Departamento de Economía y Ciencias Sociales Agrarias

Escuela Técnica Superior de Ingenieros Agrónomos

Universidad Politécnica de Madrid

Water scarcity and climate change impact and vulnerability in irrigated agriculture in Mediterranean river basins

Tesis doctoral

Paloma Esteve Bengoechea – Ingeniero Agrónomo

Directores

Consuelo Varela Ortega – Dr. Ingeniero Agrónomo (Universidad Politécnica de Madrid)

Thomas E. Downing – Dr. Geografía (Clark University)

Madrid, 2013

CAMPUS
DE EXCELENCIA
INTERNACIONAL

Tribunal nombrado por el Sr. Rector Magfco. de la Universidad Politécnica de Madrid, el día ……… de …………………. de 201…

Presidente: ……………………………………………………………………………

Vocal: ………………………………………………………………………………..

Vocal: ………………………………………………………………………………..

Vocal: ………………………………………………………………………………..

Secretario: …………………………………………………………………………..

Suplente: ……………………………………………………………………………

Suplente: ……………………………………………………………………………

Realizado el acto de defensa y lectura de la Tesis el día …… de …………. de 201… en la E.T.S.I./Facultad ……………………….

Calificación …………………………………………….

EL PRESIDENTE LOS VOCALES

EL SECRETARIO

A mi familia

Acknowledgements

This doctoral thesis has developed over five years of hard, challenging work it has tested my maturity and has taken me through some difficult times. Undoubtedly, this could not have been completed without the great support of many people who have been involved at various stages, and who have offered me their support throughout the completion of this thesis.

I want to express my immense gratitude to the directors of this thesis, without whom this work would have been far more difficult, if not impossible. To start, I want to thank Professor Consuelo Varela Ortega who coaxed me into the world of research. Consuelo has been my professor, director of my undergraduate research and more recently the director of this thesis. Consuelo graciously offered me the opportunity to be part of her team and work on projects that aroused my interests in the complicated world of water, its management and impacts. Her help has been much more than just academic, she has offered me her friendship and has helped me understand and learn from my weaknesses, whilst developing my strengths. She has always had the words to motivate and direct me when I´ve been lost.

I am very grateful to my co-director, Tom Downing, who opened the doors of his house and team to me. The time in Oxford was an important turning point in the development of this research. To him I will always be grateful for offering a new perspective on the issues of water and adaptation to climate change, and for inspiring the selection of methods to provide a social perspective to climate change.

I would further like to thank the Global Climate Adaptation Partnership (GCAP) in Oxford and the Stockholm Environment Institute (SEI) in Boston for allowing me to research at their centres. These periods were fundamental in the development of the models and applied approaches of this research. I received unquestioning support from both my co-director Tom Downing (GCAP) and David Purkey (SEI), who supervised my research stays at Oxford and Boston. Also, I would like to offer my thanks to the teams in Oxford and Boston, especially Brian Joyce of SEI-Boston, who helped me in the development of the application WEAP in the middle Guadiana, and Eric Kemp- Benedict and Jack Sieber. My time in the UK and USA were extremely important for this research and provided me unforgettable personal experiences.

In addition, I have been fortunate to have the support of the European research projects SCENES, MEDIATION and MEDPRO. They have supported me not just financially, but have been sources of understanding and inspiration and have consistently exposed me to novel methods of research. These projects have given me the opportunity to work with teams from across the world and researchers of the highest level who have contributed importantly to this investigation through intense and valuable discussions and work sessions. From the SCENES project I would like to especially highlight Professor Kasper Kok (University of Wageningen, Netherlands) for his contributions towards scenario development. I must also mention the teams at the Mediterranean Agronomic Institute of Bari (IAMB, Italy) and the Middle East Technical University (METU, Turkey), directed by Dr. Nicola Lamaddalena and Professor Erol Cakmak respectively, with whom I learned a great deal about water and agriculture in the Mediterranean.

From the MEDIATION project I want to especially highlight the help of Dr Rob Swart (Alterra, Netherlands) the coordinator of the project, Dr Sukaina Bharwani (SEI-Oxford, UK) for her contribution in methodological aspects and social approaches, Dr Paul Watkiss (collaborator at SEI-Oxford, UK) for his valuable comments on climate change adaptation economic analysis, Dr Jochen Hinkel (PIK, Germany), for his contribution to the debate on vulnerability and to Doctors Tim Carter and Stephan Fronzek (SYKE, Finland) for their contribution to climate change scenarios.

