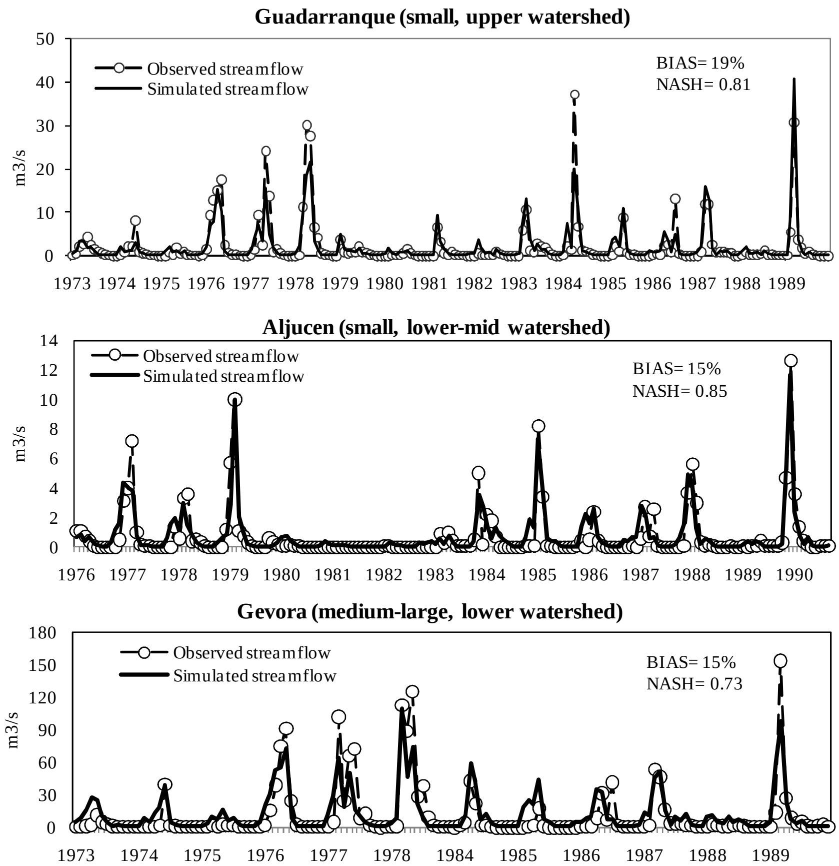
[12] $BIAS = 100\left[\left(\overline{Qs} - \overline{Qo}\right) / \overline{Qo}\right]$; $NASH = 1 - \left[\sum_{i=1}^{n}\left(Q_{s,i} - Q_{o,i}\right)^2 / \sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)^2\right]$, where $\overline{Q_s}$ and $\overline{Q_0}$ are the average simulated and observed flow rates, and Qs,i and Qo,i are simulated and observed flow rates for each time interval (i).

observed in the average climate, which had to be significant to avoid possibly biased assessments. Table 12 shows the values adopted by the hydrologic parameters with a calibrated model. Fig. 20 illustrates the computed (dashed line) and observed water flows in three selected watersheds with different sizes and locations.

Table 12- WEAP calibration parameters.

Calibration parameters	**CODE**	**Agricultural land**	**Forest**	**Pasture**	**Seminatural area**
Crop coefficient	K_c	1.17	1	0.9	0.7
Runoff resistance factor	*Rrf*	4.5	5	3	2
Flow direction	*Fd*	0.5	0.5	0.5	0.5
Root zone water capacity (mm)	*Swc*	850	750	950	150
Root zone hydraulic conductivity (mm/month)	K_1	150	150	150	150
Relative storage of the root zone (%)	Z_1	30	30	30	30
Deep water capacity (mm)	*Dwc*	1000	1000	1000	1000
Deep hydraulic conductivity (mm/month)	K_2	20	20	20	20
Relative storage of the deep zone (%)	Z_2	40	40	40	40

Fig. 20- Observed and simulated streamflows in different watersheds of the Middle Guadiana basin.



As evident in Fig. 20, the model calibration provided reasonable results, with a Nash-Sutcliff efficiency index ranging between 0.73 and 0.88 and a Bias deviation coefficient varying from -12% to +15%.

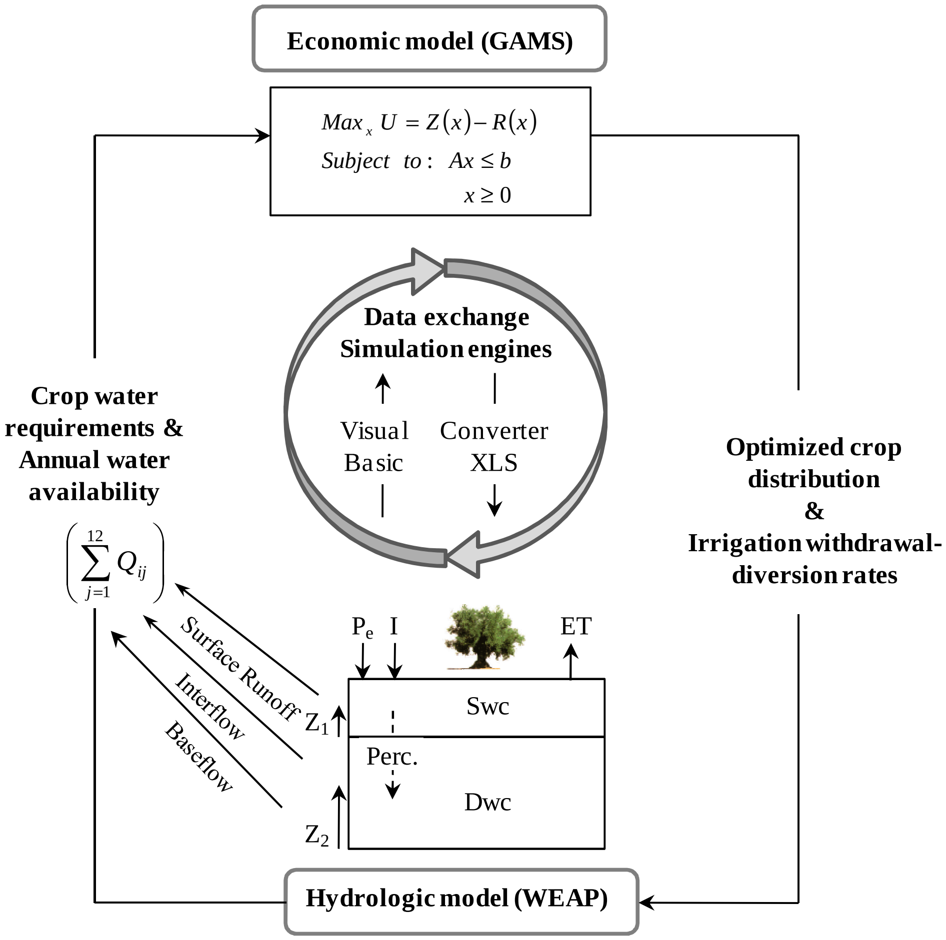
3.4.3. Hydro-economic model linkage

WEAP and GAMS offer many possibilities for interacting with external programs. The WEAP platform provides standard dynamic interfaces with other models (MODFLOW, a groundwater flow model, and QUAL2K, a surface water quality model) and facilitates its communication with other programs (e.g., KNETS, a tool for eliciting knowledge from domain experts, and PEST, a parameter estimation tool) by allowing the creation of new variables and modeling expressions, Dynamic-Link Libraries (DLL), and scripts (VB script, JavaScript, etc.). On the other hand, GAMS can be remotely activated using intermediate programs (Visual Basic, C, Java, Delphi, etc), but since GAMS algebraic statements are highly context-specific general interface routines have not yet been developed. Currently, only few tools are prepared to interact with GAMS (e.g. Matlab, Veda, Stata, Shademap) and most of the interfaces focus on the use of the multiple GAMS capabilities for importing/exporting data in a wide variety of formats (ASCII, HTLM, XLM, GDX, Excel, Database, LATEX, etc.).

In this study, WEAP and GAMS operate in a stand-alone mode, but they can also communicate with one another via a semi-automated connection developed to facilitate data-interoperability (Blanco, under revision). To develop this connection, the WEAP model was run remotely as a COM Automation Server in Excel using the Application Programming Interface (API) of WEAP (see Sieber and Purkey, 2007). Written in the Visual Basic for Applications programming language (VBA), Excel macros were recorded to activate WEAP, output results to Excel spreadsheets, edit WEAP outcomes and save them directly into the GAMS system directory as Excel files (.xls). Likewise, GAMS was set up to import data from and export data to Excel via GDX (GAMS Data eXchange) files using the GDXXRW utility (Rosenthal, 2008). Although GAMS models are capable of exchanging data in comma-separated text files (.csv), which is the format preferred by WEAP to read spreadsheet data, the GAMS results were exported into the WEAP area directory as Excel files because of the easy and transparent data manipulation provided by the GDX utilities. GAMS outcomes were then converted into CSV files using an external free program (Converter XLS) and introduced into WEAP through the WEAP 'ReadFromFile' function, thereby closing the WEAP-GAMS connection circle. Fig. 21

summarizes the data-managing interface and illustrates the iterative input-output exchange of data between the hydrology model (WEAP) and the economic model (GAMS) developed for the Middle Guadiana basin.

Fig. 21- Schematic representation of the iterative feedback loop between the hydrology and the economic model.



Notes: P_e: effective precipitation: I: irrigation: ET: evapotranspiration: Perc.: percolation: Swc: soil water capacity: Dwc: deep water capacity: Z_1: storage of the root zone ; Z_2: storage of the deep zone; U: regional utility function; Z: net income function: R: risk function: x: vector of production or activity levels (n x 1): A: matrix of technical coefficients (n x m): b: vector of input resources available (1 x m): Q_{ij}: annual water availability per irrigated catchment (*i*, irrigation community; *j*, month of the year)

As shown in Fig. 21, the models are run sequentially and provide updated information after each of the model executions. Unlike most hydro-economic models on irrigation water use (see e.g., Ahrends et al., 2008; Bharati et al., 2008; Maneta et al., 2009b) in which the hydrology model is run first to calculate the volume of water available under natural conditions, our study takes a different approach and initiates the iterations by executing the economic model first because the amount of water available for irrigation in the Guadiana basin is not unlimited, but it is clearly constrained by the annual water concessions (water allotments) granted by the River Basin Authority to the different ICs. This allows us to make a reasonable first approximation of land allocation.

In this context and based on a reference year, the economic model (GAMS) will generate yearly predictions about the optimal crop pattern, employed irrigation technologies and irrigation water withdrawals for each type of farming system, based on the maximum legal water allocation. These estimates are then used to inform the hydrology model (WEAP) about the surface cultivated under irrigation, crop areas, irrigation schemes, and water diversion rates for irrigation. The hydrology model operates using this information on a monthly time interval, and in turn, will provide aggregated yearly data on crop irrigation requirements, evapotranspiration rates, and water availability to the economic model. Additionally, the outcomes of the hydrology model will indicate whether the initial allocation of water is physically possible and whether there exists additional water-binding conditions (in time and space) that limit the actual crop distribution. The results obtained from the hydrology model in terms of new water constraints and irrigation requirements can be passed back to the economic model that will be re-executed, thus restarting the loop (second iteration). The system will converge when the optimal crop mix obtained represents a situation in which water allocation and water consumption are physically feasible, legally permissible and economically more efficient.

3.5. Results and discussion

This section analyzes the results obtained during a single loop iteration or a modeling period of 1 year. The method described in the preceding section to couple the hydrology simulation model and an economic optimization model was tested for the recent year 2007 (current situation), which corresponds to the base year in which the economic model was calibrated and validated.

The WEAP model, which was calibrated for the period 1974-1990, allows for the actual headflow and climate parameters measured in 2007 to be entered as the starting point for future simulations, which implies that it was not necessary to model the complete historical sequence before simulating the integration of the models. However, the areas of the WEAP catchments undergoing irrigation were further subdivided into different categories of farming systems and crop types to replicate the representative farms selected for the economic modeling, and consequently, some of the hydrologic parameters (*Kc*, *Rrf*, *Swc*) initially defined for the agricultural land class as a whole were specified in more detail. Other irrigation-related parameters (e.g. irrigation scheduling, upper and lower soil moisture thresholds for irrigation water use, ponding water regimes) were also further itemized within WEAP using its 'irrigation' module. Water diversions (water use permits) and watercourse conveyance losses were simulated as described in the economic model for the reference year, while other water management operations and urban water demands followed the trend indicated during the calibration period.

3.5.1. Results of the economic model

The results of the economic model in the reference year (2007) for annual farm income, public expenditure, water consumption, water productivity, water costs and labor use by the type of IC and representative farms are summarized in Table 13. The net public expenditure is calculated by subtracting the public collection from the gross public expenditure. Public collection refers to water fees and charges collected by the water authority (basically, water use tariffs), whereas the gross public expenditure includes CAP subsidy payments, which mainly depend on the current and historical crop mix of the farms.

Table 13- Economic performance of the agricultural irrigation systems in the Middle Guadiana basin.

IC code	Farm type code	Farm Income (€/ha)	Net Public Expenditure (€/ha)	Water consumption (m^3/ha)	Water productivity (€/m^3)	Water cost (€/m^3)	Labor Use (working days/ha[a])	
							Hired	Total
CDO	F_1	2039	827	9483	0.21	0.020	8.6	16.1
	F_2	1647	859	13050	0.13	0.015	0.0	6.1
	F_3	1859	1249	9483	0.20	0.020	1.7	8.4
MCM	F_4	2741	470	8075	0.34	0.028	10.7	20.3
	F_5	1564	1105	8075	0.19	0.028	4.0	14.3
MER	F_6	3915	392	5525	0.71	0.040	23.8	31.3
TDG	F_7	2699	592	6175	0.44	0.049	19.8	24.1
	F_8	1349	680	9025	0.15	0.046	2.0	7.5
TLR	F_9	1661	382	6525	0.25	0.034	7.5	12.7
	F_{10}	1182	525	6525	0.18	0.034	0.0	5.8
VA_1	F_{11}	1140	558	8720	0.13	0.019	0.0	3.7
ZUJ	F_{12}	1525	705	6300	0.24	0.045	2.2	8.7
	F_{13}	4111	-5	6300	0.65	0.045	39.8	47.3
	F_{14}	2161	1208	6300	0.34	0.045	2.5	12.1

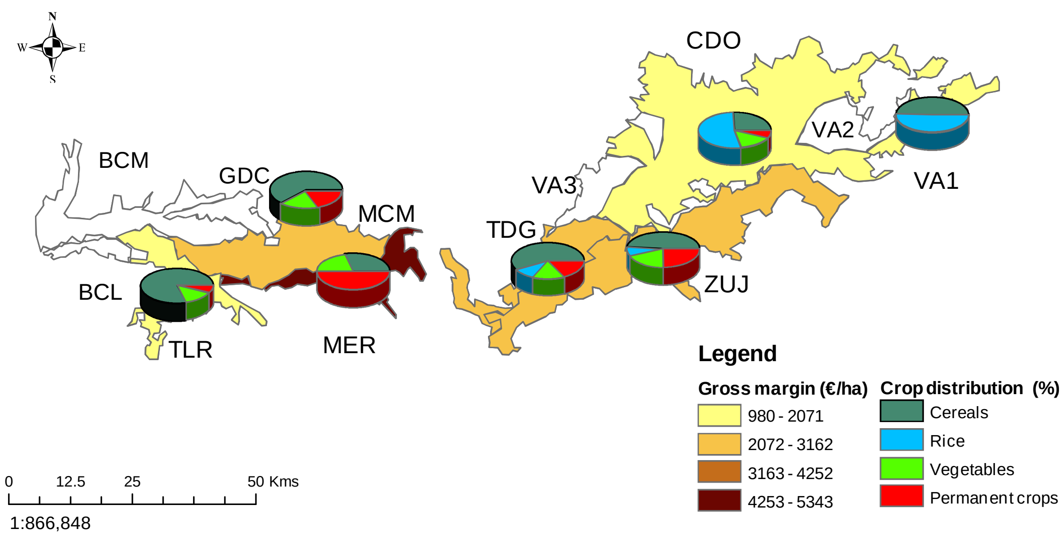
(a) It reflects the total daily labor requirement for each crop in the farm over a year.

The results show the values obtained when the expected utility is maximized at the IC level. The data obtained reveal that the agricultural and water use characteristics of agricultural systems vary widely across the different ICs and representative farms. Farm income ranges from 1140 €/ha in F_{11} (VA1) to 4111 €/ha in F_{13} (ZUJ) and water consumption varies between 5525 m^3/ha in F_6 (MER) and 13050 m^3/ha in F_2 (CDO).

As illustrated in Table 13, the medium scale farm F_{13} of the IC of ZUJ and the large scale farm F_6 of the IC of MER show the highest farm incomes (4111 €/ha and 3915 €/ha, respectively) and water productivity values (0.65 and 0.71 €/m^3). The IC of ZUJ is a modern IC with automated conveyance systems and on-demand pressurize irrigation systems, which allow farmers growing profitable crops (such as maize and tomato) to use a small amount of water (6300 m^3/ha on average). In contrast, the IC of MER is a less modern IC, but it cultivates a large surface area of permanent crops (peach trees and olive trees), which demonstrate low water requirements and provide high revenues per unit of applied water. Fruit trees and vegetables are the most profitable but also the most labor intensive. Hence, medium- to large-scale farms, such as F_{13} (ZUJ), F_6 (MER), and F_7 (TDG), must hire field hands and farm managers (from 20 to

40 working days/ha) to run the farms efficiently. Fig. 22 shows the optimal cropping pattern and the different gross margins of the farms (calculated as revenues minus variable costs) aggregated at the regional level (IC level).

Fig. 22- Spatial representation of the optimized crop pattern and the gross margins of the farms across the selected irrigation communities.



As shown in Fig. 22, there is a direct relationship between the percentage of growing area under permanent crops and the calculated gross margins of the farmers. Thus, the IC of MER shows the highest gross margin value (5343 €/ha) and the highest percentage of surface area cultivated under permanent crops (50% of the total area). The ICs of ZUJ, TDG and MCM demonstrate medium-high gross margin values ranging between 2575 €/ha and 2968 €/ha and have approximately 16-25% and 19-23%, respectively, of their total surface area covered by permanent crops and vegetables. The ICs with large rice and other cereal areas (TLR, CDO and VA1) show the lowest gross margin values, which may drop below 1000 €/ha in some regions of VA1 (968 €/ha on average). These regions also coincide with the areas of lowest farm income (1140 €/ha and 1182 €/ha in F_{11} VA1 and F_{10} of TLR, respectively) and the lowest water productivity prices (0.13 €/m^3 in F_{11} and F_2, in VA1 and CDO, respectively) (see Table 13). Wheat, barley and rice are reliable and low-risk cereal crops, but they are less profitable than vegetables and fruit trees. Rice is grown in ponded soils and, therefore, it consumes large amounts of water per hectare; it is the most water-intensive crop in the study area.

Table 13 indicates that medium-small scale rice producers, such as F_1, F_2 and F_3 in CDO, F_{11} in VA1 and F_8 in TDG, have the highest water consumption rates, which range from 8720 m^3/ha in VA1 to 13050 m^3/ha in CDO. In addition, the IC of MCM (representative farms F_3 and F_4), which demonstrates significant water losses and a low irrigation efficiency, uses high volumes of water per hectare (8075 m^3/ha). This IC is in the process of consolidating its administrative water allotment and makes weekly requests for water to the RBA.

Farms F_7 and $F_{8,}$ both of which belong to the IC of TDG, present the highest water costs (0.049 and 0.046 €/m^3, respectively) because of the extra energy costs (0.04 €/m^3) they must pay to pump water directly from the Guadiana river.

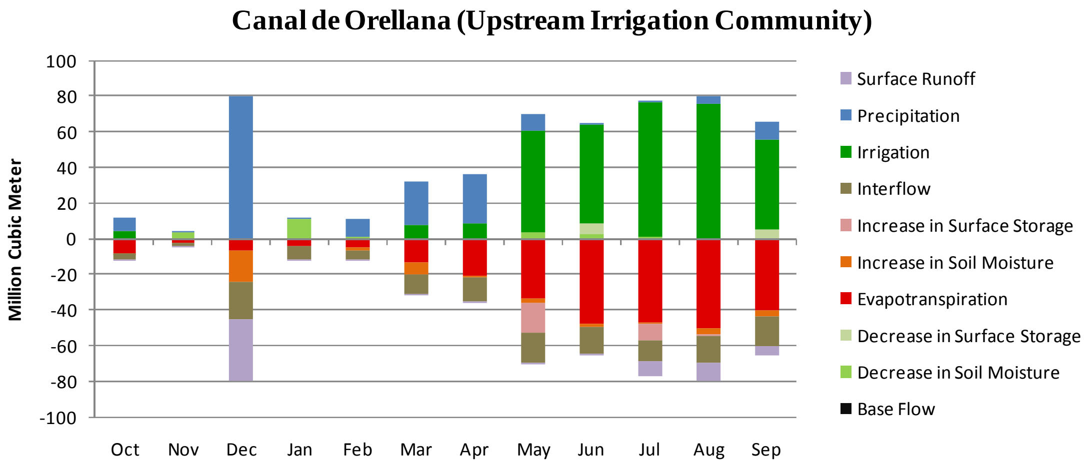
The economic model also allows one to obtain some results about the public sector (public revenue collection and expenditure). Table 13 indicates that the net public expenditure is high in cereal-producing farms, which benefit from direct CAP subsidies (e.g. F_3, F_5, F_{14}), and it is low in farms specializing in the production of fruits and vegetables, which have decoupled payments from production (F_6 and F_{13}).

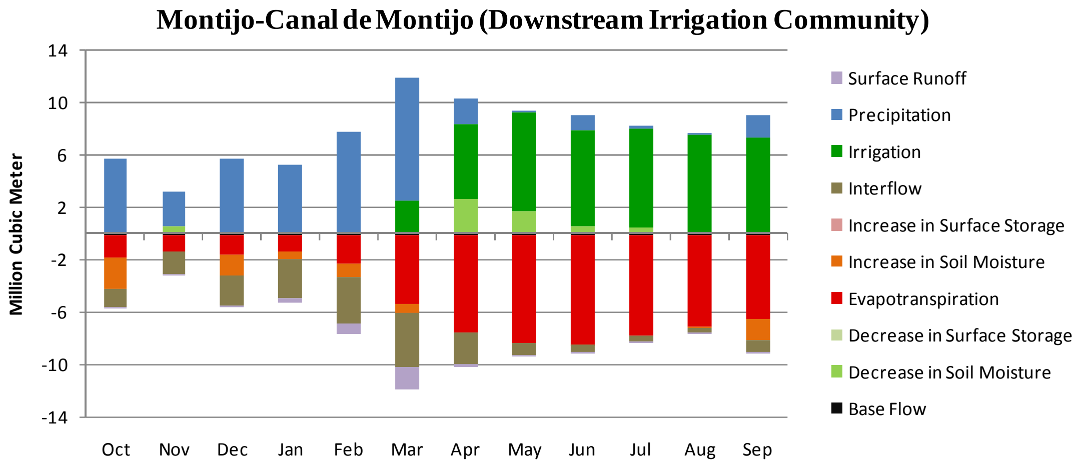
3.5.2. Results of the hydrology model

The WEAP model provided detailed information about monthly inflows and outflows for each of the catchments and their corresponding land sub-classes, subject to the hydrologic conditions of the reference year[13]. The fractional areas within an irrigated catchment were represented by the optimal crop mix obtained from the economic model. Fig. 23 shows the detailed soil water balances for two selected irrigated catchments, the IC of Canal de Orellana (CDO) and the IC of Montijo-Canal de Montijo (MCM), located upstream and downstream on the Guadiana River, respectively. Inflows are characterized by precipitation, irrigation and decreases in soil moisture. Outflows comprise surface runoff, interflow, base flow, evapotranspiration, and increases in soil moisture.

[13] The hydrologic year considered in this research extends from October 1 2006 through September 30 of 2007 and represents a year of 'normal' hydrologic conditions (MARM, 2007a).

Fig. 23- Monthly water balance calculations for two irrigated catchments of the Middle Guadiana basin using WEAP.





As evident in Fig. 23, there is a strong spatial and temporal component of the availability of water and its demands. In the reference situation, the IC located upstream on the river (CDO) received more rainfall (176 Mm^3 or 437 mm) than did that situated downstream on the river (MCM) (41 Mm^3 or 390 mm). In the IC of CDO, precipitation occurs mainly in the late fall (December) and, to a lesser extent, in the early spring months (March-April). In contrast, the IC of MCM receives most of its annual precipitation at regular intervals during the late winter months from February to April. However, as revealed by similar hydrological studies (Ji et al., 2007; Maneta et al., 2009a), in the two selected irrigated catchments, the months with high precipitation coincided with those demonstrating high lateral and deep water percolation (mostly interflow), high surface runoff losses, and low crop evapotranspiration rates. Fig. 23

also indicates that as the dry season advances in May and June, the soil moisture decreases, the ET increases and additional water for irrigation is necessary to supply the crop water requirements.

WEAP uses the Penman-Montieth formula recommended by FAO (Allen et al., 1998) and detailed crop coefficients (Kc) to calculate the different crop evapotranspiration rates. Table 14 depicts a summary of the annual crop evapotranspiration requirements (ET) and irrigation water requirements obtained using WEAP, as specified by the type of crop and irrigated catchment (IC). The ICs and crops described here are those previously simulated in the economic model.

Table 14- Annual evapotranspiration rates (ET) and water irrigation requirements by type of crop and selected irrigated catchments (hydrological year 2006/2007).