From the MEDPRO project I want to thank the support of Dr Rym Ayadi (CEPS, Belgium) coordinator of the project, and to Dr Francesco Bosello (FEEM, Italy) for his contribution to the analysis of the impacts of climate change on Mediterranean agriculture.

My research has consistently received absolute support from the Universidad Politécnica de Madrid, from the financial support that allowed me to complete this thesis, or the two scholarships that permitted me to carry out my stays in the USA and UK. Also, I must thank the Department of Agricultural Economics and Social Sciences, from the School of Agricultural Engineering (UPM), and CEIGRAM (Research Centre for the Management of Agricultural and Environmental Risks) who have supported and contributed to my training and development in their efforts to support the careers of young researchers. I especially want to acknowledge the support of their respective directors, Professor Isabel Bardají and Professor Alberto Garrido. I further want to highlight the support of the Professors of the Department of Agricultural Economics and CEIGRAM, especially Eva Iglesias and Ana Iglesias, who both contributed to my education and have provided interesting opinions and suggestions.

In the development of this research and specifically a number of tools within it, the contribution of the stakeholders of the middle Guadiana has been fundamental. I would specifically like to acknowledge the support of José Ángel Rodríguez Cabello, the head of the Planning Office in the Guadiana River Basin Authority, and to José Ramón Picatoste and his team in the Spanish Office for Climate Change. I would also like to give my thanks for the support I received from the irrigation communities of Montijo and Zujar, and, especially, Tomas Directas del Guadiana and his secretary Blas Benito de Motta, who always gave me a warm welcome on my many visits to Badajoz. Thanks also to the Department of Agriculture, Rural Development, Environment and Energy of Extremadura, to ADENEX (Association for the Defence of Nature in Extremadura) and WWF Spain, especially Alberto Fernández Lop who has worked very actively in all the consultations and participatory processes carried out. Also, I would like to thank a number of experts who participated in various consultations, in addition to the previously mentioned Alberto Garrido and Ana Iglesias, Professor Carlos Hernández Díaz- Ambrona, of the Universidad Politécnica de Madrid, Professor Lucia de Stefano, of the Universidad Complutense de Madrid, and finally to Nuria Hernández Mora from Fundación Nueva Cultura del Agua. I want to thank very especially Professor Ramón Llamas, who introduced me, in the frame of the NEWATER project, to the issues of water management in the Guadiana basin.

An extremely rewarding part of this research has been the development of the case study in Jordan. I was very fortunate to perform field work, funded by the MEDPRO project, in the Jordan Valley. This work would not have been possible without the support of Professors Muhammad Shatanawi and Khaldoun Shatanawi, of the University of Jordan, and of Johannes Stork and Nour Habjoka, of the German Agency for International Cooperation (GIZ) and advisors from the Ministry of Water and Irrigation of Jordan for the development of the National Plan for Water.

Throughout my years at the university and during the development of this research, there have been two people with whom I have shared both academic and personal concerns, successes, failures and especially many memorable moments that have made this work far easier. Irene Blanco and Gema Carmona have been my colleagues, friends and perfect exemplars. Seeing the development of their research and qualities has taught me a lot, and has helped me to cope with the challenge that has been this research.

I would also like to thank the support of a number of people during specific tasks within this work, Laura Barrios (CSIC), that advised me in the use of statistics and econometric techniques, and Jeremy Schlickenrieder who helped me through editing work.

During my time at the Department of Economics and Social Sciences at the School of Agricultural Engineering (UPM) and in CEIGRAM, I have shared fantastic moments with other PhD students and research assistants. Amongst them I want to stress Marina and Paula for their friendship, support and understanding, and Macarena, Berta, Chen, Cristian, Francisco, Jorge, Lola, Mauro, Rhys, Ruth, Silvestre and many others who formed part of my day to day life.

Finally, I would like to express my immense gratitude to my family. My husband, Manuel Barreiro, who has always been at my side to cheer me up and to celebrate every milestone achieved. My parents, who have been a model of how to deal with life's difficulties, and who have always demonstrated to me the importance of hard work in achieving one's goals.

Thank you very much to all of you!

Agradecimientos

Esta tesis doctoral se ha desarrollado a lo largo de cinco años de duro trabajo en los que he afrontado un reto de madurez complicado que me ha hecho pasar por momentos dulces y también amargos. Esto, indudablemente, no habría podido lograrlo sin el grandísimo apoyo de muchas personas que se han involucrado en este proceso y que me han ofrecido su apoyo en este difícil trabajo.

Quiero expresar mi inmenso agradecimiento a mis directores de tesis. Sin su apoyo me hubiera resultado enormemente difícil, si no imposible, realizar este trabajo. En primer lugar, quiero referirme a la Catedrática Consuelo Varela Ortega que me inició en el mundo de la investigación. Consuelo ha sido mi profesora, directora de mi trabajo de fin de carrera y en los últimos años también directora de mi tesis doctoral. Ella me ofreció la oportunidad de ser parte de su equipo y de trabajar en los proyectos que despertaron en mí el interés por la investigación y por el estudio del complejo mundo del agua, su gestión y sus repercusiones. Su apoyo, además, ha ido mucho más allá de la faceta académica, ofreciéndome su amistad y ayudándome a conocer mis debilidades, a aprender de ellas y a potenciar mis fortalezas. Siempre ha sabido ofrecerme las palabras que necesitaba, motivarme para mejorar y orientarme cuando he estado perdida.

Mi co-director, Tom Downing, me abrió las puertas de su equipo y de su casa. Mi estancia en Oxford supuso un punto de inflexión importante en el desarrollo de esta investigación. Siempre le estaré agradecida por haber aportado una visión diferente sobre los problemas del agua y la adaptación al cambio climático y por haberme inspirado en la elección de enfoques y métodos que abordan la perspectiva más social del cambio climático.

Debo agradecer también al Global Climate Adaptation Partnership (GCAP), en Oxford, y al Stockholm Environment Institute (SEI), en Boston, por haberme permitido realizar dos estancias de investigación en sus centros que han sido fundamentales para el desarrollo de los modelos y los enfoques aplicados en esta investigación. En estas estancias he contado con el inestimable apoyo de mi co-director, Tom Downing (GCAP), y de David Purkey (SEI) que dirigieron esas estancias, me ofrecieron su apoyo y simpatía. También debo agradecer la gran acogida por parte de los miembros de sus equipos, y especialmente la ayuda de Brian Joyce, de SEI-Boston, que me ayudó en el desarrollo de la aplicación de WEAP en el Medio Guadiana, y de Eric Kemp-Benedict y Jack Sieber. Ambas estancias han sido muy importantes para esta investigación y me han aportado además experiencias personales muy valiosas.

Además, he tenido la suerte de poder contar con el apoyo de los proyectos europeos de investigación SCENES, MEDIATION y MEDPRO que, más allá de la financiación de muchas de las actividades comprendidas en esta investigación, han sido fuente de conocimiento e inspiración, y me han puesto en contacto con metodologías novedosas. Estos proyectos me han brindado la oportunidad de trabajar con equipos internacionales e investigadores de gran nivel que han contribuido importantemente a esta investigación a través de intensos y ricos debates y sesiones de trabajo. Del proyecto SCENES quisiera destacar la colaboración del Prof. Kasper Kok (U. Wageningen, Países Bajos), por sus contribuciones sobre el desarrollo de escenarios, y a los equipos mediterráneos del Instituto Agronómico del Mediterráneo de Bari (IAMB, Italia) y de la Middle East Technical University (METU, Turquía), dirigidos por el Dr. Nicola Lamaddalena y el Prof. Erol Cakmak respectivamente, con los que he aprendido mucho sobre agua y agricultura en el Mediterráneo. Del proyecto MEDIATION quiero destacar especialmente el apoyo del Dr. Rob Swart (Alterra, Países Bajos), coordinador del proyecto, la Dra. Sukaina Bharwani (SEI-Oxford, Reino Unido), por su contribución en aspectos metodológicos y en enfoques sociales, el Dr. Paul Watkiss (colaborador de SEI-Oxford, Reino Unido), por sus valiosos comentarios respecto al análisis económico de la adaptación al cambio climático, el Dr. Jochen Hinkel (PIK, Alemania), por su aportación al debate sobre la vulnerabilidad y los doctores Tim Carter y Stephan Fronzek (SYKE, Finlandia) por su contribución a los escenarios de cambio climático. Del proyecto MEDPRO quiero agradecer su apoyo a la Dra. Rym Ayadi (CEPS, Bélgica), coordinadora del proyecto, y al Dr. Francesco Bosello (FEEM, Italia), por su contribución al análisis del cambio climático en la agricultura del Mediterráneo.