Crops	Indicator (m^3/ha)	Irrigated catchment code								Weighted average values (m^3/ha)
		CDO	MCM	MER	TDG_1	TDG_2	TLR	VA_1	ZUJ	
Wheat	ET	-	4488	-	-	4513	4488	4547	-	4494
	Irrigation	-	4543	-	-	4518	4543	4306	-	4454
Maize	ET	7242	7323	7323	7242	7347	7323	7188	7242	7276
	Irrigation	7832	9487	8478	7832	8035	8074	7861	7832	8122
Rice	ET	8013	-	-	-	8356	-	7870	8013	8023
	Irrigation	12333	-	-	-	12876	-	12203	12333	12356
Tomato	ET	5729	5639	5639	5729	5664	5639	-	5729	5703
	Irrigation	7258	7526	5017	5564	4993	5017	-	4839	6234
Melon	ET	-	-	-	4968	-	4942	-	4968	4967
	Irrigation	-	-	-	5508	-	4784	-	4507	5364
Olive	ET	-	3475	3475	3379	-	-	-	3379	3406
	Irrigation	-	2944	2944	2738	-	-	-	2738	2796
Peach	ET	3752	3706	3706	3752	3727	-	-	3752	3734
	Irrigation	4395	4001	3557	3370	3836	-	-	3663	3859
Prune	ET	-	-	-	-	-	3640	-	3682	3669
	Irrigation	-	-	-	-	-	3501	-	3601	3570

As shown in Table 14, different crops have different water requirements. Rice and maize are the most water-demanding crops (values for ET and water irrigation requirements range between 8000-7000 m^3/ha and 12000-7000 m^3/ha, respectively), while fruit trees and olives trees are the lowest water-intensive crops (ET and irrigation rates vary from 3000 to 2000 m^3/ha, respectively). Consistent with the results shown in Fig. 23, crop water requirements are higher in the dry southwestern regions of the basin (MCM, TLR, MER) than in the wet northeastern regions (CDO, ZUJ, TDG1). Nevertheless, it is worth pointing out that the spatial and seasonal differences observed in the evapotranspiration pattern across the different irrigated catchments are less pronounced than the oscillations examined in the precipitation regimes. Evapotranspiration exhibits a more robust behavior.

In comparison with the simulated ET values, the irrigation water requirements shown in Table 14 illustrate a higher variability among the different crops and across the selected irrigated catchments. This result can be explained by the fact that the amount of water needed to satisfy irrigation water requirements depends not only on the physiological characteristics of crops, but also on the methods used to irrigate them. Thus, modern ICs with drip and sprinkler irrigation systems, such as MER and ZUJ, will require lower amounts of water to irrigate their crops than will other ICs with less automated irrigation technologies (e.g., the ICs of CDO and MCM). The economic model takes into account the diverse irrigation water requirements and technical efficiencies of the different irrigation systems[14], but it is not able to achieve the temporal and spatial level of detail provided by the hydrology model. The irrigation water requirements provided by the hydrology model will serve to validate and ameliorate the values used as inputs in the economic model.

The WEAP hydrology model can also indicate whether there is sufficient water available to the farmers during the reference year. Table 15 restates the water allotments assigned to the different ICs (maximum amount of water that can be delivered) and summarizes the simulated results obtained using WEAP regarding the water supply delivered, water demand coverage and water demand reliability. Water demand coverage indicates the percentage of the water requirements that are fully satisfied. Water demand reliability evaluates the percentage of the time segments in which water requirements are met. Hence, the coverage illustrates how well the demands are met, and the reliability parameter allows an explanation of how often the demands are fulfilled (Sieber and Purkey, 2007).

[14] An irrigation efficiency of 0.6 for gravity, 0.75 for sprinkler and 0.9 for drip irrigation was assumed for all crops.

Table 15- Annual water supply delivered, water demand coverage and reliability according to selected irrigated catchments (hydrological year 2006/2007).

IC Codes	Water allotments (m^3/ha)	Simulated WEAP results		
		Supply delivered (m^3/ha)	Coverage[a] (%)	Reliability[b] (%)
CDO	10900	10900	87	83
MCM	7500	7500	95	75
MER	7500	7378	100	100
TDG_1	6600	6437	100	100
TDG_2	6600	6599	90	87
TLR	7500	7500	100	100
VA1	10900	10491	100	100
ZUJ	7000	6833	100	100

[a] % of water requirements met
[b] % of time steps in which water requirements are met

The results show that three of the eight selected irrigated catchments (CDO, MCM and TDG_2) have water demand coverage values of less than 100%, which indicates that they cannot fulfill their water requirements with the initial water allotments assigned. Fig. 24 shows the unmet demand by a selected irrigated catchment, which represents the amount of the water requirement that is not met and estimates the magnitude of the shortage.

Fig. 24- Unmet demand by irrigated catchment (hydrological year 2006-2007).

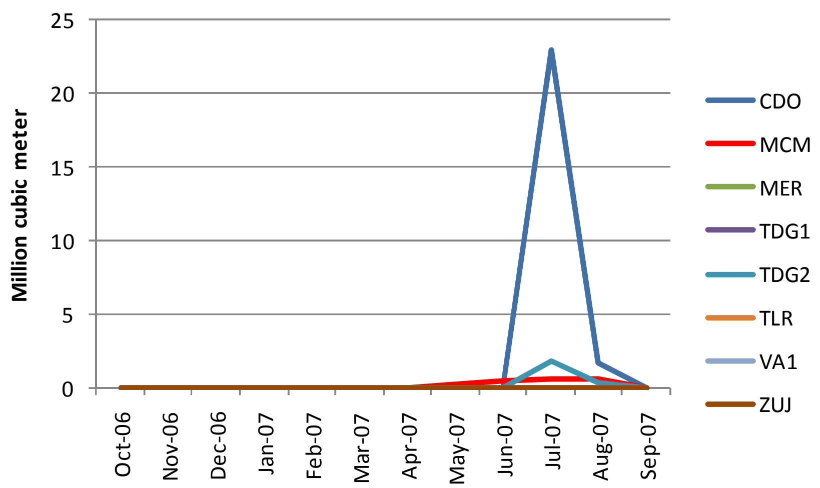


Fig. 24 illustrates the observation that unmet requirements are high in July and August, when water demand for agriculture is highest, and that these requirements are much higher in the CDO IC than in MCM or TDG_2. However, some unmet demand occurs in the IC of MCM for a long period (from May to September), which explains why the water reliability is lower in MCM than in CDO and TDG_2 (see Table 15). CDO and TDG_2 are large rice producers, and therefore, they have high water requirements. MCM also presents high water requirements due to its crop mix (maize and tomato) and low irrigation efficiency. These ICs would require larger water allotments to satisfy their requirements. These results validate those obtained in the economic model (see Table 13).

Our results show that the amount of water available in the Middle Guadiana basin for the reference year does not limit the water needed for urban uses and almost satisfies all of the agricultural demands. This is largely due to the high storage and regulatory capacity of the basin. However, the high demand peaks observed in some irrigated catchments suggest that water shortages may potentially occur more often and may even be aggravated during drought years, if highly water-intensive crops (especially rice) continue to expand and the modernization projects are not fully implemented. Additionally, if the special water allotment (10900 m^3/ha) assigned to CDO was revoked and replaced with an allotment similar to other ICs (7500 m^3/ha), this IC would experience serious adaptation problems.

3.5.3 Limitation of the models

Computer models represent a simplification and simulation of reality and, as such, certain details are inevitably excluded from them. In particular, the input data and model equations used to develop hydro-economic model condition, to a large extent the capability of these tools to represent the complex reality of hydrologic and farming systems. The limitations of hydro-economic models have been discussed elsewhere in several theoretical and empirical studies (Brouwer and Hofkes, 2008; Harou et al., 2009; McKinney et al., 1999; Medellín-Azuara, 2009).

The economic model used in this particular application of a hydro-economic model consists of a single-year model based on a static approach. This type of model implies that permanent crops are assumed to already be in full production and that individuals are considered short-sighted, which indicates that the farmers do not account for possible future conditions in their decision making (Mejías et al., 2004). Other difficulties may arise from the exclusion of financial constraints from the model, and therefore, the farmers are presumed to be financially solvent and to dispose of sufficient financial reserves and net current assets to acquire new production techniques and inputs. The representative farms simulated in the economic model are deemed statistically representative of the different agricultural systems in the study area based on the detailed information gathered during fieldwork performed at the farm level. However, the classification of farmers into homogeneous groups may imply problems of aggregation bias at the regional level (Day, 1963; Gómez-Limón and Riesgo, 2004).

The scale of aggregation is usually a key factor in integrated hydro-economic modeling (Maneta et al., 2009b). Hydrology models capture environmental processes that occur over scales that are larger than individual farms. They are based on large geographical boundaries (generally, catchments units), while economic models usually consider smaller administrative divisions (municipalities, provinces, and regions) (Brouwer and Hofkes, 2008). The hydrology model developed herein is capable of reproducing the farm types and optimal crop mix obtained from the economic model, thus partially overcoming this common limitation. Similarly, the economic model works at both the farm and regional level.

Other conflicts may arise due to the intrinsic construction of the models. Whereas the economic model uses optimization algorithms and yearly time horizons, the WEAP hydrology model uses a more simulation-based approach and shorter time scales (months). Additionally, the WEAP model can reflect the irrigation schedule and the hydro-agronomic parameters of different crops, but it cannot accurately represent the capabilities of the different irrigation systems, which, in contrast, are very well represented in the economic model. This limitation of WEAP may be important in simulating Mediterranean irrigation systems, where the use of pressurized irrigation systems is a viable alternative for efficient water use.

However, all of the limitations described above do not invalidate the use of this type of hydro-economic model, which can contribute valuable information regarding economic and water systems to promote better decision making in water resource management.

3.6. Conclusions and further steps

Physical and economic water scarcity is becoming a critical issue in many parts of the world. It is causing increasing competition for water resources among sectors and social groups and a noteworthy deterioration of water quality. These trends require a more comprehensive and integrated vision of water resources and reveal the need for integrated water management tools such as hydro-economic modeling. The integration of hydrology and economic models allows one to capture the complexity of water resources systems and provides promising insights to improve decision making in terms of planning, water allocation, and institutional and financial design.

This study examined the development of a methodology for linking a multi-scale economic optimization model and a hydrology simulation model, which communicate with each other via data-exchange simulation engines. The economic model used in the present research was written in the GAMS programming language and defined at different spatial scales to capture farmers' behavior at different levels of aggregation (farm level and regional level), which facilitate its integration with the hydrology model. Physical simulations of water demand and supply were conducted using the Water Evaluation and Planning (WEAP) modeling platform, a GIS-based, user-friendly decision support system for integrated water resource planning and management. Both the economic and the hydrology models can operate in a stand-alone mode, but they can also communicate with one another via a semi-automated connection developed in VBA to facilitate data-exchange and data-interoperability.

The prototype hydro-economic model was applied to a large-scale drought-prone area in Spain (the Middle Guadiana basin) to test its capabilities and investigate the local and regional interactions between the environment and the economy in a recent year (2007).

This particular application provided interesting insights about the private sector (farmers' income, labor use), public sector (government collection and expenditure) and the environment (crop distribution, water requirements, water restrictions, unmet demand, intra-seasonal water mass balances), offering sound guidance for water management decision making in the area of the study.

However, a more comprehensive and realistic analysis would have to include multi-year simulations. Extended simulations involving many years will allow us to examine a wider range of climate and policy issues to study how to better cope with increasing challenges in water resource management. Future climate projections, drought strategies and the effects of the European Water Framework Directive (compliance with the environmental water flows or the implementation of water economic instruments) are interesting subjects for analysis in future studies. A more dynamic analysis would also improve the performance of hydro-economic models, as the initial conditions will respond to physical and political issues by considering the decisions made in previous years (Bharati et al., 2008). In addition, computer dynamic simulations provide a good environment for testing and enhancing the applicability of different sub-models (simulation engines) to facilitate the difficult task of automating the interaction between an economic model and a hydrology model.

Hydro-economic models are valuable DSS tools that are increasingly used in participatory and negotiation processes (Harou et al., 2009; Heinz et al., 2007). Hence, future applications should consider the involvement of the stakeholders and the use of these integrated tools in participatory and decision-making processes to support well-informed decisions and to promote a shared understanding of water resources systems and problems.

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3.8. Appendix: Specification of the economic model

This appendix presents the essential elements of the economic model described in the text. Although this model was applied to the Guadiana basin, it was designed to be adaptable to any basin.

Objective Function

Based on the Hazell and Norton (1986) rationale of the mean-standard deviation analysis, the objective function of the model is defined as follows:

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

where U is the regional expected utility at the IC level, Z_f is the average net income by farm type, ϕ_f is the farmers' risk aversion coefficient (risk attitude), and σ_f is the standard deviation of the income distribution by farm type.

The net farm income is calculated by the sum of the farm revenues, including the CAP subsidies minus the variable costs of the production activities, irrigation costs and labor costs. This function is formulated as follows:

$$\begin{aligned} Z_f = & \sum_{c}\sum_{r}\sum_{d} \left(gm_{c,r,d} + sb_{c,r,d} \cdot md \cdot cp \right) \cdot X_{c,r,d,f} + sfp_f \cdot md \cdot numf_f - \sum_{l,p} lab_{l,p,f} \cdot cla_l \\ & - sirrg_f \cdot \left(it + wtarif + rbf \right) - wc_f \cdot \left(uwc + wpc \right) - tech_f \cdot \sum_{pis} ann_{pis} \cdot snp_{pis,f} \end{aligned}$$

where $X_{c,r,d,f}$ is the set of production activities defined by a combination of crop types *(c)*, production techniques (r), agricultural regions *(d)*, and farm types *(f)*; $gm_{c,k,d}$ is the gross margin (revenue minus variable costs); $sb_{c,r,d}$ is the Common Agricultural Policy (CAP) direct aids; *md* is the modulation rate; *cp* is the coupling rate; sfp_f is the single farm payment (decoupled subsidies of the CAP); $numf_f$ is the number of farms; $lab_{l,p,f}$ is the farm labor, which depends on the types of farm workers (family or hired workers) *(l)*, the season of the year *(p)* and the type of farm *(f)*; cla_l is labor costs (family labor opportunity cost and wage for hired labor); $sirrg_{i,f}$ is the irrigated surface; *it* is the tax for the irrigated surface paid to the ICs; *wtarif* is the water use tariff paid to the RBA; *rbf* is the water supply fee paid to the RBA; wc_f is the water consumption; *uwc* is the unitary water cost (uniform charge per volume paid to the ICs); wpc_f

represents water pumping costs; $tech_f$ is a binary variable that represents the need for investment in irrigation technologies; ann_{pis} is the annuity payout of the investment costs incurred when purchasing new pressurized irrigation systems (sprinkler or drip irrigation systems); and $snp_{pis,f}$ is the transformed surface with new pressurized irrigation systems.

The standard deviation of the income (square root of the variance) is generated by a set of states of nature defined by climate variability (crop yields) and market fluctuations (crop prices) as follows:

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

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

Constraints

The objective function is subjected to the following constraints:

- Land constraints, which limit (a) the area that can be cultivated to the total available land ($surf_f$); (b) the potential irrigated area to the total irrigable land ($sirrg_f$); and (c) the surface cultivated with permanent crops to the quota allocated to grow these crops ($spc_{pc,f}$):

(a) $\sum_{c,r,d} X_{c,r,d,f} \le surf_f$

(b) $\sum_{pis} \left(spis_{pis,f} + snp_{pis,f} \cdot tech_f \right) + \sum_{c,d} X_{c,fu,d,f} \le sirrg_f$

(c) $\sum_{pc,r,d} X_{pc,r,d,f} \le \sum_{pc} spc_{pc,f}$

- Labor constraints, such that the sum of the seasonal labor requirements ($lr_{c,r,p}$) cannot exceed the total farm labor capacity ($lab_{l,p,f}$):

$$\sum_{c,r,d} lr_{c,r,p} \cdot X_{c,r,d,f} \le \sum_{l} lab_{l,p,f}$$

- Water constraints indicate that the net crop water requirements ($wr_{c,d}$) must be met by the total volume of water available ($watera_f$), taking into account the technical efficiency of the different irrigation systems (h_{ri}) and the water conveyance infrastructure (H):

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

- Policy constraints mainly refer to the EU CAP requirement for farmers to remove from production ('set-aside', $X_{sa,r,d,f}$) a given fraction (a minimum of 10%, *smin*, and a maximum of 30%, *smax*) of the cultivated area for cereals, oilseeds and proteins (COP crops) ($X_{cop,r,d,f}$) as a prerequisite to obtain direct CAP payments:

$$s\min \cdot \sum_{cop,r,d} X_{cop,r,d,f} \leq \sum_{r,d} X_{sa,r,d,f} \leq s\max \cdot \sum_{cop,r,d} X_{cop,r,d,f}$$

3.9. References

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4. A dynamic economic-hydrologic analysis of ecologically sustainable water policies under diverse climate conditions and plausible development scenarios

4.1. Abstract

Balancing the trade-offs between agricultural production and ecosystem conservation is at the heart of many water management debates and water conflicts in various parts of the world, especially in arid and semi-arid areas. Researchers and practitioners are increasingly calling for integrated approaches, and policy-makers are progressively including ecological and social aspects in water management programs. Hydro-economic modeling can assist in the development and assessment of sustainable water policies by integrating environmental processes and socio-economic systems at different scales in space and time. In the present study, an integrated hydro-economic model was developed to study the potential effects of different water conservation policies (namely, the Spanish HNP and the European WFD) under diverse climate conditions on the irrigation systems of the Middle Guadiana basin, a large-scale drought-prone region located in south-central Spain. An economic optimization model of farm-decision-making was linked to the hydrologic simulation model WEAP through a multi-scale data management interface. Our findings indicate that the accuracy of the models in predicting farmers' behavior and hydrological processes improves when the economic and hydrology models are coupled together, exchanging data on optimal crop combinations, water availability, irrigation water use, and crop water requirements. Results also demonstrate that water shortages might occur if the current patterns of excessive and low-effective water consumption for irrigation continue in the future, especially in dry years and summer periods when crop water demands increase substantially, depending on the type of crop and geographical location. Incompletely modernized and poorly diversified irrigation districts will be the most economically affected by a reduction in water supply for agriculture, and the most vulnerable when facing dry climate conditions.

Key words: irrigation, economic optimization, hydrology simulation, integrated modeling, water policies, drought.

4.2. 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 addition, other factors such as global warming and the expansion of biofuel production are expected to intensify water scarcity problems, adding extra complexity to water management.

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). The increase in storage capacity over the past few decades has allowed for the expansion of irrigated areas and the distribution of water more evenly throughout the year. Historically, the evolution of irrigation has to a great extent been based on the development of publicly-funded surface irrigation networks and subsidized water deliveries. Irrigation development plans 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, raising serious questions over the environmental and economic sustainability of irrigated systems (Garrido and Llamas, 2010; Varela-Ortega et al., in press). Current 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, enacted by the European Parliament in 2000 (EC, 2000), constitutes the common European policy framework on irrigation water management. This Directive 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), including a program of measures, to help accomplish the Directive’s objectives and to manage the complex basin-scale 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). The Directive urges the use of economic instruments (e.g. water pricing policies) as part of these programs of measures (Art. 9) for recovering the full cost of all water services, and stresses explicitly the importance of performing a basin-scale economic analysis (Art. 5) to identify the most cost-effective measures to reach the WFD's environmental targets (Art. 11). Therefore, the implementation of the WFD requires interdisciplinary work and offers a unique opportunity to incorporate integrated water management strategies into the new RBMP.

In that social, environmental, and policy context, the objective of this research is to develop a consistent integrated methodology that will be able to capture the complex and multifaceted interactions between the economy and the environment to analyze the effects of different water policies and climate conditions on human and natural systems at different spatial scales (from farm-level to river basin-level).

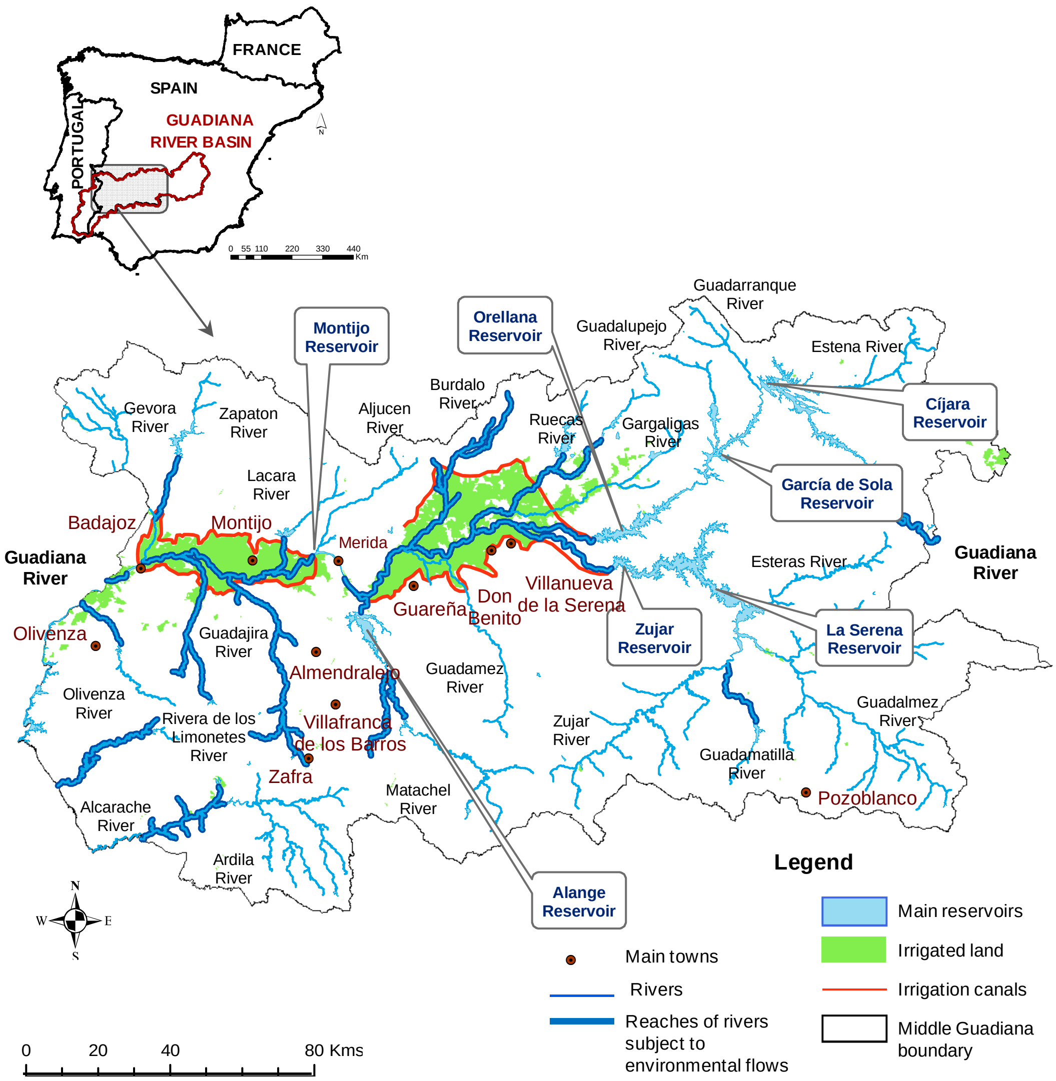
Among the different existing methods for integrated water management (mental models, Bayesian networks, metamodels, risk-assessment approaches, knowledge elicitation tools,and others, see Croke et al., 2007), hydro-economic tools offer a coherent and unique modeling framework to analyze the potential economic, engineering, environmental, and hydrologic implications of water management options and climate-related issues. (Harou, 2009). Hydro-economic models 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).

Most of the hydro-economic models reported in the literature follow a holistic approach (e.g. Cai, 2008; Draper et al., 2003; Pulido-Velázquez et al., 2008).However, compartmental approaches are gaining increasing attention. In compartmental hydro-economic models, the hydrology and economic modules are formatted independently and linked through an external connection. Loss of information may occur when data is exchanged, but independent modules can easily be solved and improved (McKinney et al., 1999). Modular approaches allow for a more complex and detailed representation of reality, as they usually combine complex hydrology and economic models with different spatial and time scales, as well as diverse resolution techniques (simulation and optimization). Recent applications have been developed to study water quality problems (e.g. Volk et al., 2008, linked the hydrology model SWAT to a linear economic model BEMO in the Upper Ems River Basin in Germany), the impact of droughts (e.g. Maneta et al., 2009, coupled the hydrology model MODHMS with a positive mathematical programming model in the São Francisco River in Brazil), groundwater management options (e.g. Qureshi et al., 2008, integrated the groundwater model MODFLOW with an economic and agronomic model in the Burdekin delta in Australia), and land use changes (e.g. Ahrends et al., 2008, coupled the hydrology model WaSIM with a non-linear economic model in the Volta Basin in West Africa).

The present study analyzes the potential implications of national and European water policies under normal and dry climate conditions, using an innovative compartmental hydro-economic model based on the integration of a multi-scale economic optimization model encoded in GAMS, and a hydrology water management simulation model built in WEAP. Both models are connected through automated simulation engines, although they can be solved independently.

Application of the model was carried out in the Middle Guadiana basin, a large-scale surface-irrigated area located on the south-western plateau of the Iberian Peninsula in Spain (see Fig. 25).

Fig. 25- Geographical location of the Middle Guadiana basin.



This region covers a large territory (of about 29402 km^2) with very diverse conditions and valuable ecosystems in biophysical, socio-economic and historical terms, but it 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. Climate change projections for the Guadiana basin indicate that warmer average temperatures and a growing number of droughts will reduce water availability (about 11% by 2030) and raise irrigation demands, increasing the pressures on irrigation systems and water ecosystems (Brunet et al., 2009; CHG, 2007). In this context, it seems likely that current water use for irrigation may be untenable in the future.

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 local to basin-wide levels.

4.3. Methodology: An integrated economic-hydrologic modeling framework

4.3.1. Data collection and analysis

Hydro-economic models, like any other multidisciplinary integrated model, require a vast amount of information and data processing (Cai, 2008). In the present study, a wide variety of sources were used and combined (statistics, publications, on-line data catalogs, experiments, fieldwork, etc.) to provide a reliable database with extensive information about land use, meteorological data, hydrologic networks, water consumption, agricultural costs and prices, agro-hydrological parameters, etc. Collected spatial-temporal data was processed and analyzed using statistical techniques and geographic information systems (GIS). Table 16 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.