Esta investigación ha contado, además, con un amplio apoyo por parte de la Universidad Politécnica de Madrid, a través de una beca para la realización del doctorado y de dos becas para la realización de estancias en centros de investigación internacionales. Asimismo, el Departamento de Economía y Ciencias Sociales de la ETSI Agrónomos y el CEIGRAM (Centro de Estudios e Investigación para la Gestión de Riesgos Agrarios y Medioambientales) me han apoyado y han contribuido a mi formación a lo largo de los últimos años en su afán por apoyar las carreras de sus jóvenes investigadores. Especialmente quiero reconocer el apoyo de sus respectivos directores, los catedráticos Isabel Bardají y Alberto Garrido, y de otros profesores del Departamento de Economía y del CEIGRAM, especialmente Eva Iglesias y Ana Iglesias, que han contribuido a mi formación y han aportado también interesantes opiniones y sugerencias.

En el desarrollo de esta investigación y concretamente de varias de las herramientas utilizadas ha sido fundamental la participación de los grupos de interés del Medio Guadiana. Especialmente, quiero reconocer el apoyo de José Ángel Rodríguez Cabello, jefe de planificación de la Confederación Hidrográfica del Guadiana, y de José Ramón Picatoste y su equipo de la Oficina Española de Cambio Climático. También quiero agradecer el apoyo de las comunidades de regantes de Montijo y Zújar, y muy especialmente de la de Tomas Directas del Guadiana y de su secretario Blas Benito de Motta, que siempre me ha acogido amablemente en mis numerosas visitas a Badajoz. Gracias, también, a la Consejería de Agricultura, Desarrollo Rural, Medio Ambiente y Energía de Extremadura, a ADENEX (Asociación para la Defensa de la Naturaleza de Extremadura) y a WWF España, especialmente a Alberto Fernández Lop que ha colaborado muy activamente en todas las consultas y procesos participativos llevados a cabo. Asimismo, quiero dar las gracias a varios expertos que participaron en diferentes consultas realizadas entre los que se incluyen, además de los ya mencionados Alberto Garrido y Ana Iglesias, el profesor Carlos Hernández Díaz-Ambrona, de la Universidad Politécnica de Madrid, la Profesora Lucia de Stefano, de la Universidad Complutense de Madrid, y Nuria Hernández Mora de la Fundación Nueva Cultura del Agua. Y de manera muy especial, quiero reconocer también la importante contribución del Profesor Ramón Llamas que me introdujo, en el marco del proyecto NeWater, en la problemática de la gestión del agua en la cuenca del Guadiana.

Una parte muy enriquecedora de esta investigación ha sido el desarrollo del caso de estudio de Jordania. Para ello he tenido la suerte de poder realizar trabajo de campo financiado por el proyecto MEDPRO en el Valle del Jordan, que no habría sido posible sin el apoyo de los profesores Muhammad Shatanawi y Khaldoun Shatanawi, de la Universidad de Jordania, y de Johannes Stork y Nour Habjoka, de la Agencia Alemana para la Cooperación Internacional (GIZ) y asesores del Ministerio de Agua y Regadío de Jordania para el desarrollo del Plan Nacional del Agua.

A lo largo de estos últimos años en la universidad y durante el desarrollo de esta investigación ha habido dos personas con las que he compartido inquietudes académicas y personales, éxitos y fracasos, y sobre todo muchos buenos momentos que han hecho más fácil el trabajo. Irene Blanco y Gema Carmona han sido mis compañeras en distintos proyectos de investigación, amigas e inestimable ejemplo. El haber sido testigo del desarrollo de sus investigaciones y de sus muchas cualidades me ha enseñado mucho y me ha ayudado a afrontar el reto que ha supuesto esta investigación.

Quisiera también agradecer el apoyo de varias personas en tareas específicas de este trabajo: Laura Barrios (CSIC) que me ha asesorado en el uso de técnicas estadísticas y econométricas, y Jeremy Schlickenrieder que me ha ayudado en labores de edición.

A lo largo del tiempo que he trabajado en el Departamento de Economía y Ciencias Sociales de la ETSI Agrónomos (UPM) y en el CEIGRAM he compartido muy buenos momentos con otros doctorandos y ayudantes de investigación. Entre ellos quiero destacar a Marina y Paula, por su amistad, apoyo y comprensión, a Macarena, Berta, Chen, Cristian, Francisco, Jorge, Lola, Mauro, Rhys, Ruth, Silvestre y muchos otros que han formado parte del día a día a lo largo de estos años.

Por último, quiero expresar mi agradecimiento a mi familia. A mi marido, Manuel Barreiro, que ha estado siempre a mi lado para animarme y para celebrar conmigo cada pequeña meta alcanzada. A mis padres, que han sido un modelo de cómo afrontar las dificultades de la vida, y que me transmitieron la importancia de esforzarme para tratar de alcanzar las metas para las que estaba preparada.

¡Muchas gracias a todos!

Summary

Water scarcity is becoming a major concern in many parts of the world. Population growth, increasing needs for food production, socio-economic development and climate change represent pressures on water resources that many countries around the world will have to deal in the coming years. The Mediterranean region is one of the most water scarce regions of the world and is considered a climate change hotspot. Most projections of climate change envisage an increase in temperatures and a decrease in precipitation and a resulting reduction in water resources availability as a consequence of both reduced water availability and increased irrigation demands.

Current policy development processes require the integration of climate change concerns into sectoral policies. However, sector-oriented studies often fail to address all the dimensions of climate change implications. Climate change research in the last years has evidenced the need for more integrated studies and methodologies that are capable of addressing the multi-scale and multi-dimensional nature of climate change.

This research attempts to provide a comprehensive view of water scarcity and climate change impacts, vulnerability and adaptation in Mediterranean contexts. It presents an integrated modelling framework that is progressively enlarged in a sequential multi-scale process in which a new dimension of climate change and water resources is addressed at every stage. It is comprised of four stages, each one explained in a different chapter. The first stage explores farm-level economic vulnerability in the Spanish Guadiana basin using a mathematical programming model in combination with an econometric model. Then, in a second stage, the use of a hydro-economic modelling framework that includes a crop growth model allows for the analysis of crop, farm and basin level processes taking into account different geographical and decision-making scales. This integrated tool is used for the analysis of climate change scenarios and for the assessment of potential adaptation options. The third stage includes the analysis of barriers to the effective implementation of adaptation processes based on socio-institutional network analysis. Finally, a regional and country level perspective of water scarcity and climate change is provided focusing on different possible socio-economic development pathways and the effect of policies on future water scarcity. For this analysis, a panel-data econometric model and a hydro-economic model are applied for the analysis of the Mediterranean region and country level case studies in Spain and Jordan.

The overall results of the study demonstrate the value of considering multiple scales and multiple dimensions in water management and climate change adaptation in the Mediterranean water scarce contexts analysed. Results show that climate change impacts in the Guadiana basin and in Spain may compromise the sustainability of irrigation systems and ecosystems. The analysis at the basin level highlights the prominent role of interactions between different water users and irrigation districts and the need to strengthen institutional capacity and common understanding in the basin to enhance the implementation of adaptation processes. The results of this research also illustrate the relevance of water policies in achieving sustainable development and climate change adaptation in water scarce areas such as the Mediterranean region. Specifically, the EU Water Framework Directive emerges as a powerful trigger for climate change adaptation. However, in Jordan, outreaching sustainable development strategies are required in addition to climate change adaptation to reduce future risk of water scarcity.

Resumen

Actualmente, la escasez de agua constituye un importante problema en muchos lugares del mundo. El crecimiento de la población, la creciente necesidad de alimentos, el desarrollo socio-económico y el cambio climático ejercen una importante y cada vez mayor presión sobre los recursos hídricos, a la que muchos países van a tener que enfrentarse en los próximos años. La región Mediterránea es una de las regiones del mundo de mayor escasez de recursos hídricos, y es además una de las zonas más vulnerables al cambio climático. La mayoría de estudios sobre cambio climático prevén mayores temperaturas y una disminución de las precipitaciones, y una creciente escasez de agua debida a la disminución de recursos disponibles y al aumento de las demandas de riego.

En el contexto actual de desarrollo de políticas se demanda cada vez más una mayor consideración del cambio climático en el marco de las políticas sectoriales. Sin embargo, los estudios enfocados a un solo sector no reflejan las múltiples dimensiones del los efectos del cambio climático. Numerosos estudios científicos han demostrado que el cambio climático es un fenómeno de naturaleza multi-dimensional y cuyos efectos se transmiten a múltiples escalas. Por tanto, es necesaria la producción de estudios y herramientas de análisis capaces de reflejar todas estas dimensiones y que contribuyan a la elaboración de políticas robustas en un contexto de cambio climático.