Table 16- 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 (DEM)	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			
- Precipitation, temperature, etc.	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 (characterization of 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 & hydrology models
- 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 schedule, 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 & hydrology models
- 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: Allen et al., (1998); CCU-SEI (2009); Young et al., (2009); etc.	Excel, text files	Hydrology model

As seen in Table 16, relevant empirical information regarding the agricultural sector was obtained from field research. Overall, 5 Irrigation Communities (Montijo-Canal de Montijo, MCM; Tomas Directas del Guadiana, TDG; Mérida, MER; Orellana, ORE; and Zújar, ZUJ) and 107 farms comprising 21 municipalities over an area of 4655 ha were surveyed from 2008 to 2010 within the framework of the SCENES project[15]. The information obtained served to characterize the irrigation districts and types of farms in the study area, as well as to obtain the technical coefficients of the economic model (yields, costs, prices, subsidies, labor requirements, etc.).

The Middle Guadiana basin has 145000 irrigated ha and comprises 21 Irrigation Communities (i.e., Water User Associations that are responsible for irrigation water management and decision-making at the local level). For the baseline analysis and for modeling purposes, irrigation districts have been represented by 12 Irrigation Communities (ICs), which cover an area of 136000 ha (95% of the total irrigated surface) and represent the variety of surface-irrigated production systems in the study area. In addition, with the aim of obtaining a close-up picture of the typical agricultural practices and techniques followed by farmers, seven ICs were characterized by one or more representative farms in terms of the irrigated area, number of farms, soil quality and crop distribution. In total, 14 representative farms covering 11 municipalities were selected. Table 17 summarizes the main characteristics of the ICs and farm types selected in the study area for the present research.

[15] 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 17- Characteristics of the main Irrigation Communities and representative farm types in the Middle Guadiana basin.

IC code	Year of creation	Area (ha)	Location (municipality)	Water allotments (m^3/ha)	Water source	Irrigation technology	Farm Types		
							Surf. (ha)	Surf. weight in IC (%)	Crop distribution [b] (%)
BCL	1960	1400	Badajoz	7500	Lobón canal	Gravity, sprinkler, drip	-	-	-
BCM	1962	10500	Badajoz	7500	Montijo canal	Gravity	-	-	-
CDO	1976	40400	Don Benito Villar Rena Sta.Amalia	10 900	Orellana canal	Gravity	35	54%	Ri (42); Ce (25); Ve (20); Fr (10); Sa(3)
							25	25%	Ri (100)
							15	21%	Ce (45) ; Ri (25) ; Ve (25); Sa(5)
GDC	1962	3363	Badajoz	7500	Montijo canal	Sprinkler, drip	-	-	-
MCM	1962	10600	Montijo Puebla Calz.	7500[a]	Montijo canal	Gravity	30	76%	Cr (46); Ve (25); Ol (5); Fr (20); Sa (5)
							10	24%	Vg (60); Ce (36); Sa (4)
MER	1959	5215	Mérida	7500	Lobón canal	Sprinkler, gravity	100	100%	Fr (30); Ma (27); Ve (20); Ol (20); Sa (3)
TDG	1993	21852	Badajoz Guareña	6600	Guadiana River	Gravity, sprinkler, drip	90	53%	Ce (40); Ve (30); Fr (15); Ol (10); Sa (5)
							20	47%	Ce (54); Ri (25); Ve (10); Sa (6); Fr (5)
TLR	1959	7176	Badajoz Talavera R.	7500	Lobón canal	Gravity, sprinkler	75	49%	Ce (68); Ve (10); Fr(10); Sa(7); Vi (5)
							25	51%	Ce (72); Ve (10); Sa (8)
VA1	1976	3757	Acedera	10 900	Dehesas c.- GarcíaSola dam	Gravity	40	100%	Ri (50); Ce(40); Sa (10)
VA2	1976	5751	Don Benito	10 900	Orellana canal	Gravity	-	-	-
VA3	1976	4925	Guareña	10 900	Orellana canal	Gravity	-	-	-
ZUJ	1990	21140	Don Benito Villanueva S. Guareña	7000	Zújar canal	Sprinkler, drip	60	49%	Ce (49); Ve (23); Ol (15); Ri (7); Sa (6)
							35	19%	Fr (60); Ri (18); Ma (15); Ve (5); Sa (2)
							25	32%	Ce (40); Ve (35); Ol (29); Sa (5)

[a] In the process of consolidating its administrative water allotment. Current water consumption is in the order of 8500 m^3/ha; [b] Ri: rice; Ce: cereals (maize, wheat); Ve: Vegetables (tomato, melon); Fr: Fruit trees (peach, plum); Ol: Olive trees; Vi: vineyard; Sa: set-aside.

As seen in Table 17, the selected ICs present very diverse characteristics regarding their year of foundation, surface area, geographical location, granted water allotments, source of water, irrigation technology and representative farm types. Located upstream on the right bank of the Guadiana River is the largest and one of the oldest ICs of the Middle Guadiana basin, the CDO IC. This IC is represented by small-scale rice growers and ponded soils. During the 1991-1995 drought period, this IC experienced severe water shortages and damages, which resulted in large administrative water concessions currently in force (10900 m^3/ha). The ICs of VA1, VA2 and VA3, which were once part of the CDO, present similar characteristics. On the left bank of the upstream river basin, the IC of ZUJ represents a highly modernized IC with small and medium-scale farms where a vast diversity of crops is irrigated with pressurized irrigation systems. This IC limits water consumption to 7000 m^3/ha and charges farmers with a binomial water tariff (122 €/ha and 0.026 m^3/ha), which encourages saving water. Located midstream and downstream on the Guadiana River are the oldest ICs (GDC, MCM, MER, TLR, BCM and BCL). These ICs are undergoing increasing modernization to avoid water loss in conveyance systems and to replace gravity irrigation by more efficient irrigation systems (such as sprinkler and drip). The largest and most representative IC in the mid-downstream regions, MCM, is characterized by very small farms growing well adapted and profitable crops (such as maize and tomato). The IC of TDG represents a very different situation. It is located all along the banks of the Guadiana River and includes irrigators that pump water directly from the rivers. In this IC, water allotments are limited to 6600 m^3/ha, although paddy fields may receive larger amounts of water. TDG is characterized by a small-scale rice-growing farm situated upstream on the Guadiana River, and by a large-scale diversified farm located downstream on the river.

4.3.2. Development of a hydro-economic model

- **The economic model**

A farm-based regional economic model of constrained optimization was developed to simulate farmers' behavior and predict their response to policy and environmental changes. According to Von Neuman and Morgenstern (1944), farmers are considered rational individuals whose behavior is characterized by a self-interested pursuit of maximum utility.

The model, written in the General Algebraic Modeling System (GAMS) programming language (www.gams.com), is formulated as a non-linear mathematical programming model wherein farmers attempt to maximize their regional expected utility (objective function), 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 and labor have to be made. As stated by Friedman and Savage (1948), we assume that farmers' decisions are highly influenced by risk and uncertain situations, and consider that most farmers tend to choose less-risky farm plans even if that means sacrificing part of their potential income (Chavas, 2004; Ellis, 1993; Mendola, 2007; Walker and Jodha, 1986).

The empirical application of the model was carried out in 7 ICs of the Middle Guadiana basin, represented by different farm types (VA_1, CDO, ZUJ, MER, TLR, MCM, and TDG; see previous section). In each of these models, the regional expected utility is calculated as the sum of the net income over all farm types that belong to the IC, minus a variation of that income (risk) due to fluctuations in price and production output. Several studies (such as Blanco et al., in press; Flichman et al., 2006; Henseler et al., 2009; Rounsevell et al., 2003) 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 at the IC level, Z_f is the average net income by farm type (f), ϕ_f is the risk aversion coefficient, and σ_f is the standard deviation of income. Farm income is defined by the following equation:

$$Z_f = \sum_c \sum_r \sum_d gm_{c,r,d} \cdot X_{c,r,d,f} + md \cdot cp \cdot \sum_d \sum_r \sum_d sb_{c,r,d} \cdot X_{c,r,d,f} + sfp_f \cdot md \cdot numf_f$$
$$- oc \cdot \sum_p fla_{p,f} - hlp \sum_p hl_{p,f} - sirrg_f \cdot \left(it + wtarif + rbf\right) - wc_f \cdot \left(uwc + wpc\right)$$

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 associated to different agricultural regions *(d)*, and farm types *(f)*; $gm_{c,k,d}$ is the gross margin of different production activities; $sb_{c,r,d}$ are the CAP subsidies coupled with production; *md* is the modulation rate of the CAP aid payments; *cp* is the coupling rate; sfp_f is the Single Farm Payment (CAP decoupled subsidies); $numf_f$ is the number of farm types f; oc family labor opportunity cost; $fla_{p,f}$ family labor availability by type of season (p) and farm (f); hlp wage for hired labor ; $hl_{p,f}$ hired labor ;; $sirrg_{i,f}$ is the irrigated surface; it water use tariff paid to the IC; $wtarif$ is the water use tariff paid to the RBA; rbf is the river basin fee; wc_f is water consumption; uwc is the unitary water cost (uniform charge per volume); and wpc_f is the cost of pumping water.

Given an average income level, farmers would choose the farm plan that provides the smallest standard deviation of the income distribution. Income variability is generated by a set of states of nature defined by climate (yields) and market (prices) variations. 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 $Z_{sn,sm,f}$ is the random income, and N is the combination of different states of nature ($N=100$).

The objective function is subjected to the following constraints:

- Land constraints, which limit (a) the total area cultivated ($surf_{,f}$); (b) the potential irrigated area ($sirrg_f$); and (c) the surface cultivated with permanent crops ($spc_{pc,f}$):

(a) $\sum_{c,r,d} X_{c,r,d,f} \leq surf_f$

(b) $\sum_{c} \sum_{d} \sum_{f} X_{c,ri,d,f} \leq sirrg_f$

(c) $\sum_{pc,r,d} X_{pc,r,d,f} \leq \sum_{pc} spc_{pc,f}$

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

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

- Water constraints indicate that 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*):

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

- Policy constraints, such that the requirement to set-aside (*$X_{sa,r,d,f}$*) a minimum (*smin*) and maximum (*smax*) of the COP (cereals, oilseeds and proteins) growing area (*$X_{cop,r,d,f}$*) as a prerequisite to receive CAP direct payments:

$$s\min \cdot \sum_{cop,r,d} X_{cop,r,d,f} \leq \sum_{r,d} X_{sa,r,d,f} \leq s\max \cdot \sum_{cop,r,d} X_{cop,r,d,f}$$

Using the NLP solver CONOPT3, the model computes the optimal solution, that is, the optimal crop-area distribution that satisfies all the constraints and gives the best possible value of the objective function (expected utility). In addition, the economic model provides yearly predictions regarding marginal values, farm income, public expenditures and revenues, water consumption, and labor use.

- **The hydrology model**

Different Decision Support Systems (DSS) for River Basin simulation have been applied to water resources modeling such as, MIKE BASIN (Jha and Das Gupta, 2003), RIBASIM (WL Delft Hydraulics, 2004), MODSIM (Labadie et al., 2000), CALVIN (Draper et al., 2003), AQUATOOL (Andreu et al., 1996), among many others. In the present study, the Water Evaluation and Planning (WEAP) modeling platform was used for its exceptional integrated approach to simulating both the biophysical processes and the engineered hydrologic components of water systems, which provide a more comprehensive view of the many factors affecting water resource decision-making (Groves et al., 2008; Sieber and Purkey, 2007; Yates et al., 2009).

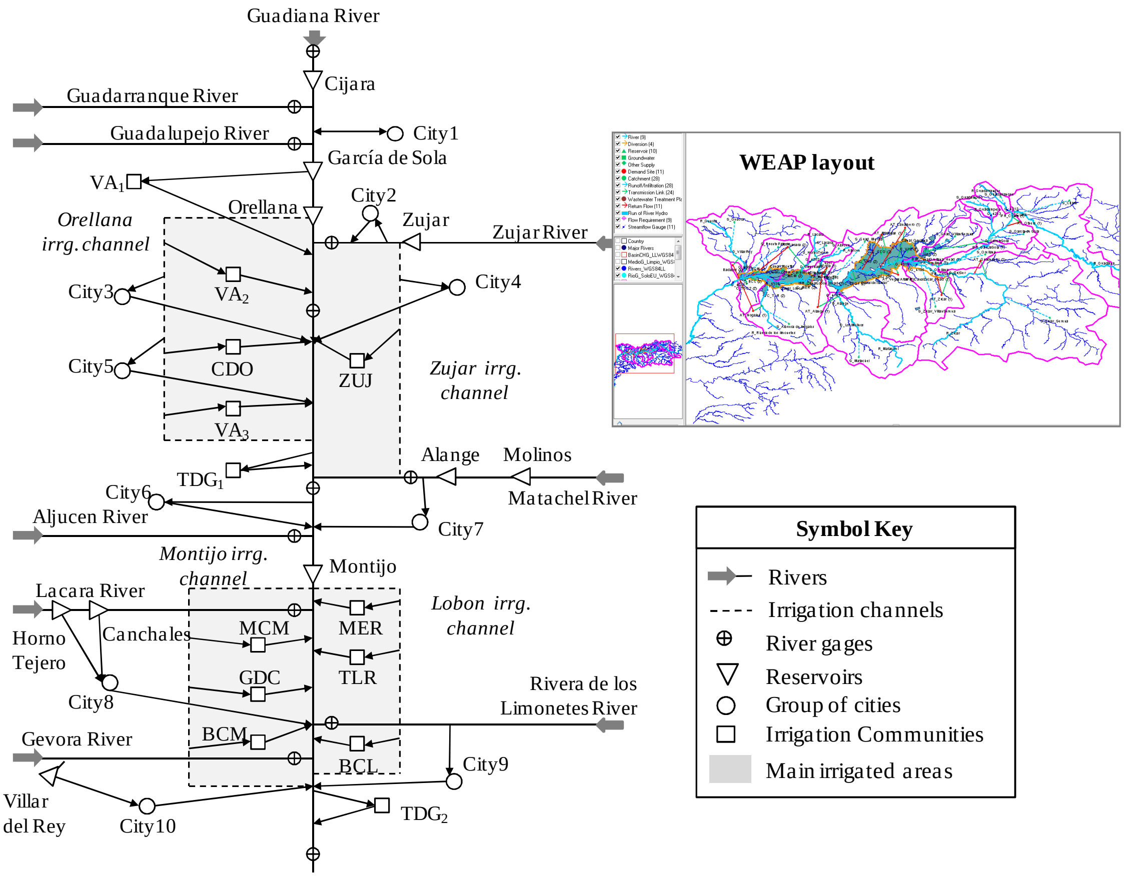
WEAP is an object-oriented computer modeling package developed by the Stockholm Environment Institute's US Center for supporting integrated water resources planning (Raskin et al., 1992) (www.weap21.org). The WEAP model operates on the basic principle of water accounting, and determines the optimal allocation 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) (see Yates et al., 2005a; Yates et al. 2005b for details).

A user-friendly GIS-based graphical 'drag and drop' interface enables users to easily construct, view, and modify the representation of the system and its related data. WEAP is also distinguished by its scenario-driven orientation (Vogel et al., 2007). Using the WEAP scenario editor, different 'what if' scenarios can be developed for exploring the performance of various water management strategies against assumptions about future climate conditions, policy changes or demand developments. These scenarios can be evaluated using different criteria (such as water demand, supply delivered, crop requirements, runoff, infiltration, stream flows, groundwater storage, pollution generation, costs, etc.) and compared, while taking into account a common starting year (the 'Current Accounts Year').

WEAP provides a practical yet robust tool to assist stakeholders and decision-makers in water planning and policy analysis, as proven by the broad range of WEAP applications in a number of basin locations worldwide (see e.g., Assaf and Saadeh, 2008, in Lebanon; Bosona and Gebresenbet, 2010, in Ethiopia; Droubi et al., 2008, in Syria and Moroco; Escobar et al., 2008, in Peru; Höllermann et al., 2010, in Benin; Rosenzweig et al., 2004, in several parts of Asia, Europe and America; Young et al., 2009, in USA; among many others). However, the model is not yet designed for internally analyzing the impact of complex individual behavior on water use and planning, nor does it consider human–environment interaction and feedback. To date, only a few studies have linked WEAP with social science methods. Some examples are those of Purkey et al. (2008), where WEAP is combined with an econometric analysis; of Kemp-Benedict et al. (2010), that illustrate the integration of WEAP with Knowledge Elicitation Tools (KnETs); and of Varela-Ortega et al. (in press) where a farm-based economic model is coupled to WEAP.

In the present study, the WEAP model was used in combination with a multi-scale economic model to analyze the impact of water policies and climate conditions on the different irrigation systems of the Middle Guadiana basin. A schematic representation of the Middle Guadiana basin WEAP application is depicted in Fig. 26.

Fig. 26- Schematic representation of the Middle Guadiana basin WEAP application.



As seen in Fig. 26, the WEAP application for the middle Guadiana River includes the major rivers (the Guadiana river and 8 tributaries); major irrigation channels (Orellana, Zújar, Montijo and Lobón, in total 320 km of channels with average flows ranging from 14 m^3/s to 40 m^3/s); main reservoirs (10 dams and reservoirs with a total storage capacity of 7500 Mm^3, that is, 95% of the total storage capacity in the Middle Guadiana basin); principal irrigation districts (12 Irrigation Communities, represented in WEAP as irrigated catchments); main municipal water demand centers (11 cities or a group of cities sharing water services and costs with a total population of 760000 inhabitants and annual water use rates that vary from 60 m^3/capita to 125 m^3/capita); key stream flow gauges (12 observation points spread spatially across the basin with a historical streamflow record of the last 50 years used to calibrate and validate the hydrology model); and different flow requirements, not represented in Fig. 26, but linked to the irrigation canals and reservoirs to represent water release rates and other common system operations.

In addition, the study area has been characterized by a contiguous set of sub-catchments that cover the entire Middle Guadiana basin. Natural hydrology processes within each catchment unit have been simulated on a monthly-time step using the rainfall-runoff hydrology module in WEAP. This method considers a one dimensional, two-compartment soil moisture scheme to calculate, based on empirical functions, the hydrograph components for each fractional area (land class) of a catchment unit. For a description of the model algorithms, see Yates et al., (2005a); Yates et al., (2005b). According to the two-bucket Soil Moisture Method, each catchment is represented with two soil layers. In the upper layer (root zone), evaporatranspiration is simulated by considering rainfall, irrigation, surface runoff, interflow, deep percolation, and changes in soil moisture, as a function of the following agro-hydrological parameters: runoff resistance factor (Rrf); crop coefficients (*Kc*); soil water capacity (*Swc*);hydraulic conductivity (K_1); preferred flow direction (*Fd*); and relative water storage of the root zone (Z_1). In the lower soil layer, deep percolation is partitioned into base flow or deep soil moisture, depending on the water holding capacity (*Dwc*), hydraulic conductivity (K_2), and relative storage of the deep layer (Z_2).

Following recent WEAP applications (Purkey et al., 2008; Yates et al., 2009; Young et al., 2009), catchments units were delineated by GIS analysis using a 90 m spatial resolution Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) and several subwatershed pour points which were selected based on the location of important infrastructure (dams, irrigation canals) and streamflow gages. In total, 15 catchments were delineated and populated with spatially interpolated climate information of 0.5 degree resolution, obtained from the Consultative Group on International Agriculture Research (CGIAR) regarding mean temperatures and precipitation, wind speed, and relative humidity (CRU TS 2.1 Global Climate Database by Mitchell and Jones, 2005).

Then, the catchments were intersected with land cover data to calculate the fractional areas (i.e., areas of similar land classes) in each of the catchment units. Land use information was mainly obtained from the CORINE Land Cover database (IGN, 2004), which contains digital land cover 1/100000-scale maps with 85 classes of land use for the region of study. With the aim of simplifying the WEAP application, the different land use classes were aggregated into five categories (non-irrigated agricultural land, irrigated agricultural land, semi-natural areas, forest, and pasture), which totaled 100% of the total catchment unit area (see Table 18).

Table 18- Characterization of catchment units in WEAP.

Catchment name	Code	Nº of irrigated sub-catchments	Land use area (Km^2)					Total (Km^2)	Total (%)
			Non-irrigated	Irrigated	Forests	Pastures	Seminatural land		
Albuera de Nogales	ALB	3[a]	1581	230	41	292	262	2407	8.8
Aljucen	ALJ	0	27	0	9	109	28	173	0.6
Cijara	CIJ	0	1107	0	629	27	1554	3318	12.1
García de Sola	GDS	0	82	0	222	215	306	825	3.0
Guadalupejo	GDL	0	45	0	40	50	95	230	0.8
Guadarranque	GDR	0	12	0	77	41	128	258	0.9
Mérida	GME	5[b]	1434	794	285	849	928	4290	15.7
Puente de palmas	PDP	4[c]	543	234	46	404	156	1383	5.1
Villanueva de la Serena	VLS	1[d]	350	38	32	140	201	761	2.8
Gévora	GEV	0	145	0	156	749	691	1741	6.4
Lácara	LAC	0	46	0	44	162	55	307	1.1
Matachel	MAT	0	1784	0	112	186	400	2482	9.1
Orellana	ORE	0	110	0	115	132	387	744	2.7
Zújar-Serena	ZSE	0	3145	0	444	1680	2184	7452	27.3
Zújar-Villanueva de la Serena	ZVS	0	445	0	17	73	415	949	3.5
TOTAL	15	13	10855	1296	2269	5111	7789	27319	100

Note: Codes of irrigated subcatchments (a) TLR, MCM, MER; (b) CDO, VA_2, VA_3, ZUJ, TDG_1; (c) TDG_2, GDC, BCL, BCM; (d) VA_1.

As shown in Table 18, 4 out of the 15 WEAP catchments (ALB, GME, PDP, and VLS) concentrate most of the irrigated land within the region of study (1296 Km^2). These catchments include 13 irrigated sub-catchments, each of them representing an irrigation district (Irrigation Community), except for the IC of TDG that was represented by 2 irrigated sub-catchments (TDG_1, located upstream on the Guadiana River, and TDG_2, situated downstream) with the aim of capturing the spatial variability of this dispersed Irrigation Community. In these irrigated sub-catchments, the fractional areas correspond to 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.

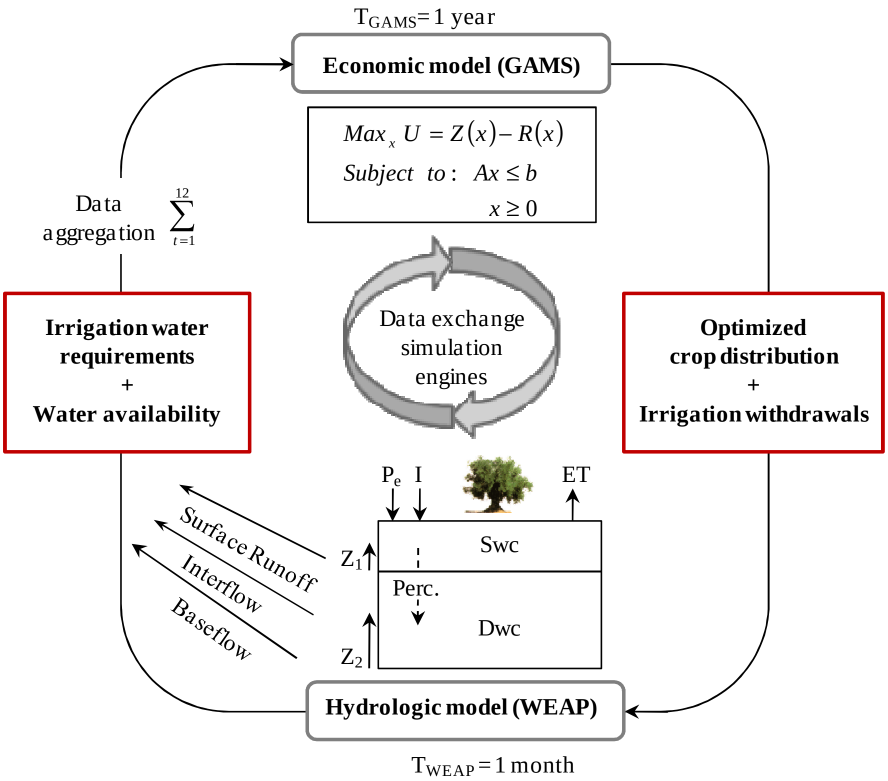
Irrigation in WEAP is determined by the crop area distribution, crop irrigation schedules, and threshold values of soil moisture content.

- **Linkage of the models**

Following Varela-Ortega et al. (in press), 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 use of spatially allocated farm typologies facilitates the linkage of the models, as it makes it possible to relate different administrative and physical boundaries (municipalities, Irrigation Communities, watersheds, etc.), disciplinary domains (socio-economic and environmental dimensions), and spatial scales (farm and river basin scales).

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) in Excel and a free program that converts and manipulates XLS/XLSX/CSV/TXT files (‘Converter XLS’). For a more technical description of the interface development, see Blanco (under revision). This straightforward wrapper interface facilitates the automatic exchange of data between the two models, while it keeps the full functionality of the individual models and avoids the ‘black-box’ integrations often used in hydro-economic modeling. Thus, the economic and hydrology models operate in a stand-alone mode, which makes management easier, but can be subsequently run following an iterative feedback loop. Fig. 27 summarizes the linking scheme followed to couple the economic and hydrology models, and illustrates the flow of information going from one model to another.

Fig. 27- Diagram of the loop linking the economic and hydrology models and the data-exchange between them.



As shown in Fig. 27, when the economic model is run, based on maximum IC water allocation constraints, the optimal cropping pattern and the total annual irrigation water use are calculated for each of the farm types considered in the study. These optimal farm plans ensure an efficient utilization of available resources of land, water and labor, taking into consideration the economic and agricultural risks for farmers. The hydrology model then operates using this resource allocation information and estimates the monthly amount of water available for the different uses and the monthly irrigation requirements of each of the land classes represented in the catchments under investigation. Monthly data is aggregated to provide the economic model with updated information on annual irrigation water requirements and the total amount of water available for agricultural use. The hydrology model allows the analysis of the physical feasibility of the water management system and up-scaling the farm-based results of the economic model to the river basin level. Finally, the economic model can be re-executed, setting off a new loop iteration. This process could be repeated iteratively until convergence occurs. In the present study, exhaustive multi-periodic optimization has not been carried out because our aim is not to achieve the optimal solution, but to analyze the implications of relevant water policies and hypothetical climate conditions from an integrated point of view.