Esta investigación pretende aportar una visión global de la problemática de la escasez de agua y los impactos, la vulnerabilidad y la adaptación al cambio climático en el contexto de la región mediterránea. La investigación presenta un marco integrado de modelización que se va ampliando progresivamente en un proceso secuencial y multi-escalar en el que en cada etapa se incorpora una nueva dimensión. La investigación consta de cuatro etapas que se abordan a lo largo de cuatro capítulos. En primer lugar, se estudia la vulnerabilidad económica de las explotaciones de regadío del Medio Guadiana, en España. Para ello, se utiliza un modelo de programación matemática en combinación con un modelo econométrico. A continuación, en la segunda etapa, se utiliza un modelo hidro-económico que incluye un modelo de cultivo para analizar los procesos que tienen lugar a escala de cultivo, explotación y cuenca teniendo en cuenta distintas escalas geográficas y de toma de decisiones. Esta herramienta permite el análisis de escenarios de cambio climático y la evaluación de posibles medidas de adaptación. La tercera fase consiste en el análisis de las barreras que dificultan la aplicación de procesos de

adaptación para lo cual se analizan las redes socio-institucionales en la cuenca. Finalmente, la cuarta etapa aporta una visión sobre la escasez de agua y el cambio climático a escala nacional y regional mediante el estudio de distintos escenarios de futuro plausibles y los posibles efectos de las políticas en la escasez de agua. Para este análisis se utiliza un modelo econométrico de datos de panel para la región mediterránea y un modelo hidro-económico que se aplica a los casos de estudio de España y Jordania.

Los resultados del estudio ponen de relieve la importancia de considerar múltiples escalas y múltiples dimensiones en el estudio de la gestión de los recursos hídricos y la adaptación al cambio climático en los contextos mediterráneos de escasez de agua estudiados. Los resultados muestran que los impactos del cambio climático en la cuenca del Guadiana y en el conjunto de España pueden comprometer la sostenibilidad del regadío y de los ecosistemas. El análisis a escala de cuenca hidrográfica resalta la importancia de las interacciones entre los distintos usuarios del agua y en concreto entre distintas comunidades de regantes, así como la necesidad de fortalecer el papel de las instituciones y de fomentar la creación de una visión común en la cuenca para facilitar la aplicación de los procesos de adaptación. Asimismo, los resultados de este trabajo evidencian también la capacidad y el papel fundamental de las políticas para lograr un desarrollo sostenible y la adaptación al cambio climático es regiones de escasez de agua tales como la región mediterránea. Especialmente, este trabajo pone de manifiesto el potencial de la Directiva Marco del Agua de la Unión Europea para lograr una efectiva adaptación al cambio climático. Sin embargo, en Jordania, además de la adaptación al cambio climático, es preciso diseñar estrategias de desarrollo sostenible más ambiciosas que contribuyan a reducir el riesgo futuro de escasez de agua.

Table of contents

List of tables

List of figures

List of abbreviations

AA: Autonomous adaptation

CAP: Common Agricultural Policy

CC: Climate change

CIMP3: Third Coupled Model Intercomparison Project

EU: European Union

GAMS: General Algebraic Modelling System

GDP: Gross Domestic Product

GHG: Greenhouse Gases

GIS: Geographic Information Systems

IA: Integrated Assessment

IC: Irrigation Community

IPCC: Intergovernmental Panel on Climate Change

IVA: Impacts, Vulnerability and Adaptation

IWRM: Integrated Water Resources Management

JVA: Jordan Valley Authority

MED11: the eleven countries from the southern and eastern Mediterranean rims

MPM: Mathematical Programming Model

MSSD: Mediterranean Strategy for Sustainable Development

MWI: Jordan Ministry of Water and Irrigation

OECC: Spanish Office for Climate Change (Oficina Española de Cambio Climático)

RBA: River Basin Authority

RCP: Representative Concentration Pathways

SH: Stakeholder

SRES: Special Report on Emissions Scenarios

SSP: Shared Socio-economic Pathways

WAJ: Water Authority of Jordan

WEAP: Water Evaluation And Planning system

WFD: Water Framework Directive

1. General Introduction

1.1 Research context

This PhD thesis is based upon research carried out from 2009 to 2013 at the Department of Agricultural Economics and Social Sciences, in the School of Agricultural Engineering, of Universidad Politécnica de Madrid. During this period, the participation in different research projects laid the groundwork for framing the problems addressed in this thesis and its objectives, and contributed to the development of the methods applied. These research projects, in which UPM's team was coordinated by Professor Varela-Ortega, include:

- **SCENES** (Water Scenarios for Europe and for Neighbouring States). Project No. 036822-2. Integrated Project, 6th Framework Programme. EU Commission, DG Research. 2007 – 2010.