4.3.3. Model testing: calibration and validation

The calibration and validation of a model is essential in minimizing errors and ensuring the credibility and reliability of the model results. The economic model was calibrated with the risk-aversion coefficient (Φ) by comparing the simulated and observed production choices (crop mix) of the different farm types. The Percentage Absolute Deviation (PAD) statistical parameter was used to measure the accuracy of the economic model in replicating the initial crop area distribution for the year 2007. According to this parameter[16], the error scores were calculated as the sum of absolute percentage differences between observed and simulated crop areas by farm type. The risk aversion coefficients estimated in this study ranged between 0.9 (F_4) and 1.4 (F_8), with the higher number representing a lesser tolerance to risk. These coefficients ensured the robustness of the model by providing PAD values that varied from 7 (F_5) to 19 (F_3) with an average of 12. According to the literature (Hazell and Norton, 1986; Kanelopoullos et al., 2010), PAD values below 10-5 indicate an excellent model's accuracy, bellow 20-15 good; whereas more than 20 mean that some changes are required before we can use the model for policy analysis. Thus, considering the results, our method is considered to be suitable for its intended use.

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. In this study, the data for the period January 1974 to December 1990 was considered for model calibration. The calibration was performed using the agro-hydrological parameters as calibration factors to modify the seasonal and inter-annual behavior of key hydrological processes (surface runoff, interflow and base flow). Table 19 shows the average values of the soil parameters used to calibrate the hydrology model.

[16] $PAD_f = \sum_{c-n}^{n} \left| \overline{X_c} - X_c \right| \cdot 100 / \sum_{c-n}^{n} \overline{X_c}$; f: farm type; c: crop indexes: $\overline{X_c}$: observed surface (%); X_c: simulated surface (%).The best calibration is reached when PAD is close to 0.

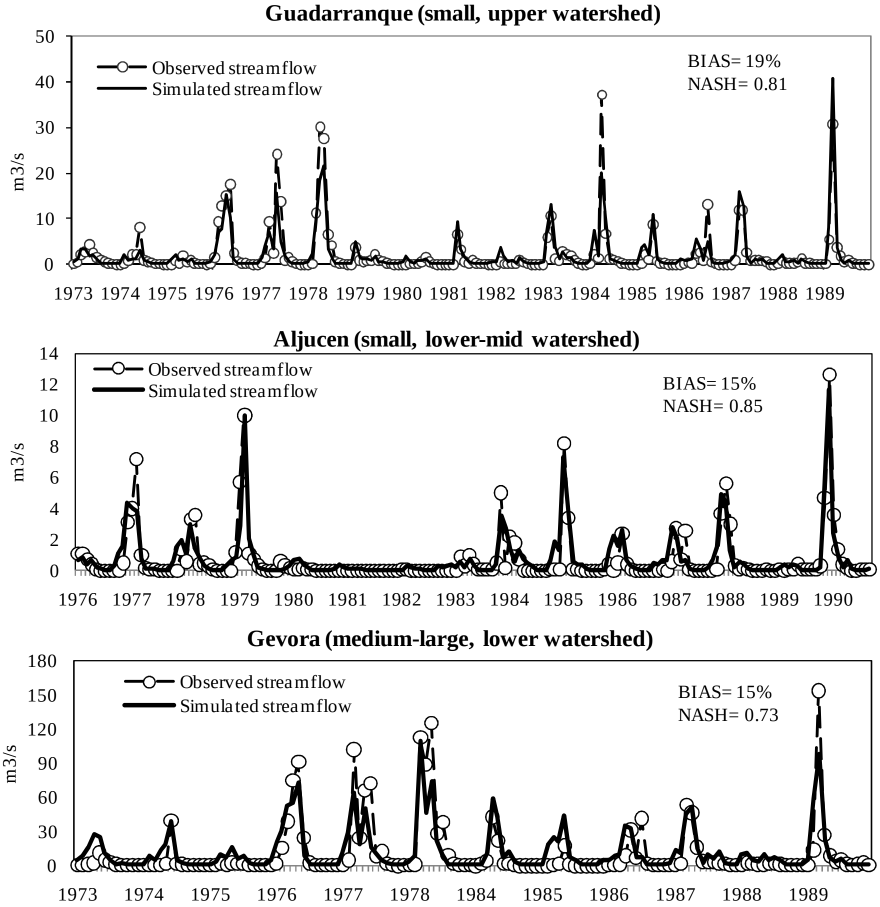
Table 19- Applied soil parameters to calibrate the hydrology model.

Agro-hydrological parameters	**CODE**	**Agricultural land**	**Forest**	**Pasture**	**Seminatural area**
Crop coefficient	K_c	1.17	1	0.9	0.7
Runoff resistance factor	*Rrf*	4.5	5	3	2
Flow direction	*Fd*	0.5	0.5	0.5	0.5
Root zone water capacity (mm)	*Swc*	850	750	950	150
Root zone hydraulic conductivity (mm/month)	K_1	150	150	150	150
Relative storage of the root zone (%)	Z_1	30	30	30	30
Deep water capacity (mm)	*Dwc*	1000	1000	1000	1000
Deep hydraulic conductivity (mm/month)	K_2	20	20	20	20
Relative storage of the deep zone (%)	Z_2	40	40	40	40

The accuracy of the model at predicting stream flows was quantified using reliable goodness-of-fit statistics such as the Bias and the Nash-Sutcliffe efficiency index[17] (Nash and Sutcliffe, 1970). Fig. 28 shows the observed and simulated streamflow values in different watersheds in terms of size and location. 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. These statistic results indicate that the hydrology model robustly represents major features of average monthly flows during the historical period 1974-1990.

[17] $BIAS = 100\left[\left(\overline{Qs} - \overline{Qo}\right)/\,\overline{Qo}\right]$; $NASH = 1 - \left[\sum_{i=1}^{n}\left(Q_{s,i} - Q_{o,i}\right)^2 / \sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)^2\right]$, where $\overline{Q_s}$ and $\overline{Q_0}$ are the average simulated and observed flow rates, and $Q_{s,i}$ and $Q_{o,i}$ are simulated and observed flow rates for each time step (i) and (n). The best calibration is reached when Bias is close to 0 and Nash is close to 1.

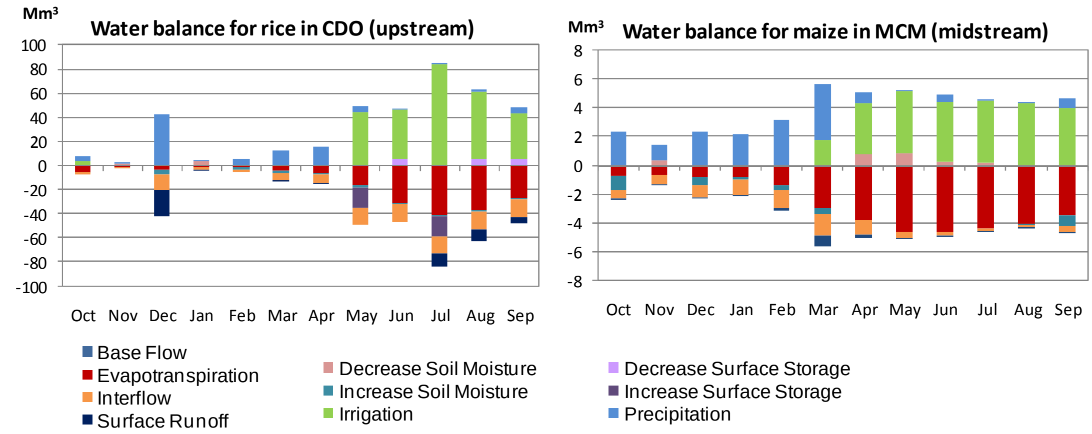
Fig. 28- Observed and simulated monthly streamflow for three separate watersheds in the Middle Guadiana basin.



Finally, the calibrated economic and hydrology models were tested (validated) for the base year 2007 to assure that the models properly assess all the variables and conditions that can affect model results when coupled together. Thus, the optimal cropping pattern by farm type obtained from the calibrated economic model (see Table 17) was replicated into the hydrology model, which, in turn, using new climate parameters and head-flow values for the reference year 2007, estimated the different crop irrigation requirements. The hydrology model computes monthly soil water mass balances for each of the land classes considered in the study and estimates the different crop water needs as the portion of the evapotranspiration requirement that precipitation and the stored soil water cannot meet. Fig. 29 illustrates monthly soil water balances and irrigation needs (in Mm^3) for rice and maize crops in two

Irrigation Communities, and the IC of CDO and the IC of MCM, located upstream and midstream on the middle Guadiana River, respectively.

Fig. 29- WEAP water balance calculations for rice and maize crops in two Irrigation Communities situated upstream and midstream on the middle Guadiana River respectively.



As shown in Fig. 29, there is a strong spatial and temporal variability in water availability and water demand. In the IC situated upstream on the river (CDO), precipitation is concentrated in December and spring (March and April), whereas it occurs more regularly from October to March in the IC located midstream on the river (MCM). As the summer session approaches, soil moisture decreases and crop evapotranspiration and irrigation demand increase. Similar to the precipitation pattern, in the upstream IC of CDO, irrigation demands take place in a more concentrated period of time. Rice is irrigated between May and September with a clear peak in July. In contrast, in the midstream IC of MCM, maize irrigation starts in March and ends in September, hitting its highest value in May. Months with high rates of surface runoff, interflow and surface storage coincide with periods of high precipitation, except for rice fields, where water percolation also occurs in summer due to the water-ponding activities required for rice cultivation. The WEAP model permits the observation of all these different behaviors and provides the economic model with more accurate estimations on crop water requirements. Table 20 summarizes the net irrigation requirement values used to calibrate the economic model (observed values) and the new WEAP estimated annual irrigation requirements (simulated values) by type of crop and zone of study considered.

Table 20- 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

As shown in Table 20, different crops have diverse net irrigation water requirements. Simulated results indicate that maize and rice crops are the most water intensive crops with irrigation water requirements ranging from 5874 to 6056 m^3/ha and 7400 to 7693 m^3/ha, respectively. Permanent crops (olive and fruit trees) are low water-demanding crops with water needs that vary from 2567 to 2650 m^3/ha and 2464 to 2625 m^3/ha, respectively. It can be also observed that irrigation needs are higher in the dry southwestern areas of the basin (midstream and downstream regions) than in the wet northeastern areas (upstream region). In comparison to the simulated data, observed values overestimate crop irrigation requirements by 5% on average. In particular, overestimations are significant in the case of fruit trees and maize crops, where observed values can be 10-17% higher than simulated values. Observed values represent historical average values from 1999 to 2001 obtained from studies carried out by the Spanish Ministry of Environment and the Regional Agricultural Department of Extremadura (see, JE, 2009; MAPA, 2005) in the Middle Guadiana basin at the agricultural region level ('comarcas'). One important limitation found in observed data is that they do not distinguish among types of fruit trees crops. Simulated results derived from actual climate data (2007) permit to obtain more realistic and detailed data (in time and space) regarding crop water requirements.

With the aim of testing the accuracy of the WEAP model estimations for the reference year 2007, the simulated crop irrigation requirements were re-entered into the economic model and the latter re-executed. The optimal crop distribution obtained using the new 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.

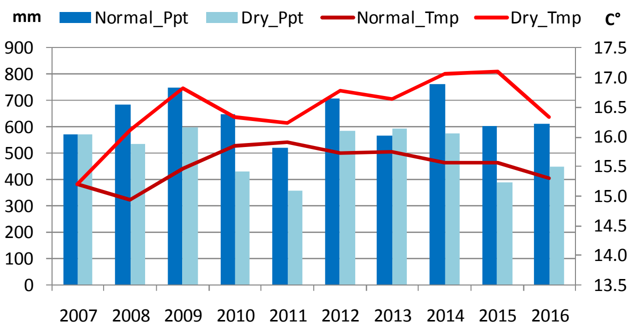
4.3.4. Scenario simulation

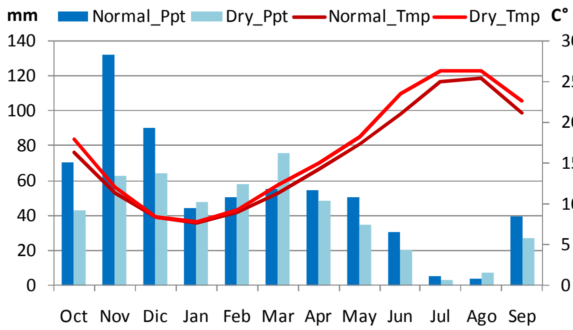
A set of scenarios were developed and simulated in both models with the purpose of analyzing the socio-economic and environmental implications of different water policies and climate conditions for water resources and agricultural production systems in the Middle Guadiana basin. The analysis starts in the base year 2007 and goes up to 2015, which corresponds to the deadline established by the WFD for achieving environmental goals. The simulated scenarios are as follows:

- **Baseline scenario**. This scenario is considered as the starting point for subsequent simulations. It offers a thorough description of the present and potential future situation in the basin under the assumption that recent trends continue during the time frame considered (2007-2015) ('business-as-usual'). In this scenario, we have assumed that current water policies, and therefore current water allotments for agricultural use, persist until 2015. The EU Common Agricultural Policy (CAP) will continue its steady process of reform initiated in 2003 towards a more sustainable agricultural model for Europe. As established by the latest review of the CAP (the CAP 'Health Check'), which sets out the new CAP framework until 2013, direct farm payments were gradually decoupled from production and incorporated into the Single Payment Scheme (SPS), compulsory set-aside requirements were abolished by 2010, and the modulation rate was increased from 5 percent in 2007 to 10 percent by 2012 (EC, 2009). Future input costs for agricultural production were derived by replicating the evolution of fertilizer prices, seed prices, pesticide prices and machinery costs observed in the region of study over the last decade (MARM, 2010). On average, total input costs were supposed to increase up to 5 percent from 2007 to 2015. Price forecasts for crops were mainly based on the EU and OECD-FAO prospects for agricultural market and income, which foresee an increase in food prices (mainly, cereals and oilseeds) from 3 percent to 7 percent by 2015, due to the increased global demand for food and bio-fuels raw materials (Nowicki et al., 2007; Nowicki et al., 2009; OECD-FAO, 2009). Crop yields were assumed to remain constant during the simulated period. Population growth was inferred by extrapolating recent trends to the year 2015.

Monthly hydrological simulations were performed until 2015 which considered two types of climate sequences: normal and dry. Both sequences were obtained by studying the historical records of precipitation and temperature over the past century (1901-2001) in sequential periods of ten years. The climate sequence defined as 'normal' corresponded to the ten-year period that registered the median total precipitation. 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. The two climate sequences selected were: normal from 1981 to 1990 and dry from 1941 to 1950. The defined sequences where projected in time to cover the modeling period 2007-2015. Fig. 30 depicts the two climate sequences simulated.

Fig. 30- Normal and dry climate sequences simulated over the period 2007/2008-2015/2016.





- **Spanish national water policy scenario.** In this scenario, the maximum amount of water delivered to the different Irrigation Communities is subject to the historical water rights established by the Spanish National Hydrological Plan (NHP) (Ley 10/2001). According to the NHP, the Irrigation Communities that take water directly from the river can receive up to 6600 m^3/ha, whereas the remaining ones can obtain up to 7500 m^3/ha. Other assumptions made for the baseline scenario are kept constant. Thus, this scenario has also been assessed under the previously defined 'normal' and 'dry' climate cycles.

- **European water policy scenario.** This scenario analyzes the potential implications of maintaining the Environmental Flow Requirements (EFR) determined by the Guadiana River Basin Authority (GRBA) to fulfill the objectives of the EU Water Framework Directive (WFD) by 2015. Although the WFD does not use the term 'environmental flows' explicitly, it is widely accepted that the implementation in minimum environmental flows is a key measure for restoring and maintaining the good functioning of maintain the functioning of freshwater-dependent ecosystems (Acreman and Ferguson, 2010). In total, the GRBA identified 19 river reaches where some minimum flows should be maintained (see Fig. 25)[18]. In the present research, we have considered 10 river reaches as being the remaining ones located outside of the study area boundaries. Table 21 shows the minimum river flow requirements simulated in the study area at a monthly time scale using WEAP.

Table 21- Environmental flow requirements of selected river reaches simulated in WEAP.

River reach name	Catch. code	Monthly environmental flows (m^3/s)											
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Guadiana IV	CIJ	0.47	0.52	0.91	0.85	0.70	0.64	0.63	0.57	0.26	0.08	0.06	0.14
Guadiana VI	ADN	7.54	9.46	14.31	14.16	11.55	9.12	8.19	6.10	2.85	0.78	0.68	2.16
Guadiana V	ZVI	7.05	8.81	13.47	13.34	10.86	8.68	7.88	5.97	2.78	0.78	0.67	2.08
Guadamatilla	ZSE	0.51	0.58	1.98	2.70	2.84	1.78	0.96	0.30	0.05	0.01	0.00	0.02
ZujarII	ZVI	14.05	24.68	26.29	52.18	75.69	38.67	24.00	9.76	1.96	0.12	0.18	1.90
MatacheII	MAT	1.57	3.15	6.41	8.04	9.01	6.05	4.25	1.05	0.18	0.00	0.01	0.12
MatacheIII	GME	2.20	4.72	9.30	11.67	13.10	8.70	5.90	1.42	0.26	0.01	0.01	0.17
Lacara	LAC	1.16	2.27	3.17	4.18	5.06	2.95	1.34	0.38	0.04	0.00	0.00	0.02
ZapatonII	GEV	2.90	4.27	8.47	8.56	9.53	5.76	2.45	0.74	0.07	0.00	0.00	0.08
Rivera Limonetes	ADN	0.80	1.08	2.06	1.44	2.63	0.97	0.78	0.25	0.05	0.00	0.00	0.08

Source: Own elaboration based on CHG (2009).

In this scenario, environmental flows were given the highest water demand priority, followed by urban and agricultural uses. The impact of complying with the established EFR under normal and dry conditions will be analyzed according to the assumptions defined in the baseline scenario.

4.4. Results and discussion

The analysis of results has focused 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

[18] A detailed description of the methods used by the GRBA to characterize the minimum flows needed to maintain the basic ecological functioning of particular river reaches in the middle Guadiana basin can be found in CHG (2009).

of farming systems that exist in the area of study in terms of location, crop diversification, and types of irrigation systems (see Table 17). 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.

4.4.1 Baseline scenario: following current trends

- **Socio-economic impacts**

Baseline simulation results on agricultural income, public expenditure, water consumption, water productivity, water costs, labor, and land use are summarized in Table 22. Simulated values are presented for the first and last year of the simulation period (2007-2015) by type of Irrigation Community.

Table 22- 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 show that there are essential differences in the performance of agricultural systems among the different irrigation districts selected in the study. Mid-stream on the Guadiana River, the IC of MCM shows the highest farm income value, with 2573 €/ha in the present situation (2007). In MCM, farmers cultivate profitable crops (such as tomato, maize, and peach), but they use high volumes of water per hectare (7480 m^3/ha) due to the significant water loss of old conveyance systems and the low technical efficiency of gravity irrigation systems. Upstream on the river, larger amounts of water (9622 m^3/ha) are being used to produce rice in ponded soils in the old IC of CDO. Rice is well adapted to the local agro-ecological conditions of the upstream regions, but it demonstrates low profitability and high water demand. Hence, the IC of CDO presents the lowest farm income value (1911 €/ha) and the lowest water productivity rate (0.2 €/m^3). In contrast, the IC of ZUJ, also located upstream, presents the highest water productivity (0.381 €/m^3) and a moderate-high farm income (2270 €/ha). This IC presents a high diversity of crops and a large surface area cultivated under permanent crops (olive and fruit trees), which actually require very little water and provide high revenues per unit of applied water. Fruit trees and vegetables are the most lucrative crops, but also the most labor intensive. Almost 17 working days/ha need to be employed to run a farm efficiently and profitably in the ICs of MCM and ZUJ. In addition, the ZUJ IC includes pressurized irrigation systems (sprinkler and drip), which allow farmers to use relatively small amounts of water per hectare (5961 m^3/ha). The IC of TDG also benefits from pressurized irrigation systems and a wide variety of crops, but it shows the highest water cost (0.048 €/m^3) due to the extra energy cost that farmers must pay for pumping water directly from the Guadiana river.

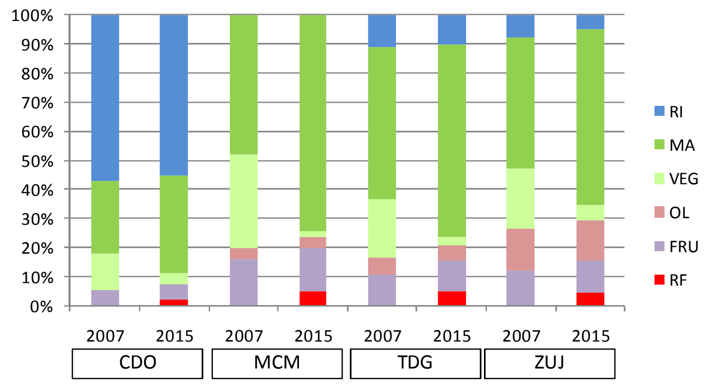
Results also indicate that if we continue on our current path, farm income will be reduced by between 12% in the water-intensive farming systems of CDO and 4-5% in the most diversified farms of MCM and ZUJ by 2015. These results are in line with those obtained by the CAPRI model (Common Agricultural Policy Regionalized modeling system) 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). This will mainly be produced by a reduction in CAP direct payments, as a consequence of the introduction of the full decoupling scheme and the progressive increase of the CAP modulation rate[19]. In the present study, the net public expenditure, calculated as the difference between the CAP payments (gross public

[19] Modulation is the transfer of EU CAP funds from Pillar 1 (coupled payments, single farm payments) to Pillar 2 (rural development and agri-environmental schemes). By 2012, direct farm payments will be reduced by 10% and transferred from Pillar 1 to Pillar 2.

expenditure) and the revenues collected through water fees (public collection), will be reduced from 19% in ZUJ to 10% in MCM, from 2007 to 2015.

The future situation in 2015 will also produce a shift in agricultural production. As seen in Table 22, 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; Balkhausen et al., 2008; Bartolini et al., 2007; Blanco and Varela-Ortega, 2007; Oñate et al., 2007; Varela-Ortega, in press), 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. 31 shows that rice is slightly reduced, but tomato, which is highly subsidized in the present situation (it receives the highest amount of direct payments, 2200 €/kg) 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. 31- Crop area distribution by Irrigation Community in the baseline scenario.



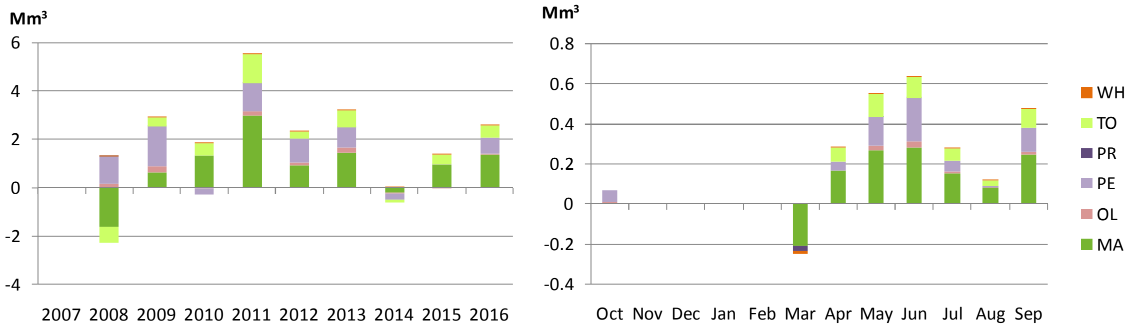
- **Climate impacts**

The impact of climate on agricultural crops varies in time and space depending mainly on the distribution of the precipitation and temperature patterns during the vegetation period. The historical dry climate sequence defined in this study and projected from 2007 to 2015 (see Fig. 30) includes two consecutive years of significant meteorological drought from 2009 to 2011.

On average, the simulated dry sequence decreases precipitation and increases temperature (by 20% and 1°C, respectively). However, it is worth noting that rainfall can be higher during the dry climate cycle in some specific hydrological years (such as 2013/2014) and months (from January to March). Impact studies based on average (mean) climate conditions may lead to misleading results when analyzing the consequences of political or climatic stimuli (Flichman et al., 1995; Smit and Skinner., 2002).

Results indicate that evapotranspiration values stay quite stable from one year to another, but, as seen in Fig. 32, crop water demands are very sensitive to climate variations. Crop irrigation requirements increase considerably in years preceded by periods of little precipitation (2009, 2013 and 2016) with a peak of 5.5 Mm^3 (20% of the average normal water demand) in 2011, which correspond to the end of the two-year meteorological drought. 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 (it even decreases in March), but increases at the beginning and the end of the crop growing season (late spring and late summer), especially in May-June and September.

Fig. 32- Annual total and monthly average crop water demands in a dry climate cycle relative to normal in the midstream IC of MCM.



As also reported in other studies (Döll, 2002; 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%). Similar results have been obtained by Moneo-Laín (2008) in a nearby region, the Tajo basin, in Spain. Olives and fruit trees are the most affected crops due to the little water requirements shown by these crops during normal years (see Table 20) 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. Yet, even with the differential variations mentioned above, rice and maize are still the crops that show the highest water demands. 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.