- **MEDIATION** (Methodology for Effective Decision-making on Impacts and AdaptaTION to Climate Change). Project No. 244012. Collaborative Project (Small). 7th Framework Programme. EU Commission, DG Research. 2010 – 2013

- **MEDPRO** (Prospective analysis for the Mediterranean region). Project No. 244578. Collaborative Project (Small). 7th Framework Programme. EU Commission, DG Research. 2010 – 2013.

The aim of the SCENES project was to develop future water scenarios to 2050 for Europe and Neighbouring countries from the Middle East and North Africa. Within the scope of the study, four case studies (Baltic region, Black Sea, Danube and Mediterranean) illustrated the scenario development process which comprised the development of storylines from the local/basin level to the Pan-European. Within the case studies, the Mediterranean region included three pilot areas: the Seyhan basin in Turkey, the Candelaro basin in Italy, and the Guadiana basin in Spain. This project provided the knowledge base for the thesis development and supported fieldwork in the study area and interaction with stakeholders.

The MEDIATION project aimed at developing methodologies for supporting decision-making for climate change adaptation. In this project the Guadiana basin constituted a case study in which different methods were applied for informing adaptation decisions in the area of water and agriculture. This project provided different approaches for the assessment of climate change impacts and adaptation.

Finally, the MEDPRO project's main goal was to perform prospective analysis in the Mediterranean region, based on the development of qualitative and quantitative scenarios for socio-economic and geo-political development in the region. In this project one of the fields of study was water and agriculture. The study of future scenarios for water use in the region provided the methodological approach and the case studies for the assessment of water resources management and climate change impacts in the Mediterranean region. Also, in the frame of this project, specific field work was carried out in Jordan, including interviews of researchers, policy-makers and farmers.

In parallel to the involvement in these projects, the collaboration with different international research teams enriched the research and provided support in specific methodological and thematic areas. In particular, two research stays abroad, funded by Universidad Politécnica de Madrid, were completed at different international research institutions and contributed to the development and completion of this doctoral research. First, a three-month stay (June-September 2011) at the Stockholm Environment Institute, Boston Office (Boston, United States), where work was conducted with the Water Group under the supervision of Dr. David Purkey. This stay laid the foundations of the development of the application of the hydrology model WEAP for the Middle Guadiana Basin.

Second, a two-month stay (October-December 2012) at the Environmental Change Institute (Oxford University) and the Global Climate Adaptation Partnership (Oxford, United Kingdom) was completed under the supervision of Prof. Thomas E. Downing, who is co-supervisor of this thesis. This stay provided the basis for the adaptation assessment both from the bio-physical point of view and from the social side of adaptation.

The background, objectives, methods and structure of this thesis are explained in the following sections.

1.2 The challenge of climate change: state of the art

Climate change has already been felt in many parts of the World. Observed river flows are lower than they used to be and hydrological drought frequency is increasing (EC, 2012a). The water resources sector is one of the most vulnerable sectors to climate change. Projected changes in precipitation, humidity, river runoff and evapotranspiration will largely affect the hydrological systems and the overall water cycle (Ragab and Prudhomme, 2002), with important consequences for population, ecosystems and economic sectors (Kundzewicz et al., 2007). Most model-based studies project increased exposure to climate change of the arid and semi-arid regions of the world, including the Mediterranean region, which will face significant reductions of water availability (Bates et al., 2008). This fact together with projections of population growth and development of specific sectors such as agriculture, point to the likely increase in water stress in many regions of the World such as the Mediterranean region, Europe, Central and Southern Africa and central and southern America (Arnell, 2004). This will require the improvement of current water management systems that may not be robust enough to face the increasing pressures on water resources. In line with this, improving understanding on the potential impacts and implications of climate change and planning adaptation of water dependent economic sectors, such as agriculture, and of water management practices are priority tasks that cannot be postponed.