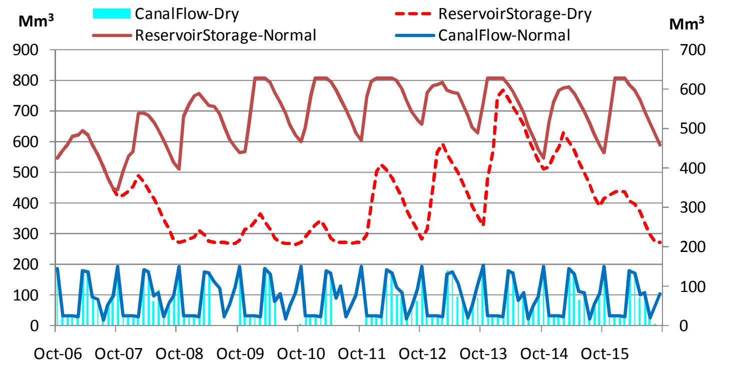
Even though water courses are highly regulated in the Middle Guadiana basin due to the high number of dams and reservoirs, prolonged drought might reduce water availability and produce negative impacts on surface irrigation systems (CHG, 2007). Fig. 33 shows the water level fluctuations of the two major reservoirs and irrigation channels located upstream on the Guadiana River (Zújar-Serena and Orellana)[20] under a normal and dry climate cycle.

[20] The Zujar-Serena reservoir and the Orellana reservoir (with a storage capacity of 3533 Mm^3 and 808 Mm^3, respectively) hold 55% of the total storage capacity in the middle Guadiana basin and regulate the water delivered to the Zújar and Orellana irrigation channels, which irrigate 60% (75000 ha) of the total irrigated area in the basin.

Fig. 33- Water level fluctuations in major reservoirs and irrigation channels under normal and dry climate conditions.

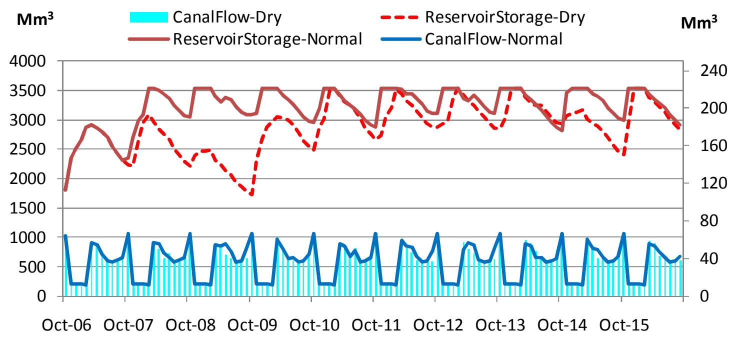
(a)

Orellana



(b)

Zújar-Serena



As depicted in Fig. 33, water reserves in reservoirs increase during the winter and the spring, whereas they decline increasingly in the summer months in order to satisfy all water uses during this season. On the other hand, water flow in irrigation channels decreases in the winter and the summer, coinciding with the periods of the lowest and the highest irrigation demands. In a dry climate cycle, the reservoir levels drop sharply, especially in the Orellana reservoir and also during the driest years from 2008 to 2011 and 2015/2016. In the summer months during these dry periods, water flow in the Orellana channel can become zero, which may provoke substantial delivery shortages to the irrigation districts (CDO, VA2 and VA3) that take water directly from this irrigation channel. On average, water shortages in the Orellana irrigation channel under a dry climate cycle imply annual reductions of about 120 Mm^3/year (28% of the average annual water consumption) in the amount of water delivered to the IC of CDO. In the Zujar-Serena reservoir, water fluctuations are less pronounced, which evidence the high capacity of the big reservoirs to mitigate potential drought impact. The irrigation districts that are situated downstream on the Guadiana River are not necessarily affected by scarce water situations upstream, as they receive important return flows from their upstream neighbors and new water inflows from significant tributaries of the Guadiana River (such as the Matachel River, Aljucen River, Rivera de los Limonetes River, etc.).

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

The results of the simulation of the HNP water allotments under normal and dry climate conditions are depicted in Table 23. This table summarizes the impact of the application of the Spanish water policy on farm income, water and land use, water productivity, water cost, and water shadow prices (marginal or dual values of water) for each of the Irrigation Communities studied at the end of the simulation period. The reference situation refers here to the baseline situation in 2015.

Table 23- 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

As seen in Table 23, 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[21]. Consequently, a decrease in water consumption raises the unit cost of water (€/m^3) (especially in the CDO and MCM ICs where water tariffs, based on fixed rates per hectare, are unresponsive to variations in water use) and provokes farm income losses. Results show that the application of the HNP water allotments entails a farm income decrease 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. Under the dry climate cycle, farm income decreases by 15% in CDO, 9% in MCM, and 5% in TDG, and the productivity of water drops across all the irrigation districts varying from 9% in ZUJ to 2% in TDG.

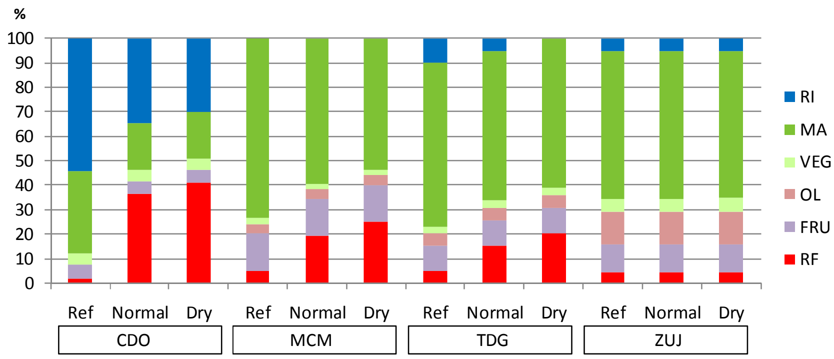
Nonetheless, different behavior can be observed in the very modern IC of ZUJ. In the normal baseline situation, the water consumption rate of this IC is already below the new established water allotments, and therefore, farmers are not affected by the implementation of the HNP. Moreover, the highly efficient 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. In this regard, the IC of ZUJ could benefit from a water banking system if the water saved during wet periods could be stored and used later during dry periods.

Table 23 also indicates that the marginal value of water (in other words, what farmers are willing to pay to use one additional unit 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. In the case of the ZUJ IC, farmers would be satisfied with the amount of water available in normal and dry years to fulfill the irrigation water requirements and, therefore, would not be willing to pay to get extra units of water (water shadow values becomes zero). 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. (in press) 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.

[21] Water availability in the IC of TDG is only binding for the representative farm situated upstream on the Guadiana River, which cultivates a large surface of rice.

In this study, farmers adapt to changes in weather patterns and water availability by changing their crops and technologies to minimize expected adverse impact. As seen in Fig. 34, rain-fed cereals (wheat) increase considerably in the old irrigation districts of CDO and MCM when the new water allotments are implemented. The planted areas of the most water intensive crop (rice) 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, 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. Only farms that belong to the IC of ZUJ, where water is not binding under the dry climate cycle, did not significantly change crops, but rather increased the amount of water for irrigation to compensate for increased evapotranspiration and decreased precipitation.

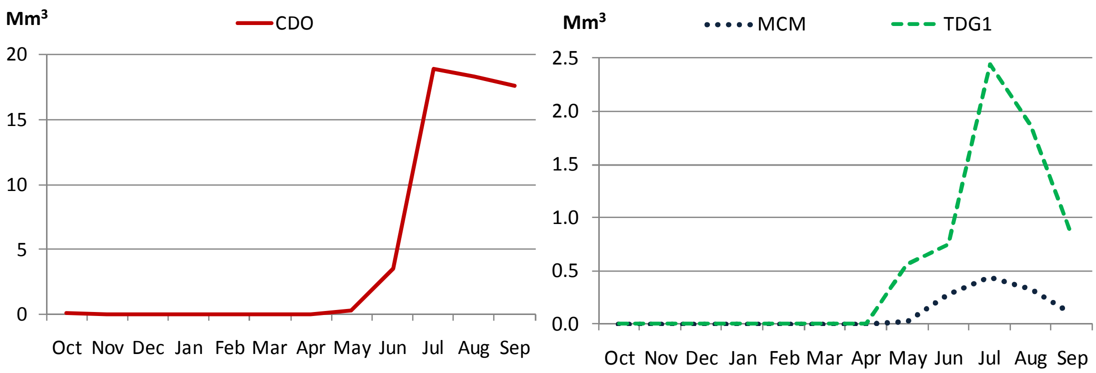
Fig. 34- Cropping patterns adopted by farmers in the reference situation when the HNP water allotments are implemented under normal and dry climate conditions.



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 Challinor et al., 2007; Iglesias et al., 2003; Maneta et al., 2009; Reidsma and Ewert, 2008; Smit and Skinner, 2002; Smit et al., 1996; Varela-Ortega et al., in press; among others), 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.

On the hydrology side, results indicate that the established HNP water allotments can be fully delivered to the different irrigation districts of the Middle Guadiana basin under normal and dry climate conditions. However, in a dry climate cycle cycle, irrigation requirements exceed the allowed water supply, giving rise to situations of unmet demand (that is, when the crop water requirements are not fully met) in the ICs of CDO, MCM and TDG. As seen in Fig. 35, unmet demand occurs during summer months with a peak in July, coinciding with the period when plants require most water.

Fig. 35- Monthly average unmet demand for agriculture in the Irrigation Communities of CDO, MCM and TDG under dry climate conditions and HNP water constraints.



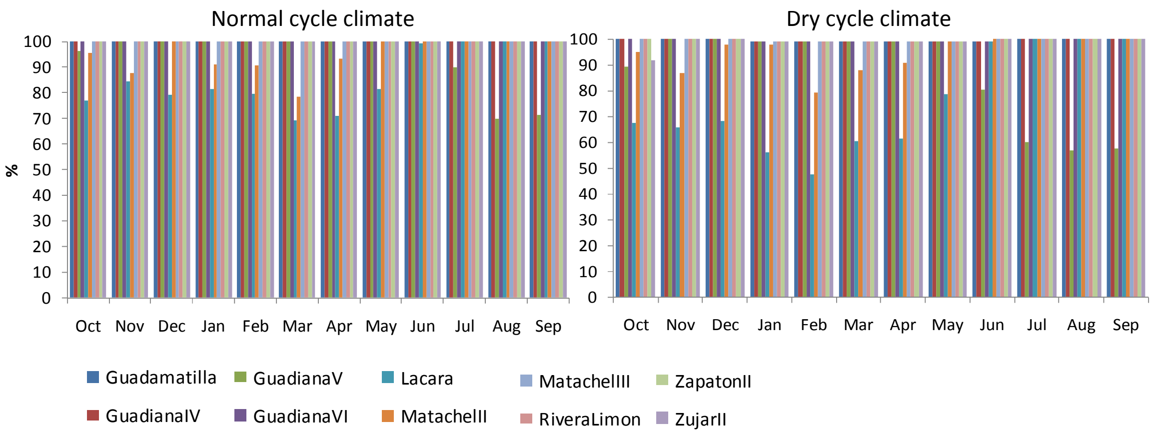
Note: TDG_1 refers to the rice-growing irrigation district located upstream on the Guadiana River that takes water directly from the Guadiana River and therefore, belongs to the IC of TDG.

CDO agriculture (based on rice cultivation) is simulated to experience 59 Mm^3 of unmet demand (which represents approximately 19% of its total water requirements) during the months of May through October. Similarly, irrigation demands in MCM and TDG_1 go unmet from May to September-October, registering average unmet values of 1.2 Mm^3/year and 5 Mm^3/year respectively (that is, 2% and 10% of their total water requirements). The implementation of the HNP encourages land use changes and irrigation modernization, but additional efforts should be made to support rain-fed and low water-intensive agriculture to equilibrate water supply and irrigation requirement reductions.

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

In the present study, water coverage (percent of demand satisfied) is maximized for all human and ecosystem demands, subject to mass balance, demand priorities (instream flow requirements are satisfied before urban and irrigation needs), and system constraints (storage and conveyance capacities). Fig. 36 shows the average monthly percent coverage of environmental demands for the analyzed period (2007-2015) under normal and dry climate conditions.

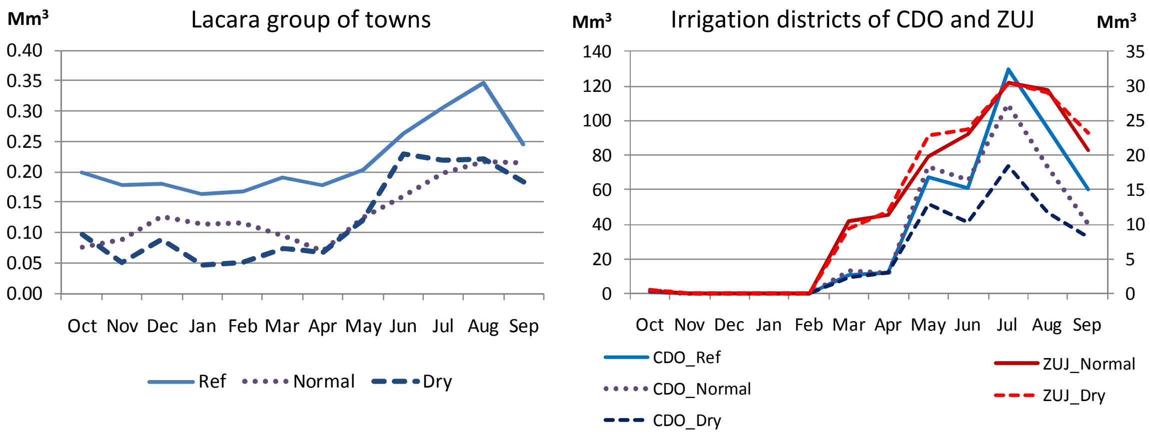
Fig. 36- Monthly average flow requirement coverage (% of requirement met) under a normal and a dry climate cycle.



As seen in Fig. 36, the minimum environmental flows specified in Table 21 are not completely covered in some river reaches (Lacara, Matachel II and Guadiana V). In a normal climate cycle, Lacara and Matachel II lacks water from October to April-June, whereas in Guadiana V, low summer flows are insufficient to maintain the basic ecological functioning from July to October. In a dry climate cycle, the number of months with unmet flow requirements increases and monthly coverage rates decrease, reaching a minimum of 47% in February at Lacara, 79% also in February at Matachell II, and 57% in August at Guadiana V. Additionally, about 92% of flow requirements are met in October at Zujar II under drought conditions.

Our findings also 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. Fig. 37 shows the amount of water delivered to the different users under normal and dry climate conditions. In particular, the group of towns of Lacara and the IC of CDO experience water supply shortages due to the minimum instream flow requirements imposed on the river reaches of Lacara and Guadiana V, respectively.

Fig. 37- 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. 37, 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 the 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 (baseline) 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 Orellana 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. In the neighboring upstream region of Zujar, the minimum flows imposed on the river reach Zujar II do not significantly affect the flow regime of the irrigation channel of Zujar. As seen in Fig. 37, the irrigation district of ZUJ increases the amount of water used during a dry climate cycle by 8 Mm^3/year (about 6% of its average normal water consumption) by intensifying water demand for irrigation in the spring and fall months of May and September.

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 24.

Table 24- 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

As evidenced above and depicted in Table 24, the application of environmental flows in the Middle Guadiana basin results in substantial water use reductions and farm income losses for the upstream and low modernized IC of CDO. In this irrigation district, 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 availability shortages and increased evapotranspiration force CDO farmers to change their crop choice, mainly based on rice cultivation, and substitute a large surface of water-intensive 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.

In the ICs of MCM, TDG and ZUJ, environmental flow requirements are not adding water-binding restrictions. Water use is limited by the water allotments defined in the reference situation, so in these ICs (MCM, TDG and ZUJ), the baseline scenario and the environmental flow scenario generate the same simulation results.

As shown in Table 24, 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 helps 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.

4.5. Conclusions and reflections

The present study has illustrated the application of a hydro-economic model to evaluate the potential implications of the Spanish HNP and the European WFD under different climate conditions and plausible development scenarios on the large-scale irrigation systems of the Middle Guadiana basin in Spain.

The farmers' behavior was simulated using a multi-scale economic optimization model encoded in GAMS, 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. The model linkage developed in this research avoids the use of 'black-box' integrations and improves the dynamic operability of the hydro-economic model in terms of multi-scale data management. The results obtained also indicate 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), our analysis 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. Additionally, water shortages may occur in dry periods if the current patterns of excessive and low-effective water consumption followed by rice-growers upstream on the Guadiana River continue in the future. While evapotranspiration values stay quite stable throughout the simulation period (2007-2015), crop water demands vary widely, mimicking climate variations. Under dry conditions, 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).

A downward revision of the existing water concessions for agricultural use, and adjusting current water consumption rates to the levels established by the Spanish HNP, 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 periods, when some situations of unmet demand occur, especially during the summer months when the crops require the most water. 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 the environmental requirements of the WFD 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 specific 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 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 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.

4.6. Acknowledgments

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5. Final conclusions

5.1. A summary of major findings

The integrated economic-hydrologic analysis of water management strategies for balancing water and food, and water and nature in the Guadiana River Basin reveals important disparities among irrigation systems and regions that lead to diverse water conservation options and differential effects on human and natural systems.

In the Upper Guadiana Basin, water is perceived as a scarce and costly commodity. Irrigators are subjected to strict water quota allotments and pay the full financial cost of their irrigation equipment and operation. The overexploitation of the Mancha Occidental aquifer and the degradation of valuable groundwater-dependent wetland ecosystems caused by excessive and unregulated groundwater pumping, have provoked important water-related conflicts between the Guadiana River Basin Authority and the farmers, legal and illegal irrigators, small and big landholders, environmental conservation groups, farmer collectivities, and other affected parties. Therefore, the involvement of the stakeholders and the evaluation of negotiated water conservation solutions have proven to be extremely valuable in this region. Efficient and modern irrigation technologies allow for the cultivation of highly profitable crops such as vegetables and vineyards. The results showed that, in this part of the basin, small vineyard farms, mostly irrigated from unregistered wells, would be the most affected, in economic terms, by the implementation of water conservation policies addressed, firstly to control illegal groundwater pumping, and ultimately, to reduce groundwater consumption and promote the recovery of the aquifer.

On the other hand, in the Middle Guadiana Basin, water is perceived as an abundant and free commodity. Irrigators are granted rights to large water allotments and only pay part of the financial costs of water services. The excessive use of surface water for irrigation and the development of numerous water regulation projects have promoted the socio-economic development in the region, but have also caused important environmental damages (loss of fish ladders, water pollution, etc.). In this area, the establishment of minimum ecological flows and the potential reduction of water use for irrigation are the main points of friction between farmers and the Guadiana River Basin Authority, farmers and environmental conservation groups, upstream and downstream irrigators, and other concerned parties. The results obtained indicate that the location of use within the basin, crop diversification potential, and access to modern irrigation systems are key factors that determine the capacity in which farmers have to adapt to climate and political stimuli. Thus, the old rice-based farming systems located upstream on the middle Guadiana River would be the most economically affected by a reduction in water supply for agriculture, and the most vulnerable when facing dry climate conditions. Still, on the whole, the large storage capacity of the Middle Guadiana Basin would mitigate the negative impacts of drought spells.

Thus, the results obtained hint that to attain efficient and sustainable use of water resources in the Guadiana Basin, the new Guadiana River Basin Management Plan should contemplate appropriate and cost-effective measures addressed to achieve the ecological objectives of the WFD, while taking into account the different agro-climatic, structural and institutional characteristics of all affected territories.

As seen in previous sections, the Guadiana Basin covers a large proportion of leading and present issues for water resource management and therefore, it constitutes an emblematic case study where to apply and learn from IWRM. The IWRM approach reveals many problems, both in concept and in implementation. Transferable IWRM experiences across basins have been limited due to the lack of guidance and poorly reported empirical evidence of the successful implementation of IWRM, especially in complex water situations involving conflicting interests. The analysis presented in this research suggests that the implementation of IWRM in the Guadiana Basin, meaning the adoption of integral, efficient, technically feasible, socially acceptable, and environmentally sustainable water management solutions, is a promising approach, but it will be difficult to achieve in the short term due to the intricate water-related problems that currently face the Guadiana Basin. IWRM strategies in this region need to be accompanied by social, cultural, institutional, and economic adaptations. Further involvement of the stakeholders in the design and implementation of policies and measures would be crucial in supporting a real change in water resource management in the mid and long-term.

The development of integrated methodologies can make a significant contribution in closing the knowledge gap between the theory and practice of IWRM. Certainly, the integrated economic-hydrologic modeling framework developed in the present study shed a light on how the integration between human and natural systems can be addressed and ultimately achieved, as well as the benefits of such integration. While most of the studies focus on model predictions, this study has paid attention to the contribution of integrated models both as process and product. Particularly, in the case of cross-cutting domains and disciplines, the value of modeling activities is tied to knowledge-acquisition and the modeling process rather than to the model itself. The methodological path followed in this research permitted the emphas on the progressive complexity of the tools adopted for putting IWRM into practice. The modeling process started with the design and implementation of a simplified static economic optimization model based on hydrology-related components, and ended-up with the implementation of a dynamically linked economic–hydrologic optimization-simulation model. The results obtained indicate that the accuracy of the models in predicting farmers' and water systems' behavior improves when the economic and hydrology models are dynamically linked together, evidencing the potential of integrated tools in replicating the reality of complex water systems under risky and uncertain situations.

In addition, the research findings point out that the involvement of the stakeholders in the defining of problems, selection and validation of analytical tools, and design of simulation scenarios from the very outset of the research work, contributed to substantially enriching the prediction of the economic and hydrology models. It also provided an esteemed social dimension of to the research endeavor. The obtained modeling outcomes resulted in not only being unbiased, but also meaningful to stakeholders. Especially in the case of the Upper Guadiana Basin, where conflicts exist between many collectivities, stakeholder needs and knowledge of local, social, economic, political, and environmental conditions provided the yardstick for measuring what was an acceptable solution; in other words, what was desirable and achievable. In agreement with other studies, this research reveals that the use of integrated tools and the participation of the stakeholders in water management decision-making processes would promote a shared understanding of water resource systems and problems, and support better-informed decisions.

The integrated methodology developed in this study provided interesting insights about the potential impacts of a set of scenarios on the different irrigation systems of the Guadiana Basin, regarding the private sector (farmers' income, and labor use), the public sector (government collection and expenditure), and the environment (crop distribution, soil moisture, crop water needs, streamflows, and other hydrological indicators).

In the Upper Guadiana Basin, a simplified economic optimization model with hydrological-linked considerations was applied to analyze, at the local and regional scale, the cost and effectiveness of different water conservation measures (namely, the closing-up and taxed-legalization of unlicensed wells, uniform volumetric and block-rate water prices, water quotas, and water markets) to reduce water consumption and assure the sustainability of the Mancha Occidental aquifer. The model results indicate that attaining the goal of the aquifer's sustainability will require an effective combination of measures addressed to halting illegal drilling and eliminating excessive groundwater use for irrigation. Controlling illegal water mining through the taxed-legalization of unlicensed wells would be a suitable solution, but is not sufficient to recover the aquifer. Effective water management in this area will require the implementation of other demand management instruments as well, such as water prices, water quotas or water markets. Aggregated results showed that net social costs across the studied instruments are hardly different, so none of the considered water demand management instruments is clearly more cost-effective than the others. However, there are significant differences between private and public costs, which will be decisive in determining the application for the practice of these policies. Water prices will entail the lowest net social cost, but will bring about important income losses (especially, uniform volumetric water prices) to low-diversified and small-sized farms, which might put the viability of these farms at risk as well as the social acceptance of the policies. The quota system is the most costly option for the government, and therefore, the least cost-effective policy. Yet, it induces low income losses to the farmers and can reduce income inequality. Lastly, the water market has the lowest private cost, but does not provide as much profit gains as the mainstream neo-classical theory would suggest. According to these results, it could be concluded that no single policy can solve the complex problems related to irrigation water management in the Upper Guadiana Basin. A combination of market and non-market measures would be highly advisable to attain the sustainability of water and agrarian systems in the Mancha Occidental aquifer.

In the Middle Guadiana Basin, a dynamically linked economic–hydrologic optimization-simulation model was applied to analyze the socio-economic and environmental implications of different water conservation policies (namely, the Spanish HNP and the European WFD) under diverse climate conditions, both in the short and the mid-term (from 2007-2015). The present analysis suggests that the on-going CAP 'Health Check' reform and the progressive liberalization of agricultural markets will reduce farm income between 4-12% and produce a shift in agricultural production by 2015. Rain-fed farming is encouraged, but changes in land-use practices (e.g., an increase in water-intensive cereals and a decrease in tomatoes for processing) might not be reflected in lower water use rates, which indicate that further integration between water policies and agricultural policies should be encouraged. A downward revision of the existing water concessions for agricultural use to the levels historically established by the HNP will entail significant farm income losses in the oldest and less modernized irrigation communities of the Middle Guadiana Basin (Canal de Orellana and Canal de Montijo), regardless of their geographical location. On the other hand, the implementation of minimum environmental flows to meet the WFD's ecological goals will have differential effects on water and human systems in the Middle Guadiana Basin in time and space. Low flows will be insufficient in maintaining the basic ecological functioning in those river reaches classified 'at risk' (Lacara, Matachel II, and Guadiana V), which will imply a reduction of water supplied for other uses (agricultural and urban uses) in the Irrigation Community of Canal de Orellana and the aggregation of towns of Lacara, respectively. In periods of prolonged drought, the implementation of minimum environmental flows will endanger the economic viability of small-scale rice farms situated upstream on the middle Guadiana River, which might justify the establishment of less stringent environmental flow regimes. In fact, negative policy impacts will be accentuated in dry periods, and particularly in the summer months, when water shortages for irrigation occasionally occur and there is an important increase of crop water requirements. Results indicate that while evapotranspiration values stay quite stable from one year to another, crop water demands are very sensitive to climate variations. Under dry weather conditions, irrigation requirements increase moderately for cereals and vegetables and substantially for permanent crops, especially in the driest areas of the basin (midstream and downstream regions), imposing an additional stress on water supply systems.

In the study area, as in many other arid regions where agriculture is by far the main water user, water management plans are trying to curb this trend by encouraging a more efficient use of water for irrigation, rather than increasing the regulation capacity of the water systems. The implementation of the WFD, an act clearly geared by the concept of ecological sustainability, does not permit discrimination between efficient and inefficient irrigation models, and therefore it will not encourage water-saving strategies. This study underlines the necessity to develop other dimensions (social, economic, institutional, political, etc.) within the WFD umbrella and establish clear guidelines to assist policy makers on how to proceed with the Cost-Effectiveness Analysis, or how to fulfill the 'polluter pays' principle and the cost recovery objective.

The integrated economic-hydrologic analysis developed in this study allows for a more comprehensive vision of the many factors affecting water management, both in present and uncertain future situations, and therefore, it constitutes a useful tools to assist policy-makers and stakeholders in the development of rational policies for sustainable water resources in the context of intensively irrigated semi-arid regions, such as the Guadiana basin.

5.2. Original contributions and implications of the research

This thesis addresses the most important challenges in water resources within a coherent integrated analytical framework. It illustrates the empirical application of an integrated economic-hydrologic modeling system to the specific case of the Guadiana River Basin, offering a detailed description of the process and benefits of such implementation. The models developed and experiences acquired in the present study are transferable to other semi-arid regions, forerunner and by the way original. The methodology developed in this research constitutes a privileged tool for conducting IWRM and helping closing the gap between IWRM theory and practice.

Most of the review methods for IWRM have a strong focus on water quality and consider the basin scale as an indivisible and unique unit for analysis. However, this study deals with quantitative aspects of water management and different decision-making scales. On the one hand, European water policies are dominated by qualitative aspects due to the high density of population in Northern Europe and their impact on drinking water and aquatic ecosystems.

Nonetheless, in Spain, as in other southern European countries, the challenge resides in how to balance water for food production and water for nature protection, or in other words, how to comply with the WFD requirements of GES, and at the same time, guarantee the availability of water to all users to meet rational consumption needs. This research focuses on these quantitative aspects, and therefore, it provides an original point of view on the European arena of water policies. On the other hand, the river basin is widely accepted as the appropriate unit for the analysis and management of water resources. However, this study demonstrates that modeling agricultural systems would require integrating farm-scales with river-basin scales. Any analysis of irrigation systems effectuated exclusively at the river basin level would miss important differences at the local level (in terms of farmers' behavior and preferences, technological conditions, and site-specific institutional factors), as well as important interactions among the different levels of analysis. The multi-scale economic model developed in this research provides more realistic outcomes by providing simulation results at the farm level and the regional level. Furthermore, when coupled with the hydrology model, the results of the economic model can be up-scaled to the sub-basin level.

This thesis offers an important extension of the available hydro-economic modeling tools in terms of model performance and model integration. It describes the novel integration of a farm-based economic optimization model with the WEAP (Water Evaluation And Planning) model. The economic model, described as a non-linear mathematical programming model of constrained optimization, was developed using the GAMS language in order to optimize land use decisions and to replicate the behavior of different farm types. Concurrently, a hydrology water resources simulation model WEAP, configured as a contiguous set of sub-catchments, was developed to simulate watershed hydrologic processes and to provide basin-scale insights about water management and planning. The integration of the economic and hydrology models was made empirically by replicating irrigation demands and simulating the same scenarios in both models, and technically by an automated wrapper interface built in Visual Basic for Applications. The developed interface permits the improvement of the dynamic operability of the models and avoids the use of 'black-box' systems so widely used in model integration. In addition, the novelty of research resides in the approach taken in starting the communication between the hydrology and the economic models. While most hydro-economic models are driven by variations in hydrological state variables, in this research, the hydro-economic model is primarily driven by economic conditions.

The application of the models is also somewhat original. First of all, whereas few ecological-economic models are capable of assessing the socio-economic impacts of environmental changes, the integrated hydro-economic model developed in this research has been used to assess the ecological and socio-economic effects of the implementation of minimum environmental flows in the Middle Guadiana Basin. This analysis also allows for the study of potential changes such as demographic growth, the evolution of markets, uncertain climate conditions, and policy variations. Secondly, only some studies deal with both 'participatory' and 'integrated' water resource management at the same time. In this thesis, integrated modeling has been enriched with the participation of the stakeholders. Stakeholders provided interesting insights about the complex water-related problems of the Guadiana Basin, and also on the concrete application of the various instruments to promote an efficient and sustainable use of water resources. This study seeks to avoid inefficiencies and conflicts that are a feature of less-integrated approaches.

5.3. Limitations and recommendations for further research

This section briefly discusses the limitations of the study, and opens up new questions to be addressed in the future. Different ways of extending the scope of the research are also presented here.

Models are an idealized representation of reality, and therefore, they are subjected to many interpretations, limitations, and assumptions. The predictive capacity of models depends to a large extent on the quality and relevance of the input data used, as well as the chosen model equations. To perform this study, high quality data was collected from reliable data sources and subjected to contrast analysis. However, key data still remains uncertain, particularly in the case of the Upper Guadiana Basin with regard to water table levels, groundwater abstractions, number of illegal wells, and spatial crop distribution.

The developed economic model deals with some specific limitations. Firstly, the model does not consider different vegetative cycles for multiannual crops. It assumes that permanent crops are always in full production, and that it is too costly to uproot them before the end of their usual life. Only in the case of vineyard crops in the Upper Guadiana Basin model were these constraints slackened to represent the vineyard restructuring programs conducted in the

Castilla-La Mancha region. Secondly, farmers are presumed to be financially solvent and to dispose of sufficient financial reserves and current net assets to support the farm's daily operations and acquire new production techniques. Financial constraints should be included in further analysis.

The application of the hydrology model WEAP to the Middle Guadiana Basin has also revealed some modeling weaknesses, mainly related to the representation of irrigated crops. In WEAP, the timing and quantity of water applied for irrigation is determined by the upper and lower relative storage irrigation thresholds and the different irrigation schedules. Furthermore, detailed WEAP ponding parameters allows for a model of flooding for rice cultivation. This Thesis demonstrates that rice irrigation patterns can be accurately characterized in WEAP. However, the model does not correctly discriminate irrigation water needs among different irrigation systems (e.g., furrow irrigated maize, sprinkler irrigated maize, and drip irrigated maize), which may be an important limitation in Mediterranean environments, where the use of pressurized irrigation systems is an essential alternativeto surface irrigation for efficient water use. A good assessment of crop water requirements is also of a big significance for land use planning, especially in the case of drought. This type of analysis can contribute to identifying the combination of crops most suitable to diverse climate changes. Additional efforts should be made in future work to improve crop water use estimates, either using crop models linked to WEAP such as MABIA, or utilizing other specialized DDS tools such as CROPWAT. Furthermore, demand priorities, supply preferences, loss and reuse fractions, and consumption fractions cannot vary by type of crop, which limits the representation of different agricultural activities. In the present study, the hydrology model WEAP has been used to simulate predominantly the most important water demands of the Middle Guadiana Basin (irrigation, urban, and environmental demands). However, other competitive water users (industrial processes and hydropower generation) are steadily gaining attention and should be included in further analysis.

Linking the economic and the hydrology models has also presented some difficulties because of their different time scales. While the hydrology model simulates bio-physical processes at monthly time steps, the economic model generates yearly predictions in optimal cropping patterns. The development of a more detailed economic model running at monthly intervals would improve its integration with the hydrology model, and would allow for a better representation of the crops' vegetative cycle. Multi-periodic optimization processes are hard to execute using modular or compartment hydro-economic models. The wrapper interface developed to link the economic model and the hydrology model should be improved to make this connection more flexible. The potential capabilities of the script in WEAP should be further analyzed as well as the use of open-sources interfaces for water management models, such as HydroPlatform (www.hydroplatform.org).

In future work, it would also be interesting to analyze the impacts of regionalized climate change scenarios, the implementation of water banks (stakeholder-driven suggestion), and the vulnerability of socio-ecological systems. Although quantitative aspects are predominant in the Mediterranean countries of Southern Europe, quality issues should be analyzed and strongly included in IWRM strategies. Diffuse pollution derived from agriculture is one of the major causes of poor water quality in Southern Europe today.

Finally, a strong emphasis should be put on the dissemination of the research results. Some of the findings obtained during the development of the present Thesis were presented to the stakeholders in Ciudad Real. The remaining ones will be displayed at a stakeholder meeting next January in Badajoz. The dissemination of results among stakeholders has been proven essential for improving systematic learning. However, a broader diffusion of results, among policy-makers and the general public, would certainly help to bridge the gap between science and policy. Virtual globe systems such as Google Earth enable people around the world to share their data and research results in a visually attractive and easily understandable manner. Recently, the WEAP model has been linked to Google Earth to facilitate the visualization of the water systems and the potential WEAP outcomes (see http://wikiadapt.org/index.php?title=Google_Earth_Project_California). Although it is still an incipient project, it offers promising results. In this study, the application of the WEAP model has been linked to Google Earth to validate the spatial representation of the Middle Guadiana Basin. Future work might also permit the connection of the WEAP-Middle Guadiana Basin results to Google Earth.

While acknowledging such limitations, this research exhibits a coherent framework for IWRM that can contribute to a better understanding of the complex ecological, hydrological and socio-economic interactions within water systems from local to basin-wide levels and ultimately, promote an efficient and sustainable use of water resources in semi-arid environments.

6. References

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Annexes

7.1. Annex A- Data Collection

Farmer urveys conducted in the Upper Guadiana basin in the context of the NeWater project

NEW APPROACHES TO ADAPTIVE WATER MANAGEMENT UNDER UNCERTAINTY

DATOS E INFORMACIÓN SOLICITADA PARA EL PROYECTO NEWATER

ENCUESTA A LAS EXPLOTACIONES

1. Información general sobre la explotación
1.1 Localización de la explotación: provincia, comarca, municipio

2. Datos agronómicos y de las explotaciones agrarias
2.1 Superficie de la explotación (sin contar caminos, etc.):
2.2 ¿Usted tiene la tierra en propiedad, en renta o la usa en aparcería?
2.3 ¿Está usted acogido al Plan Agroambiental 7.1? ¿Al 50% o al 100%? ¿Cuánto recibe de ayudas? ¿Cuántas Has tiene acogidas? ¿Se acoge con toda la explotación?
2.4 ¿Qué tipos suelos tiene usted en la explotación? ¿Cultiva más unos cultivos en un tipo de suelo que en otro distinguiendo entre suelo bueno, malo y regular?
2.5 Especificación de la superficie cultivada por tipo de cultivos, método de riego (lluvia, gravedad, aspersión, goteo), y técnica de riego (lluvia, algo de riego, riego intensivo):

- Proporción de cultivos en secano:

TIPO DE CULTIVO	SECANO (ha)	SUELO

- Proporción de cultivos en regadío:

TIPO DE CULTIVO	REGADÍO (ha)	Técnica de riego	SUELO

2.6 Rendimientos diferenciados por cultivos y por secano/regadío y por tipo de suelos (bueno, malo y regular) (Kg por hectárea):

	SECANO	REGADÍO
1.Cultivo:		
2.		
3.		

- Rendimiento por tipo de suelos:

	BUENO	MALO	REGULAR
1.Cultivo:			
2.			
3.			

- Ordene de mayor a menor los cultivos en función del riesgo por los factores climáticos. ¿Cuánto puede variar el rendimiento en año bueno y año malo, en regadío y en secano?

2.7 Necesidades de agua diferenciadas por cultivos y por secano/regadío (metros cúbicos):

	SECANO	REGADÍO
1.Cultivo:		
2.		
3.		

2.8 Necesidades de mano de obra diferenciadas por cultivo, secano/regadío e invierno/verano (horas/ha): preparación, abonado, siembra, fitosanitarios…

Cultivo1:	Otoño	Invierno	Primavera	Verano
Secano				
Regadío poco intensivo				
Regadío intensivo				

…………

2.9 Entrantes y labores de cada cultivo

Cultivo 1	Cantidad (Kg/ha; l/ha)	Periodo	Precio Unitario (€/Tn)
Semillas			
Fertilizantes			
Insecticidas			
Funguicidas			
Herbicidas			
Preparación			
Abonado			
Siembra			
Poda			
Recolección			
Mantenimiento			
Venta			

…………

3. Datos económicos

3.1 ¿A cuánto está en €/ha el alquiler en la zona (secano y regadío)? Igualmente, ¿a cuánto está la venta (secano y regadío)?

3.2 Precios de los cultivos (euros/kg):

	Precio
1.Cultivo:	
2.	
3.	

- Ordene de mayor a menor los cultivos en función de la variación de los precios en el mercado.

3.3 Primas o subvenciones recibidas y diferenciadas por cultivos (euros/ha):

	Primas (euro/ha)
1.Cultivo:	
2.	
3.	

3.4 Ayudas recibidas con el nuevo Pago Único. ¿Ha visto usted reducida su ayuda? ¿Cuánto?

3.5 ¿Y cuánto cree usted que debería ganar para subsistir una familia media (renta mínima)?

3.6 Costes variables especificados por cultivos y por secano/regadío (euros/ha):

En este apartado se consideran todos los costes variables menos los asociados a la mano de obra (Seguridad Social, personas contratado…) y a lo que se paga por el riego, ambos los considero separadamente.

	SECANO	REGADÍO
1.Cultivo:		
2.		
3.		

3.7 Costes fijos:

- ¿Cuánto cuesta poner en marcha una Ha en aspersión? ¿En goteo? ¿Qué vida útil tienen estos equipos? ¿En cuál de estos sistemas se pierde menos agua?
- ¿Cuánto cuesta construir un pozo? ¿Qué vida útil media tiene un pozo? ¿Cuánto cuesta extraer el agua (gasolina, electricidad) en €/m3? ¿Cuántos Kw cuesta subir un m3 de agua? ¿Cuánto cuesta un Kw?

3.8 Financiación:

- A corto plazo: Por ejemplo, financiación de las semillas, fertilizantes…, etc. Es decir, todo lo que se utilice en la misma campaña. ¿Quién financia esto? ¿Las casas de fertilizantes, semillas…, o piden un crédito bancario? ¿Qué garantía: hipotecaria, la de la PAC, etc.? Especificar el tipo de interés, la anualidad…, etc.
- A largo plazo: Por ejemplo, construcción de los pozos, puesta en práctica de los sistemas de aspersión, goteo.... ¿Quién financia esto? ¿Se pide un crédito? Especificar el tipo de interés, la anualidad…, etc.

4. Mano de Obra:

4.1 Mano de obra familiar. ¿Qué labores hace: gestión, laboreo, supervisión, etc.? ¿Cuántas horas trabaja usted al día en Otoño-Invierno-Primavera-Verano?
4.2 ¿Se utiliza mano de obra contratada fija o/y eventual? ¿Cuántas horas trabajan respectivamente al día en Otoño-Invierno-Primavera-Verano? ¿Para qué funciones y/o cultivos la contrata?
4.3 ¿Cuánto cuesta en (€/h) la mano de obra contratada fija? ¿Y la eventual?

5. Agua:

5.1 ¿De cuánto agua dispone en total (metros cúbicos) por 'resolución administrativa'? ¿Cuánto le permite regar el régimen de extracciones?
5.2 ¿Tiene usted caudalímetros? ¿Cuál es la cantidad de agua bruta que usted utiliza? ¿Qué pasa si su pozo se queda obsoleto? ¿Tienen derecho a hacer otro, a reprofundizar? ¿Cuántos pozos tiene y qué características tienen esos pozos? Profundidad (m), diámetro (cm), tipo de bomba, superficie máxima regada, etc.
5.3 ¿Qué tarifas paga por el agua?
   - A la C.R.: ¿Cuántos €/pozo? ¿Cuántos €/Ha regadío? ¿Cuántos €/Ha acogida al Plan de Humedales?
   - A la Confederación: por limpieza de pozos, etc.
   - ¿Otras tarifas relacionadas con el agua?

<u>SOLUCIÓN AL CONFLICTO</u>

- ¿Qué opina del centro de intercambio de derechos propuesto en el borrador del PEAG, 2006?

- ¿Considera apropiadas las cantidades de indemnización de 3.000-10.000 €/ha para los no-leñosos y 3.000-6.000 €/ha para los leñosos?

- ¿Quién cree usted que se va a acoger? ¿Usted vendería sus derechos?

- ¿Qué opina usted de que en el PEAG no se haya hecho mención a las captaciones ilegales?

- ¿Cuántos pozos ilegales tiene usted? ¿Por qué son ilegales: porque los ha cambiado de sitio, porque ha reprofundizado, porque los ha construido sin permiso, porque no ha respetado la distancia mínima obligatoria? ¿Los tiene en la misma explotación con pozos legales? ¿Cuáles son las diferencias con un pozo legal: es decir, diámetro, profundidad, bomba, etc.?

- ¿Cuántas Has ilegales tiene usted? ¿Por qué son ilegales: porque las riega desde un pozo ilegal, porque las riega con un pozo legal pero se pasa de la superficie permitida, etc.?

- ¿Qué cultivos son los que produce en esa superficie llamada "ilegal"? ¿Cuáles son las diferencias respecto a la parte legal: utiliza los mismos tipos de suelo (bueno, malo, regular), obtiene mayores rendimientos, etc.?

Data Collection Matrix for the Middle Guadiana basin economic model

Entry data	Downloaded/gleaned from	Type of data	Format
Statistical sources (public use)			
o Agriculture sector	- INE (Spanish National Statistic Institute) (www.ine.es)	- Cuentas económicas. GDP of the agriculture sector. Level: region (CCAA), province.	- Online (Excel, PDF)
o Cultivated surface and number of farms - Region (CCAA), Agricultural region, municipality	- INE (Spanish National Statistic Institute) (www.ine.es) - MARM (Ministry of Environment, Rural and Marine Affairs) (www.mapa.es)	- Censo Agrario 1999 (each 10 years; by municipality; by farm size ranges) - Encuesta sobre la estructura de las explotaciones agrícolas en Extremadura 2007 (Yearly) (CCAA) (to update the Agrarian Census) - Avances sobre superficies y producciones (each 2 months) (CCAA)	- Online (Excel, PDF)
o Crops surface, crop insurance	- Junta de Extremadura, Consejería de Agricultura y Desarrollo rural (www.aym.juntaex.es). Portal Agralia	- Datos estadísticos sobre el sector agropecuario y forestal de Extremadura. Superficies de cultivo por munipio (Badajoz), 2007	- Online data (PDF)
o Crops-Technical itineraries (irrigation schedules, crop labor requirements, etc.)	- MARM (Ministry of Environment, Rural and Marine Affairs) (www.mapa.es) - Book	- MARM, 2005. Evaluación de la zona regable de Montijo (Badajoz). Technical itineraries, crop-related economic data, data about the operation of the Montijo IC. - De Juan Valero, J.A., Ortega Alvarez, J.F. y Tarjuelo Martin-Benito, J.Ma., 2003. Sistemas de cultivo: evaluación de itinerarios técnicos. Ediciones Mundi-Prensa, 835p.	- Report (PDF) - Book (PDF)
o Crops-Variable costs of inputs for crop production (seeds, fertilizers, machinery, etc.)	- MARM (Ministry of Environment, Rural and Marine Affairs) (www.mapa.es) - Book - CHG (Guadiana River Basin Authority) (www.chguadiana.es)	- MARM, 2007. Resultados técnico-económicos de las explotaciones agrarias de Extremadura en 2006. - MARM, 2005. Evaluación de la zona regable de Montijo (Badajoz). Technical itineraries, crop-related economic data, data about the operation of the Montijo IC. - De Juan Valero, J.A., Ortega Alvarez, J.F. y Tarjuelo Martin-Benito, J.Ma., 2003. Sistemas de cultivo: evaluación de itinerarios técnicos. Ediciones Mundi-Prensa, 835p. - CHG (Confederación Hidrográfica del Guadiana), 2006. Análisis económico de la Demarcación Hidrográfica del Guadiana según la Directiva Marco del Agua. MARM. Economic crop balance.	- Report (PDF) - Report (PDF) - Book (PDF) - Report (PDF)
o Crop subsidies, cross-compliance measures	- FEGA (Spanish Agricultural Guarantee Fund) (www.fega.es) – MARM - Junta de Extremadura, Consejería de Agricultura y Desarrollo rural (www.aym.juntaex.es). Portal Agralia	- Single Farm Payments, Crop subsidies, cross-compliance schemes. Regional level - Datos estadísticos sobre el sector agropecuario y forestal de Extremadura.	- All
o Farmland prices	- MARM (Ministry of Environment, Rural and Marine Affairs) (www.mapa.es)	- Precios de la tierra. At regional and national level. 2008 - Cánones de arrendamientos rústicos. At regional and national level.	- Online (PDF)

Entry data	Downloaded/gleaned from	Type of data	Format
		2005. Used for the calibration of the economic model.	
o Crop prices, yields, farm gross margin	- MARM (Ministry of Environment, Rural and Marine Affairs) (www.mapa.es)	- Encuesta sobre superficies y rendimientos (ESYRCE), 2009. At national and regional level. Crop surface, yields. - Red Contable Agraria Nacional (RECAN), 2005. Gross margin. At national and regional level. - Precios percibidos y pagados por los agricultores. Yearly and monthly. - Anuario de estadística agroalimentaria y pesquera, 2007. Summary.	- Online (PDF) - Online (PDF) - Online (PDF) - Online (PDF)
Fieldwork (restricted use)			
o Irrigation Communities	- Montijo Canal de Montijo, Zújar, Tomas Directas del Guadiana	- Municipalities, year of creation, number of irrigators, surface, land cover (crops), type of soils, economic structure of the IC (water tariffs, revenues, expenses), staff, water allocation rules, water allotments, types of irrigation systems, source of water, modernization works,	- Excel
o Individual irrigators	- 107 farms: in 21 municipalitiees (all of them in Badajoz), 3 ICs (MCM+TDG+MER). In total, 4655 has (15% of the total irrigated surface in MCM+TDG+MER).	- Most representative farms, surface, crop distribution, crop rotation, soils, insurance, cooperatives, yield, prices, gross margin of crops, crops water requirements, single farm payment, investments at short and long term (new permanent crops, new irrigation techniques, seeds, etc.), crop labor requirements, water consumption, number of wells, water prices	- Excel
o Technicians, experts	- TEPRO (agricultural consultancy group) (www.tepro.es)	- Farm typology, farmland prices, labor costs, insurance, variable costs of crops, crop yields, technical water efficiency	- Excel

Data Collection Matrix for the Middle Guadiana basin WEAP application

Entry data	Downloaded/gleaned from	Type of data	Format
Characterization of the basin			
o Administrative Divisions - Towns - Municipalities, provinces, regions - Agricultural regions	- Goggle Earth (open access) - IGN (National Geographic Institute of Spain) (www.ign.es) (open acess, www.idee.es 'Infraestructura de Datos Espaciales de España') - CHG (Guadiana River Basin Authority) (open and restricted access) (http://planhidrologico2009.chguadiana.es/)	- Shapefile (.shp); The geographic coordinates of the most populated towns were digitalized in ArcGIS - Database 'Datos de Líneas Límites' (BDLL), resolution 1:200,000 (.gml) - Official report (open access): CHG (Confederación Hidrográfica del Guadiana), 2006. Análisis económico de la Demarcación Hidrográfica del Guadiana según la Directiva Marco del Agua. Confederación . Badajoz, Spain. Database (restricted access) Shapefiles (.shp) and tables.	- GIS - GIS - GIS, Excel
o Hydrologic network (River Basin boundaries, watersheds, main rivers, river segments, river nodes, reservoirs, streamgages, etc.)	Main source (open access): - CHG (Guadiana River Basin Authority) (www.chguadiana.es) Completed with (open access): - EEA (Environmental European Agency)(www.dataservice.eea.euro pa.eu/) - JRC (Joing Research Center) (http://ccm.jrc.ec.europa.eu) - SIA (Integrated Water Information System of Spain) – MARM (www.marm.es) - IGN (National Geographic Institute of Spain) (http://www.ign.es/ign/es/IGN/ane_tablaDatos.jsp)	- Basin boundaries, rivers, watersheds, reservoirs, surface water, groundwater. Shapefiles (.shp). - EEA European Catchment and Rivers Network System. Watersheds, rivers, streamgages. Shapefiles (.shp). - CCM River and Catchment Database for Europe, version 2.1 (CCM2). Catchments, river segments, river nodes, lakes. (.shp). - Database about water related issues. Watersheds, rivers, irrigation canals. Shapefiles (.shp) - Atlas Nacional de España. Online consultation on wetlands, reservoirs, rivers	- GIS - GIS - GIS -GIS, Excel, PDF - Online data
o DEM (Digital Elevation Model)	Main source (open access): - NASA/U.S.Geological Survey (USGS) (http://www.seamless.usgs.gov/) Matched with (open access, under request): - IGN (National Geographic Institute of Spain)	- NASA Shuttle Radar Topographic Mission (SRTM) Digital Elevation Data. 3 arc second (approx. 90m resolution). ArcInfo ASCII and GeoTiff format - 200m x 200m, obtained from the elevation curves of the Topographic map 1:200.000. ASCII format.	- GIS - GIS
o Soils&Geological data (hydraulic properties)	- Join Research Center (JRC) of the EU (www.eusoils.jrc.it/Data.html) (open access)	- ESDBv2 Raster Library (1km x 1km)- a set of rasters derived from the European Soil Database distribution v2.0 (European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN), by Marc Van Liedekerke, Arwyn Jones, Panos Panagos, 2006	- GIS
o Land cover (Land classes with land cover attributes)	Main source (open access, under request): - IGN (National Geographic Institute of Spain) Completed with (open access, under request): - MARM (Spanish Ministry of Environment, Rural and	- CORINE Land Cover database. Digital maps at 1/100,000. 85 land classes. 1990-2000 and changes. Arcinfo (.e00) - 'Mapa de cultivos y aprovechamientos' (1999-2008). Digital maps at	- GIS - GIS

Entry data	Downloaded/gleaned from	Type of data	Format
	Marine Affairs)	1/50,000. Shapefile (.shp)	
o Irrigation districts (ICs)	Main source: - MARM (Spanish Ministry of Environment, Rural and Marine Affairs) (http://wms.marm.es/sig/Regadios/wms.aspx) - FENACORE (National Federation of Water Users Communities of Spain) (www.fenacore.org) Completed with: - Different web pages of the ICs	- Irrigation Communities where digitalized from the Web Map Service (WMS) of the MARM. - Inventory of Irrigation Communities - Images (.jpg)	- WMS, GIS - Online data - JPG
Climate data			
o Precipitation o Temperature	Main source: - Consultative Group for International Agriculture Research (CGIAR) (http://cru.csi.cgiar.org) Completed with: - AEMET (Spanish State Meteorological Agency (www.aemet.es)	- CRU TS 2.1 global climate database. Monthly time series of mean temperature and precipitation for the period 1901-2002 - Official report: AEMET, 2004. Guía resumida del clima en España 1971-2000. Plan Estadístico Nacional 2001-2004. Ministerio de Medio Ambiente. Dirección General del Instituto Nacional de Meteorología.	- GIS - Excel (CD ROM)
o Humidity o Wind	- Irrigation Advisory Service of the Extremadura Autonomous Community (REDAREX) (http://aym.juntaex.es/) - Agroclimatic Information System-MARM (www.mapa.es/siar/)	- 20 agroclimatic stations (monthly data). Temperature, precipitation, humidity, wind, radiation, evapotranspiration. 1999-2010.	- Online data
o Latitude	- CHG (Guadiana River Basin Authority) (www.chguadiana.es)	- Catchments'' latitude. Obtained in ArcGIS.	- GIS
Demand sites (urban, agriculture)			
o Agriculture - Farm size (rainfed & irrigated) - Irrigation technique - Water source in hectares - Agricultural crop distribution (rainfed & irrigated)	- CHG (Guadiana River Basin Authority)- MARM (Spanish Ministry of Environment, Rural and Marine Affairs) (open and restricted access) (http://planhidrologico2009.chguadiana.es/)	- Official report: CHG, 2006. Análisis económico de la Demarcación Hidrográfica del Guadiana según la Directiva Marco del Agua. Badajoz, Spain. Scale of analysis: agricultural region. Synthesis report (open access). Database (restricted access)	- GIS, Excel
- Water allotments	- Field work, ICs' web pages	- Water allotment rights through administrative concessions (m^3/ha)	- Excel
- Irrigation schedule	- Field work, different studies	- MARM (Ministerio de Agricultura, Medio Rural y Marino), 2005. Evaluación de la zona regable de Montijo (Badajoz). Centro Nacional de Tecnología de Regadíos - Polo-García, M.U., Pinilla-Ruiz, C., Leco-Berrocal, F., 2001. Seguimiento de una campaña de riego en el plan Badajoz: comprobación de la superficie regada y posibilidad de determinación	- Doc (word, pdf)

Entry data	Downloaded/gleaned from	Type of data	Format
		de fraude en el riego por medio de la teledetección. Mapping,69, ISSN 1131-9100, pags. 18-24	
o Urban			
- Association of towns (inventory)	- MPT (Spanish Ministry of Territorial Policy) (http://www.dgal.map.es/cgi-bin/webapb/webdriver?MIval=mancomunidades&NREG=0506005&n_prov=Badajoz) (open access) - General Directorate of Infrastructures and Water (D.G. Infraestructuras y Aguas), Consejería de Fomento, Junta de Extremadura (http://fomento.juntaex.es/infraestructuras/agua-infraestructurashidraulicas/mancomunidades.html) (open access)	- Association of towns in the province of Badajoz - Association of towns in Extremadura. Inventory and maps. November, 2009	- Online data - Online data, images (jpg)
- Population (inhabitants, density) and trends	- Spanish National Statistics Institute (INE) (www.ine.es) (open access)	- INE. 'Censo de población y viviendas' in Badajoz (1970, 1981,1991,2001). Ministry of Economy and Tax, Madrid, Spain. - INE, 2008. 'Cifras oficiales de población: padrón municipal', 2008. Ministry of Economy and Tax, Madrid, Spain.	- Excel - Excel
- Water consumption rates (annual and monthly) - Water return rates	- CHG (Guadiana River Basin Authority) (open and restricted access)	- CHG (Confederación Hidrográfica del Guadiana), 1998. Plan Hidrológico de la Cuenca del Guadiana I. Spanish Ministry of the Environment and Rural and Marine Affairs. Badajoz, Spain. - CHG (Confederación Hidrográfica del Guadiana), 2006. Análisis económico de la Demarcación Hidrográfica del Guadiana según la Directiva Marco del Agua. Spanish Ministry of the Environment and Rural and Marine Affairs. Badajoz, Spain	- Excel
Water supply&resources			
o Streamgages	Main source: - CHG (Guadiana River Basin Authority) (restricted access) Complementary source: - SAIH (Automatic System of Hydrologic Information) – CHG (open access, under request) (http://portal.saihguadiana.com/)	- Average monthly and annual data on streamflows (Mm^3/month, Mm^3/year). From 1924 to 2000. Based on the GRBMP (Guadiana River Basin Management Plan) of 1998. - Hydrologic information in real time. 222 control points for measuring streamflows, flows in canals, volume of water storage in reservoirs and in aquifers, some meteorological variables.	- Excel - Excel
o Rivers (streamflows)	- CHG (Guadiana River Basin Authority) (restricted access)	- Average monthly and annual data on river inflows by river segments (dataset of 258 river segments) (Mm^3/month, Mm^3/year, mm/year) From 1946 to 1997. Based on the GRBMP (Guadiana River Basin Management Plan) of 1998.	- Excel
o Environmental flow requirements	- CHG (Guadiana River Basin Authority) (restricted access)	- Minimum environmental flows by river segments (Mm^3/month). Based on the GRBMP (Guadiana River Basin Management Plan) of 1998.	- Excel

Entry data	Downloaded/gleaned from	Type of data	Format
		- CHG, 2009a. Caudales ecológicos por modelización del hábitat en la parte española de la demarcación hidrográfica del Guadiana. Elaboración del Plan Hidrológico 2009 en la parte española de la Demarcación Hidrográfica del Guadiana. Programa de medidas. September, 2009. - CHG, 2009b. Requerimientos de caudales ecológicos en la demarcación hidrográfica del Guadiana. Elaboración del Plan Hidrológico 2009 en la parte española de la Demarcación Hidrográfica del Guadiana. Programa de medidas. November, 2009.	- Pdf - Pdf
o Reservoirs - Physical data (Storage capacity; max., min., initial values; curve volumen-elevation; evaporation; surface; height) - Operational data (levels of conservation, security, inactivity)	Main source for reservoirs' physical and operational data: - CHG (Guadiana River Basin Authority) (restricted access) Complementary sources for physical data: - MARM (Spanish Ministry of Environment, Rural and Marine Affairs) 'Hydrologic bulletin' (open access) (http://servicios3.mma.es/BoleHWeb/inicio.jsp) (open access) - SAIH (Automatic System of Hydrologic Information) – CHG (open access, under request) (http://portal.saihguadiana.com/) Complementary sources for operational data: - CHG-MARM (open access)	- Average monthly and annual data on storaged water volume from 1951 to 2003 (Mm^3/month; Mm^3/year). Data by reservoirs on average max., min. storage capacity; curve volumen-elevation; evaporation; surface; height, etc. - Weekly data from 1988-2010 - Hydrologic information in real time. 222 control points for measuring streamflows, flows in canals, volume of water storage in reservoirs and in aquifers, some meteorological variables. - CHG (Confederación Hidrográfica del Guadiana), 2007. Plan Especial de Sequías de la Cuenca del Guadiana. Spanish Ministry of the Environment and Rural and Marine Affairs. Badajoz, Spain.	- Excel - Online data, pdf - Excel - Pdf
o Hydroelectric production	Main source: - CHG (Guadiana River Basin Authority) (restricted access)	- Hydroelectric production (GWH) by reservoir. From 1955 to 2004.	- Excel
o Canals' diversions	- CHG (Guadiana River Basin Authority) (restricted access)	- Monthly average rates (Mm^3/month; m^3/s)	- Excel
o Technical efficiency of irrigation canals/ modernization works	- State Society of Agricultural Infrastructure for the Southwest of Spain (SEIASA Meseta Sur, www.mapa.es/seiasa).	- Modernization works on the different irrigation canals	- Online data
Calibration of the model			
o Observed streamflows→ see streamgages in water supply and resources entry data			
o Agronomic-hydrologic parameters	- FAO reports (open access) - Irrigation Advisory Service of the Extremadura Autonomous Community (REDAREX) (http://aym.juntaex.es/) (open access) - Agroclimatic Information System-MARM (www.mapa.es/siar/) (open access) - MARM (Ministerio de Agricultura, Medio Rural y Marino) (oficial report, open access)	- Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998. Crop Evapotranspiration; Guidelines for Computing Crop Water Requirements , FAO Irrigation and Drainage Paper, 56, Food and Agriculture Organization of the United Nations, Rome - 20 agroclimatic stations (monthly data). Crop evapotranspiration. 1999-2010. - MARM (Ministerio de Agricultura, Medio Rural y Marino), 2004. Evaluación de la zona regable de Montijo (Badajoz). Centro Nacional	- Pdf - Online data - Doc (Word, Pdf)

Entry data	Downloaded/gleaned from	Type of data	Format
	- Similar WEAP applications (open acess)	de Tecnología de Regadíos - CCU-SEI, 2009; Escobar *et al.*, 2008; Young *et al.*, 2009; Yates *et al.*, 2009).	

7.1. Annex B- Methodology

WORKING PAPER:

Exploring the Interactions Between the General Algebraic Modeling System (GAMS) and the Water Evaluation And Planning System (WEAP)

By

Irene Blanco-Gutiérrez, PhD Candidate

Stockholm Environment Institute, USA

Universidad Politécnica de Madrid, Spain

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SEI STOCKHOLM ENVIRONMENT INSTITUTE

The author conducted this study during her international research stay as a visiting scholar at the Stockholm Environment Institute US Center and the University of California at Davis in 2009. This working paper is part of an ongoing PhD thesis to be submitted to the Universidad Politécnica de Madrid (Spain). The judgments and conclusions are solely those of the author, and are not necessarily endorsed by the Universidad Politécnica de Madrid, by the Stockholm Environment Institute or by any other agency.

Contents

1. Introduction

This synopsis is part of an ongoing PhD thesis. It addresses WEAP users and aims to provide some insight to the potential integration between the GAMS and WEAP models. It has been assumed that the readers are familiar with the WEAP platform, so more emphasis has been placed on describing some of the GAMS system's features and, most importantly, GAMS's interfaces. This document is intended to be a starting point for those interested in proceeding with the development of an automated GAMS-WEAP interface.

2. The GAMS Software and Interactions Between Modeling Systems

2.1. GAMS Overview and Main Integrated Tools

GAMS[22], one of the most powerful tools used in applied economics, was originally developed by physicist Alexander Meeraus while working on a research project at the World Bank during the 1970s. The General Algebraic Modeling System (GAMS) is a modeling language for mathematical programming, specifically designed for modeling optimization problems (LP, NLP, MIP, etc.). GAMS models are described by using algebra statements in a flexible way. The user can easily program a model entering data in list or table form, specifying variables or equations, and choosing the solver. The formulation can be easily and quickly modified, however it is highly case-specific. In other words, each model responds to a specific problem, and therefore, the mathematical formulation of the problem may change. It is true that similar problems can be faced with the GAMS model structure, but some modifications, related to data storage assignments, intermediate calculations or input-output statements, are usually required to be performed manually by the user. Hence, developing standard interfaces between GAMS and other software packages remains a difficult task.

To date, little software and few tools have been successfully linked with GAMS. Furthermore, some of them have not been officially supported by the GAMS Development Corporation, which has slowed down the use and development of these tools. Some of the programs that have already been prepared to interact with GAMS are the following[23]:

[22] Visit GAMS Home Page for more information: http://www.gams.com/

[23] More information about these software tools can be found at http://interfaces.gams-software.com/doku.php?id=user:user_contributed_software_and_tools

- *MATLAB*. A programming language for performing tasks computationally. The interface allows the visualization of GAMS models directly within MATLAB and vice-versa.
- *LAGO (Lagrangian Global Optimizer).* Software used to solve MINLP problems. It can generate solver executables for GAMS.
- *VEDA (Versatile Data Analyst)*. A tool that generates tables and graphs to help in the analysis of results of complex mathematical models. The interface allows analyzing data and parameters used in GAMS (model preparation or model solution).
- STATA. Data analysis and statistical software. STATA output files can be translated to be used in GAMS.
- *EMACS*. A text editor. GAMS can now be used in EMACS.
- *MAPINFO*. Software used to create and use geographic maps. GAMS can create MapInfo© maps through the routine GAMSMAP.
- *SHADEMAP*. A tool for shading and coloring regions in a world map (the world map comprises the regions used by the GTAP model). The GAMS interface allows GAMS to produce colored maps.
- *GNUPLOT*. A software-package used to display high quality graphs for publication or educational purposes. Output results from GAMS can be used in Gnuplot. Gnuplot figures and shade maps obtained from GAMS can also be loaded and emptied into Powerpoint.

2.2. Types of GAMS Interfaces

GAMS can either exchange data with other programs or be executed from other applications. Most of the routine applications that exchange data in GAMS are set up in the GAMS directories when the program (after version 21.0) is installed. GAMS can import and export[24] the following:

- *ASCII files (American Standard Code for Information Interchange).* Text files (*.txt, *.csv) where each byte corresponds to one character (according to the ASCII codes).
- *HTML (Hyper Text Markup Language).* Markup language for web pages.

[24] For further details about the different tools for data exchange in GAMS, please visit http://interfaces.gams-software.com/doku.php

- *XLM (Extensible Markup Language).* Textual data format for encoding documents electronically.
- *GDX files (Gams Data Exchange).* Binary files that can contain information regarding sets, parameters, variables and equations.
- *Excel files (*.xls and *.xlsx).* GAMS can communicate with Excel via GDX files.
- *Database.* DB2; MS Access; My SQL; SQL Server; Oracle; Sybase.
- *Latex files.* Specific language for the TeX typesetting program.
- *MPS (Mathematical Programming System) files.* File format for presenting and archiving LP and MIP problems.
- *NETGEN/GNETGEN files.* Generators for network and generalized network problems.

In some cases, passing information from external software-packages to the GAMS program may be very laborious and highly time-consuming. GAMS has not yet released general interface routines for GAMS files use within other software with different programming languages, but there are many intermediate programs able to remotely activate GAMS, provide data, run GAMS models, and receive back solution information. Some of these programs are the following[25]:

- *Visual Basic.* Event-driven programming language and integrated development environment from Microsoft. Its graphical performance allows the creation of a visual window where a GAMS model can be specified and run through a GAMS button.
- *C.* Computer programming language for use with the Unix operating system. Gams.exe is brought up using a C invocation.
- *Visual C++.* Commercial integrated development environment made by Microsoft Windows. Gams.exe is brought up from a C++ application.
- *C-Sharp.* Computer programming language developed by Microsoft Windows.
- *Java.* Programming language of the Java Platform. Java invokes GAMS using the *Exec* method.
- *Delphi.* Programming language successor of the MS-DOS-based Turbo Pascal for Windows.

[25] For further information about the computing interfaces of these programs, please consult http://interfaces.gams-software.com/doku.php?id=env:executing_gams_from_other_environments

- *Web server or HTTP server.* GAMS is executed from the server via a Common Gateway Interface (CGI).

3. GAMS-WEAP Model Integration

Linking GAMS results or input to WEAP can be done by two fundamentally different ways: manually or automatically. In the first mechanism, each model works independently and the result data from one of the models is manually incorporated into the other model as it starts up. On the contrary, in the second mechanism, a third program is responsible for the whole process, and the results from one model are interactively included into the other model.

3.1. Manual GAMS-WEAP Interface

This section gives a brief overview of how the GAMS and WEAP models exchange data following a manual interface. Data exchange is carried out by manually entering the solution information from GAMS into WEAP, and vice-versa. The word “manually” means that this methodology does not use any external software to launch the GAMS and WEAP models remotely. However, some processing work still needs to be done to adjust the format of the models’ result files to the models’ input files. Several intermediate software-packages could be used to facilitate this task.

As seen in section 1.2, GAMS can interact with other applications in many different formats. On the other hand, the WEAP model admits a narrower range of file extensions, and this is why the GAMS result files will preferably be transformed into a WEAP valid format. WEAP uses a specific function (the “ReadFromFile” function[26]) to read data in a text file format (*.csv or .*txt), whereas it can export result data either in an Excel format (*.xls; *.xlsx) or a comma-separated values (*.csv) format. The “ReadFromFile” function can be used for any variable with time-series data (annual, monthly, daily, etc.). Time data should be placed in the first columns. Then, WEAP will automatically locate the time data and will start numbering the data

[26] ReadFromFile (FilePathDirection\FileName.csv, DataColumnNumber, YearOffset, DisaggregationMethod). For details, please consult Sieber and Purkey (2007).

columns after the time columns[27]. Although it's not essential that the text file be strictly located in the same directory as the WEAP area, it is highly recommended to do so.

All these specifications can be done using the GAMS utilities for data exchange (Brooke et al., 2008; McCarl et al., 2009). As explained below, two types of data exchange will communicate GAMS with WEAP.

1. *Data exchange with Excel files.* GAMS interacts with Excel via GDX (GAMS Data Exchange) files using the "GDXXRW" utility[28]:

    a. *From GAMS to Excel.* First, unload the data from GAMS to a GDX file using the "execute_unload" command. Second, transform the GDX file to an Excel file using the GDXXRW tool. Since the GAMS output data will be stored in an Excel file, the Excel file has to be subsequently converted to a CSV file. This can be done within Excel (using the "Save As CSV" functionality) or by making use of a specialized commercial software-package.
    b. *From Excel to GAMS.* First, create the GDX file from the Excel file using the GDXXRW and GDXIN tools. Then, import data via the LOAD command.

2. *Data exchange with CSV files[29].* Different methods can be used to exchange data with CSV files.
    a. *From GAMS to CSV.* This may be done:
        - Writing a set of "put file" instructions and using the put file "PC" command.
        - Programming the "libinclude" routine called "Gams2csv".
        - Using the GDXVIEWER tool. This routine will create a .gdx file and will then transform this file into a .csv file.
    b. *From CSV to GAMS.* CSV files can be included in GAMS using the $ondelim and $offdelim commands as well as the $include tool.

[27] Thanks to the last version of WEAP the head line (usually, the variable comment line entered as a text) has not to begin any more with ";" or "#". Any line that not starts with a number will be ignored.
[28] For details, please consult GAMS Development Corporation (2009).
[29] This method would be also valid with other text files, such as the *.txt files.

Example: Transferring Crop-distribution Data from GAMS to WEAP

We have several farm-based models of constraint optimization written in GAMS, and a basin-based hydrology model specified in WEAP. The economic model maximizes a utility function subject to technical, economic and policy constraints, and provides, among other outputs, the optimal farmers' crop distribution. The cropping pattern of different farm types has been reproduced in WEAP within the catchments nodes (including irrigated areas) and the percentage of the share area of different crops has been imported from an Excel file (this one, previously exported by the GAMS model) into WEAP.

In this case, GAMS and WEAP communicate via Excel because of its flexibility in unloaded tables with a suitable format for WEAP. The GDXXRW tool allows us to easily specify the folder where the input file for WEAP will be placed (the same directory of the WEAP area) and define where and how the data will be unloaded into the Excel spreadsheet. The CSV interface also store files in the WEAP area directory, but the results need to be transposed before importing them into WEAP. Following the data exchange routine with Excel, the crop distribution of each farm type was exported to an .xlsx file within the WEAP area directory. Since all the .xlsx files were previously formatted in GAMS, any changes needed to be done apart from the Excel-CSV transformation. Among the different methods to convert Excel to CSV, we used the "Convert XLS" tool. This software can be easily downloaded from the Internet and the only thing to be careful about is that if the Excel file contains more than one spreadsheet, only the first one will be converted. To avoid this problem, all of our data was carefully stored in different files. Therefore, using the Convert XLS program, all the files were transformed from Excel to CSV at once in only 3 seconds runtime. Finally, as explained before, the CSV files were imported to WEAP using the ReadFromFile function.

The WEAP-GAMS interaction has also been developed manually. In this case, the quantity of water available for each farm type will be exported from WEAP and imported into GAMS. This data exchange is very simple because GAMS values for water availability are presented as "scalar" data, which means that only one cell in the GAMS input spreadsheet needs to be changed at each model run.

3.2. Automated GAMS-WEAP Interface

Another possibility of linking GAMS and WEAP is to use an external compiled program to be responsible for the interface. Such an effort involves technical computing expertise, which is beyond my own capabilities and the scope of my PhD thesis. Consequently, below I will only discuss some general issues and briefly describe which steps, according to the literature, should be followed in order to accomplish this task.

As seen in section 1, many programs can spawn GAMS remotely. Among them, Visual Basic for Applications seems to be one of the most suitable tools, as it is able to create macros in Excel spreadsheets from which GAMS can easily be invoked. Both models, GAMS and WEAP, can import and export data to Excel files (*.xls and *.xlsx) straightforwardly. However, the use of macros will further allow editing and changes to different databases, as well as running GAMS in the background by pressing just one button in Excel. It remains to be seen if these Visual Basin Macros are also able to call the WEAP program remotely, in which case we would have a perfect two-way interaction.

An example of the Excel-GAMS interface as it is applied to a transportation model has been reported by McCarl (2000) [30]. According to the author, several steps should be followed to set up this application:

1. Prepare the GAMS model
    a. Locate the GAMS system directory and trace its path.
    b. Store a copy of the GAMS model in the temporary directory of Windows (c:/temp).
2. Set up the GAMS model for exchanging data with Excel
    a. Develop an “Include” statement for importing data from Excel into GAMS. Use the on/offdelim to import .csv files.
    b. Write a “File” and a “Put” statement for exporting data from GAMS to Excel (also in .csv format).
3. Organize the Excel spreadsheets

[30] For details, please consult MacCarl (2000) document or follow the next link edited by the GAMS Corporation (http://interfaces.gams-software.com/doku.php?id=env:spawning_gams_from_excel).

a. Create separate sheets for inputs and output results. The input sheet to be imported in GAMS might be the output sheet for WEAP. On the contrary, the result sheet from GAMS might be the input sheet in WEAP. Develop additional sheets when necessary for supporting the application (other databases are allocated in additional sheets).

b. Configure the Excel sheets containing the input data for GAMS and WEAP. Adjust the format of the data to be imported in both models.

c. Link data from one spreadsheet to so it can change when modifying specific data. Databases might be modified by copying the solution data from the results sheet. The input sheet might be also affected by changes produced in other databases.

4. Develop Visual Basic Macros to:

    a. Pass data to GAMS. Indicate the name, range, and location of the input sheet. Use the Visual Basic utility "XL2Txt".

    b. Run GAMS. Name the file to be run and create the GAMS's call.

    c. Retrieve data from GAMS. Check that GAMS has run correctly; get back output files using the Visual Basic utility "txt2 xc"; check optimality status, and open .lst GAMS files if errors occur.

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Sieber, J., Purkey, D., 2007. User Guide for WEAP21 (Water Evaluation And Planning System). Stockholm Environment Institute, 219 pp.

7.3. Annex C- Results

Cost-Effective Analysis of water management policies in the Mancha Occidental aquifer: Farm Type F1

Indicator	Baseline Scenario	Uniform Water Pricing (P=0.210 €/m^3)	Block Water Pricing (P=0.102 €/m^3)	Water Use Quota	Water Market (P=0.238 €/m^3)
Income (000 €)	60232.71	28083.18	34715.23	43941.10	43941.10
Income loss (000 €)	-	-32149.53	-25517.47	-16291.61	-16291.61
Income loss (%)	-	53.38	42.36	27.05	27.05
Public collection (000 €)	-6477.17	9077.94	2445.88	-3663.53	-3663.53
Public collection increase (000 €)	-	15555.11	8923.06	2813.65	2813.65
Public collection increase (%)	-	240.15	137.76	43.44	43.44
Net social cost (000 €)	-	-16594.42	-16594.42	-13477.96	-13477.96
Net social cost (€/ha)	-	-292.84	-292.84	-237.84	-237.84
Net social cost (€/m^3)	-	-0.0864	-0.0864	-0.0702	-0.0702
RANKED COST-EFFECTIVENESS(*)		**2**		**1**	

(*)Simulated management instruments have been ranked from 1 to 3, having the #1 the highest cost-effectiveness

Cost-Effective Analysis of water management policies in the Mancha Occidental aquifer: Farm Type F2

Indicator	Baseline Scenario	Uniform Water Pricing (P=0.210 €/m^3)	Block Water Pricing (P=0.102 €/m^3)	Water Use Quota	Water Market (P=0.238 €/m^3)
Income (000 €)	33369.47	-2398.09	4810.51	13034.87	13044.46
Income loss (000 €)	-	-35767.56	-28558.96	-20334.60	-20325.01
Income loss (%)	-	107.19	85.58	60.94	60.91
Public collection (000 €)	-3034.59	32422.22	25213.63	13636.63	13858.17
Public collection increase (000 €)	-	35456.81	28248.22	16671.22	16892.76
Public collection increase (%)	-	1168.42	930.87	549.37	556.67
Net social cost (000 €)	-	-310.74	-310.74	-3663.38	-3432.24
Net social cost (€/ha)	-	-5.62	-5.62	-66.30	-62.12
Net social cost (€/m^3)	-	-0.0030	-0.0030	-0.0348	-0.0326
RANKED COST-EFFECTIVENESS(*)		**1**		**3**	**2**

(*)Simulated management instruments have been ranked from 1 to 3, having the #1 the highest cost-effectiveness

Cost-Effective Analysis of water management policies in the Mancha Occidental aquifer: Farm Type F3

Indicator	Baseline Scenario	Uniform Water Pricing (P=0.210 €/m^3)	Block Water Pricing (P=0.102 €/m^3)	Water Use Quota	Water Market (P=0.238 €/m^3)
Income (000 €)	20751.38	9907.70	14979.15	18629.28	18629.28
Income loss (000 €)	-	-10843.68	-5772.23	-2122.10	-2122.10
Income loss (%)	-	52.26	27.82	10.23	10.23
Public collection (000 €)	-5786.93	4219.90	-851.56	-5395.97	-5395.97
Public collection increase (000 €)	-	10006.83	4935.37	390.96	390.96
Public collection increase (%)	-	172.92	85.28	6.76	6.76
Net social cost (000 €)	-	-836.85	-836.85	-1731.14	-1731.14
Net social cost (€/ha)	-	-21.55	-21.55	-44.57	-44.57
Net social cost (€/m^3)	-	-0.0114	-0.0114	-0.0235	-0.0235
RANKED COST-EFFECTIVENESS(*)		**1**		**2**	

(*)Simulated management instruments have been ranked from 1 to 3, having the #1 the highest cost-effectiveness

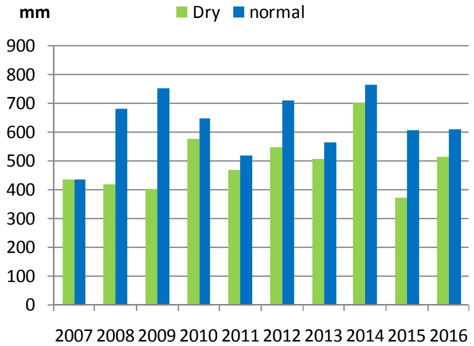
Cost-Effective Analysis of water management policies in the Mancha Occidental aquifer: Farm Type F4

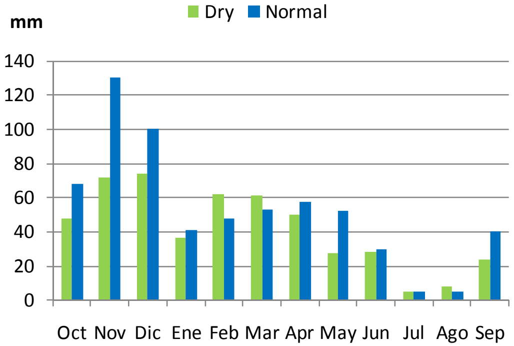
Indicator	Baseline Scenario	Uniform Water Pricing (P=0.210 €/m^3)	Block Water Pricing (P=0.102 €/m^3)	Water Use Quota	Water Market (P=0.238 €/m^3)
Income (000 €)	29992.09	17795.30	22540.93	28553.06	28570.71
Income loss (000 €)	-	-12196.79	-7451.16	-1439.03	-1421.38
Income loss (%)	-	40.67	24.84	4.80	4.74
Public collection (000 €)	-14015.17	-3482.83	-8228.47	-13466.92	-13472.51
Public collection increase (000 €)	-	10532.33	5786.70	548.24	542.66
Public collection increase (%)	-	75.15	41.29	3.91	3.87
Net social cost (000 €)	-	-1664.46	-1664.46	-890.79	-878.72
Net social cost (€/ha)	-	-21.69	-21.69	-11.61	-11.45
Net social cost (€/m^3)	-	-0.0183	-0.0183	-0.0098	-0.0097
RANKED COST-EFFECTIVENESS(*)		**3**		**2**	**1**

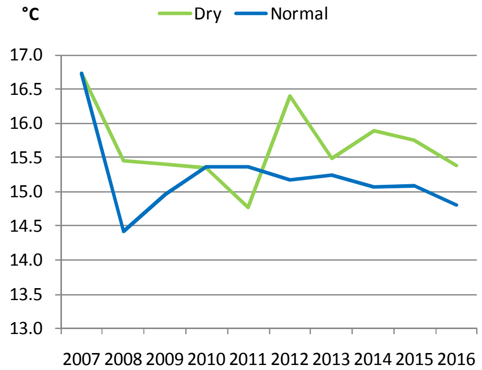
(*)Simulated management instruments have been ranked from 1 to 3, having the #1 the highest cost-effectiveness

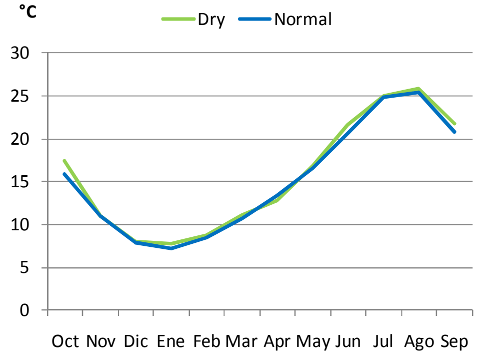
Normal and dry climate sequences simulated over the period 2007/2008-2015/2016.

- ***Upstream region***

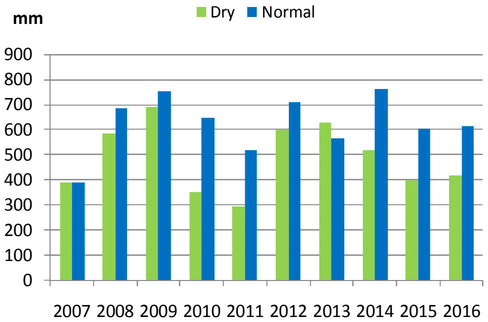


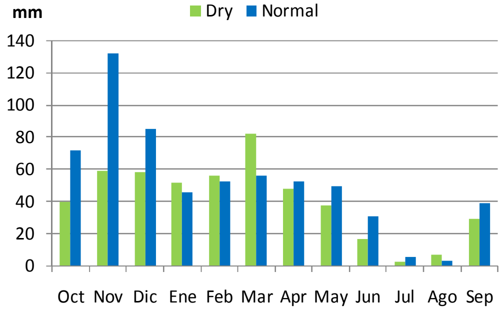


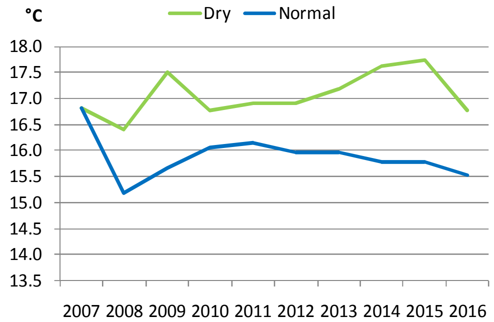


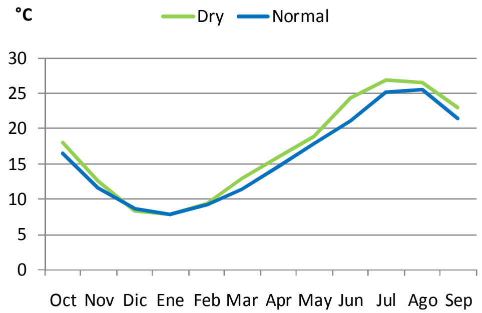


- ***Midstream region***

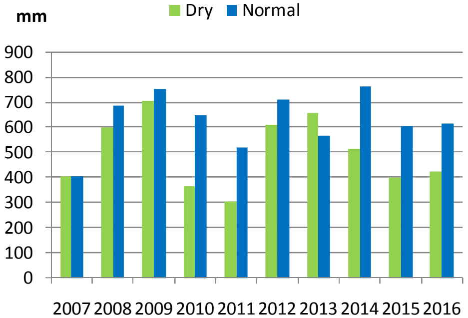


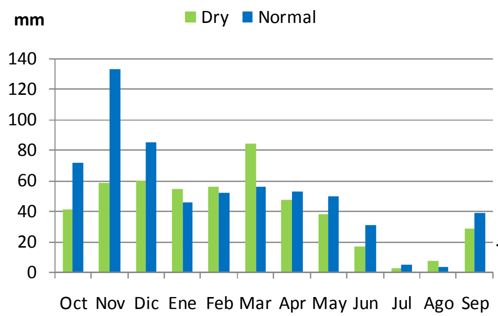


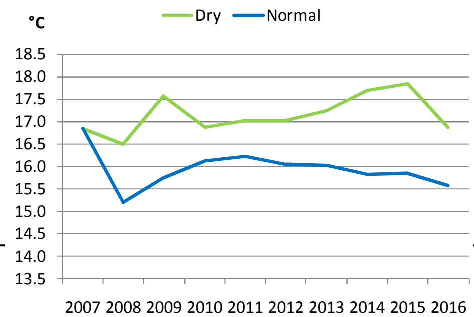


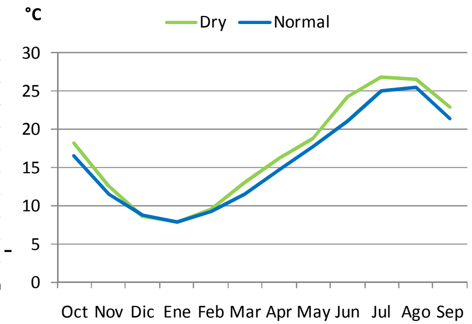


- ***Donwstream region***



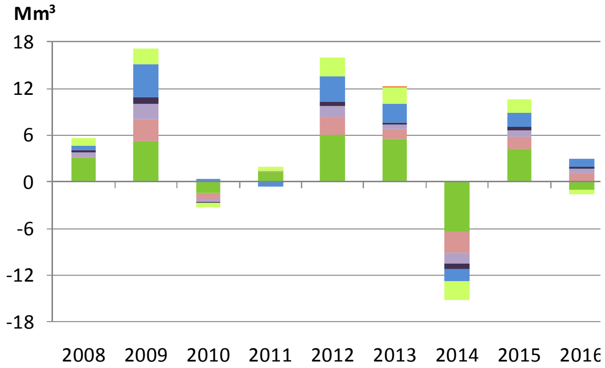


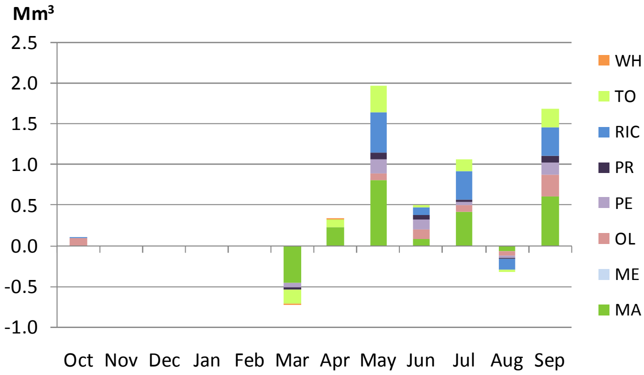




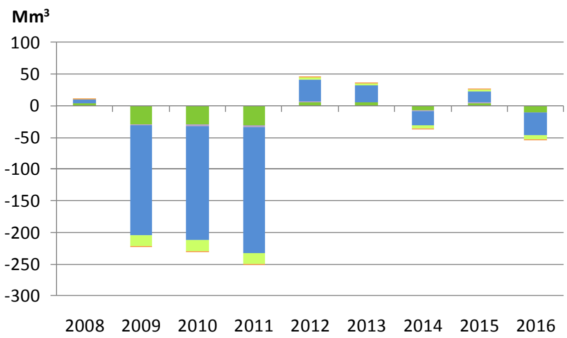
Annual total and monthly average crop water demands in a dry climate cycle relative to normal in the middle Guadiana Basin:

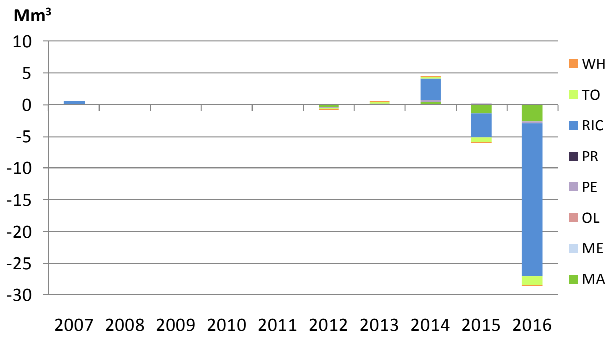
- ***<u>Irrigated catchment of Zújar</u>***



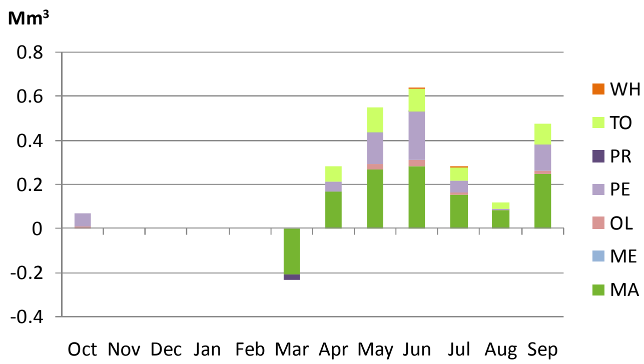


- ***<u>Irrigation catchment of Canal de Orellana</u>***

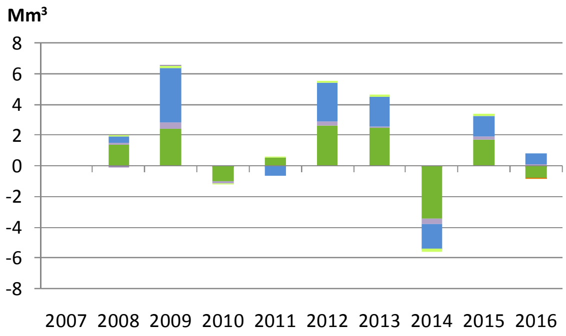


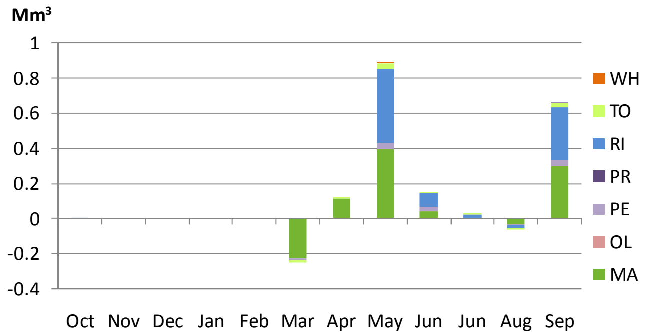


- ***<u>Irrigation catchment of Montijo-Canal de Montijo</u>***

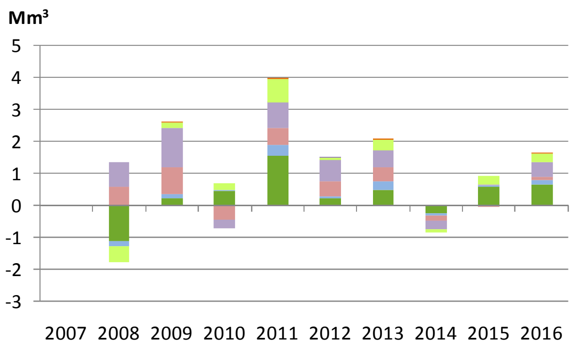


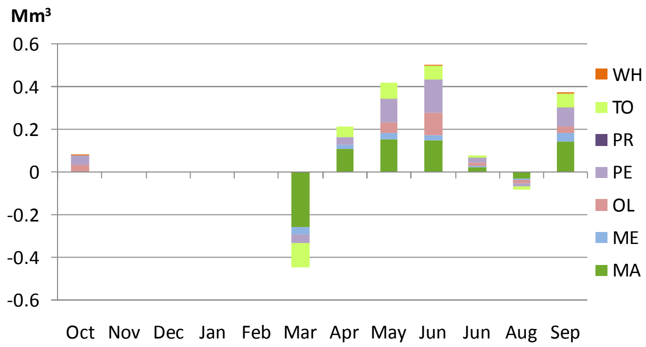
- ***Irrigated catchment of Tomas Directas del Guadiana 1***





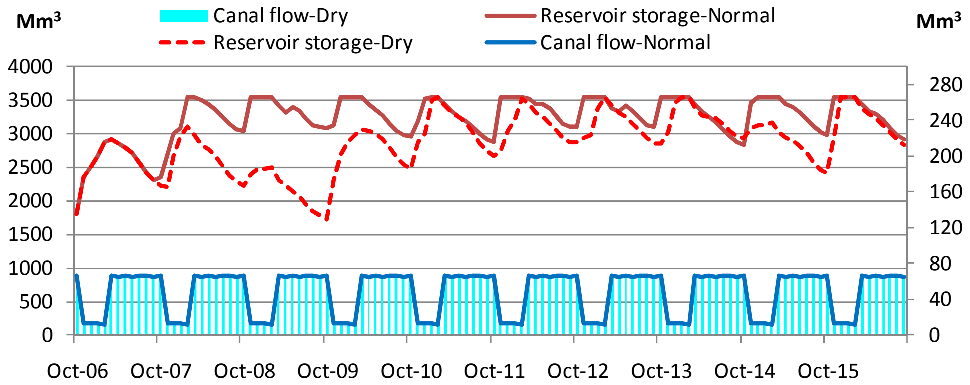
- ***Irrigated catchment of Tomas Directas del Guadiana 2***



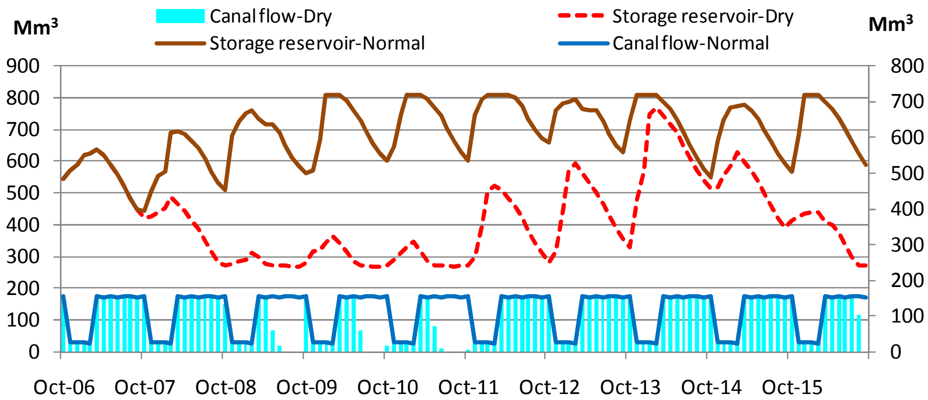


Maximum water level fluctuations in main irrigation channels and near reservoirs and under normal and dry climate conditions:

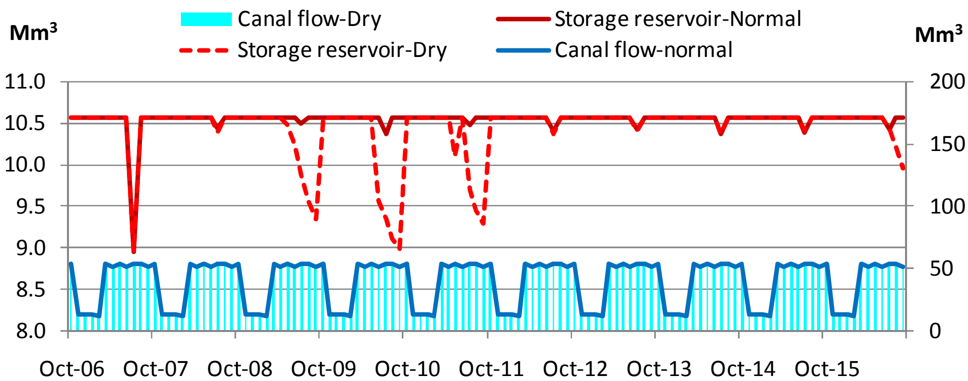
- ***Zújar-Serena reservoir and Zújar Irrigation canal***



- ***Orellana reservoir and Orellana Irrigation canal***



- ***Montijo reservoir and Montijo Irrigation canal***



Baseline values for the first and last year of the simulation period (2007-2015) by type of Irrigation Community and <u>representative farm</u>.

Indicator	Year	CDO			MCM		TDG		ZUJ		
		F_1	F_2	F_3	F_4	F_5	F_7	F_8	F_{12}	F_{13}	F_{14}
Income (€/ha)	2007	2030	1699	1858	2827	1770	2744	1401	1571	4228	2187
	2015	1977	1423	1181	2769	1546	2599	1239	1441	4210	2025
Public expenditure (€/ha)	2007	769	882	1249	487	1175	623	670	701	65	1208
	2015	765	822	798	455	998	457	611	561	112	945
Water use (m^3/ha)	2007	8938	12300	8194	7443	7597	5741	7834	6233	6300	5344
	2015	8873	12210	8467	7387	7775	5966	8062	6018	5643	6043
Water productivity (€/m^3)	2007	0.227	0.138	0.227	0.379	0.233	0.477	0.179	0.252	0.671	0.409
	2015	0.224	0.117	0.140	0.372	0.197	0.435	0.153	0.239	0.746	0.335
Water Cost (€/m^3)	2007	0.021	0.015	0.023	0.029	0.029	0.049	0.047	0.047	0.034	0.051
	2015	0.022	0.016	0.023	0.029	0.028	0.049	0.047	0.046	0.047	0.046
Labor (working days/ha)	2007	11	9	8	21	5	24	7	8	49	11
	2015	11	6	11	17	2	13	9	6	46	9
Irrigated/Rainfed (%)	2007	100/0	100/0	100/0	100/0	100/0	100/0	100/0	100/0	100/0	100/0
	2015	99/1	100/0	100/0	95/5	93/7	90/10	100/0	91/9	100/0	100/0

Effects of the application of the HNP water allotments under normal and dry climate conditions by type of Irrigation Community and representative farm.

Indicator	Water policy	Climate sequence	CDO			MCM		TDG		ZUJ		
			F_1	F_2	F_3	F_4	F_5	F_7	F_8	F_{12}	F_{13}	F_{14}
Income (€/ha)	Ref.	Normal	1977	1423	1181	2769	1546	2599	1239	1441	4210	2025
	HNP	Normal	1854	1125	1076	2639	1434	2529	1193	1455	4189	2015
		Dry	1757	1047	1014	2535	1371	2476	1170	1436	4177	2005
Water use (m^3/ha)	Ref.	Normal	8873	12210	8467	7387	7775	5966	8062	6018	5643	6043
	HNP	Normal	6375	6375	6375	6600	6600	6175	6175	6343	5343	5722
		Dry	6375	6375	6375	6600	6600	6175	6175	6647	6187	6472
Water productivity (€/m^3)	Ref.	Normal	0.224	0.117	0.140	0.373	0.198	0.435	0.153	0.239	0.746	0.335
	HNP	Normal	0.291	0.176	0.169	0.400	0.217	0.410	0.193	0.229	0.784	0.352
		Dry	0.276	0.164	0.159	0.384	0.208	0.402	0.190	0.216	0.674	0.309
Water Cost (€/m^3)	Ref.	Normal	0.022	0.016	0.023	0.029	0.028	0.050	0.048	0.046	0.047	0.046
	HNP	Normal	0.031	0.031	0.031	0.034	0.034	0.047	0.047	0.046	0.050	0.048
		Dry	0.031	0.031	0.031	0.034	0.034	0.047	0.047	0.044	0.046	0.045
Dual values (€/m^3)	Ref.	Normal	0.022	0.047	-	0.033	0.026	0.042	-	-	-	-
	HNP	Normal	0.039	0.047	0.039	0.034	0.027	0.038	0.004	-	-	-
		Dry	0.036	0.043	0.036	0.031	0.026	0.036	0.002	-	-	-
Irrigated/Rainfed (%)	Ref.	Normal	99/1	100/0	100/0	95/5	93/7	90/10	100/0	91/9	100/0	100/0
	HNP	Normal	65/35	51/49	82/18	80/20	74/26	90/10	79/21	96/4	96/5	96/6
		Dry	60/40	46/54	78/22	74/26	69/31	85/15	74/26	95/5	98/2	98/2

Effects of the application of environmental flows under normal and dry climate conditions by type of Irrigation Community and <u>representative farm</u>.

Indicator	Water policy	Climate sequence	CDO			MCM		TDG		ZUJ		
			F_1	F_2	F_3	F_4	F_5	F_7	F_8	F_{12}	F_{13}	F_{14}
Income (€/ha)	Ref.	Normal	1977	1423	1181	2769	1546	2599	1239	1441	4210	2025
	Env.F	Normal	1904	1170	1115	2768	1546	2599	1239	1441	4209	2025
		Dry	1652	982	943	2604	1445	2526	1194	1425	4191	2008
Water use (m^3/ha)	Ref.	Normal	8938	12300	8529	7387	7775	5966	8062	6018	5643	6043
	Env.F	Normal	8045	8045	8045	7387	7775	5966	8062	6018	5643	6043
		Dry	5816	5816	5816	7387	7775	5966	8719	6300	6283	6300
Water productivity (€/m^3)	Ref.	Normal	0.221	0.116	0.138	0.373	0.198	0.435	0.153	0.239	0.746	0.335
	Env.F	Normal	0.238	0.146	0.139	0.373	0.198	0.435	0.153	0.239	0.746	0.335
		Dry	0.284	0.169	0.162	0.350	0.184	0.423	0.137	0.226	0.667	0.319
Water Cost (€/m^3)	Ref.	Normal	0.022	0.016	0.023	0.026	0.025	0.049	0.047	0.046	0.047	0.046
	Env.F	Normal	0.028	0.028	0.028	0.026	0.025	0.049	0.047	0.046	0.047	0.046
		Dry	0.037	0.037	0.037	0.026	0.025	0.049	0.046	0.045	0.045	0.045
Dual values (€/m^3)	Ref.	Normal	0.022	0.047	-	0.033	0.026	0.042	-	-	-	-
	Env.F	Normal	0.037	0.045	0.036	0.033	0.026	0.042	0.000	-	-	-
		Dry	0.039	0.047	0.039	0.030	0.024	0.034	0.002	0.014	-	0.008
Irrigated/Rainfed (%)	Ref.	Normal	99/1	100/0	100/0	95/5	93/7	90/10	100/0	91/9	100/0	100/0
	Env.F	Normal	69/31	55/45	100/1	95/5	93/7	90/10	100/0	91/9	100/0	100/0
		Dry	55/45	41/59	72/28	82/18	80/20	86/14	95/5	90/10	100/0	98/2

Irene Blanco Gutiérrez

Department of Agricultural Economics and Social Sciences

Research Centre for the Management of Agricultural and Environmental Risks

E.T.S. Ingenieros Agrónomos, Universidad Politécnica de Madrid

E: irene.blanco@upm.es

T: +34 91 3365798

F: +34 91 3365797

W : www.etsia.upm.es

www.ceigram.upm.es/