Climate change research has grown progressively since the 1960s and developed more profusely from the 1980s onwards. The different disciplines involved in climate change analysis are grouped around three main analytical frameworks based on the use of climate models, integrated assessment (IA) and impacts, vulnerability and adaptation (IVA) assessments (Moss et al., 2010; Van Vuuren et al., 2012, 2013). This division is confirmed and demonstrated in the structure of the Intergovernmental Panel on Climate Change (IPCC) which compartmentalises the study of climate change around these three axes that correspond to the three IPCC Working Groups: Physical science (WGI), Impacts Vulnerability and Adaptation (WG II) and Mitigation (WGIII).

Climate models are representations of the climate system that are used for the study and simulation of climatic processes and the effect of changes in human and natural systems on climatic parameters (IPCC, 2007a, Randall and Wood, 2007). Integrated assessment models combine tools from different scientific disciplines to analyse the interactions of the physical, biological, economic or social dimensions to analyse the implications of environmental change and the potential effects of policy actions (IPCC, 2007a). They are frequently used for the generation of emission scenarios and for the assessment of climate policies (Moss et al., 2010) especially in the field of climate change mitigation. Finally, the assessment of impacts, vulnerability and adaptation include a broader array of tools and modelling techniques and very often combine both quantitative and qualitative analytical frameworks and include participatory approaches (Moss et al., 2010). This type of assessment contributes to increase preparedness and to develop specific sectoral policies aiming at minimising the adverse effects of climate change. They also contribute to identify climate change mitigation needs.

Analysing potential impacts of climate change raises the question of whom, which individuals or communities, or which geographical areas will suffer more greatly from the negative outcomes from climate change and what the reasons for this may be in order to tackle them. This gives rise to vulnerability research.

The study of vulnerability has been undertaken from different scientific fields, including natural hazards and disasters, poverty, sustainable livelihoods, food security and climate change. Similar to the varied approaches to vulnerability analysis, definitions of vulnerability are also diverse. In the context of climate change research, the IPCC Fourth Assessment Report glossary defined vulnerability as "*the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*" (IPCC, 2007a). Nonetheless, IPCC definitions and understanding of concepts continuously evolves along with research advances. Two fundamental approaches have been used for understanding vulnerability (O'Brien et al, 2007; Füssel and Klein, 2006; Füssel, 2007; Rothman et al., 2013): vulnerability as an outcome or the "end point" of the analysis of the impacts of a specific hazard (outcome vulnerability), and, vulnerability as the socio-economic conditions that determine the effects of that hazard or the "starting point" of the analysis (contextual vulnerability). The first approach focuses on the exposure domain of vulnerability (with respect to IPCC's definition), while the second one focuses on sensitivity and adaptive capacity. The choice of adopting one approach or the other will depend on the aim of the study or the specific type of science-driven or policy-driven questions that the research tries to answer. In this sense, vulnerability assessments that focus on outcomes are usually oriented to find adaptive solutions, mostly technical, that reduce exposure to hazards. By contrast, socio-economic vulnerability approaches pursue a better understanding on the root causes of vulnerability to identify most vulnerable individuals and ways to reduce that vulnerability by improving adaptive capacity and reducing sensitivity.

The study of vulnerability allows for improvements in preparedness and offers the ability to plan and implement adaptation actions. The IPCC fourth assessment report defines adaptation as "*initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects*" (IPCC, 2007a). The two approaches adopted in vulnerability research have given rise, accordingly, to two distinct approaches for adaptation assessments (Downing, 2012; Wheeler et al., 2012): bio-physical and economic assessments, based on natural and economic sciences, and actor-oriented social assessments based on social sciences. Adaptation assessments based on physical systems and economics, e.g. analysis of crop yields, crop productivity, infrastructure development, economic valuation and costs of adaptation, relate to physical and economic vulnerability and focus on the impacts of climate change-related events. These assessments usually involve the use of biophysical and economic models as well as economic valuation methods, cost-benefit, cost-effectiveness and multicriteria assessments that assist in evaluating the adaptive potential of different measures and help to identify the most appropriate according to specific criteria. Actor-oriented adaptation assessments are linked to social vulnerability and resilience research, and focus on the analysis of social systems and adaptive capacity emphasising the socio-institutional, economic and policy contexts. The physical or economic based approaches aim to support specific sector-oriented policies. Socially-based approaches, which are transversal with respect to the different sectors affected by climate change, are normally oriented towards the development of adaptive capacity and improving understanding on social interactions and socio-ecological systems. Table 1 summarise the two main streams of vulnerability and adaptation research.

Table 1. Two distinct approaches to vulnerability and adaptation research

Vulnerability approach	Adaptation focus	Key features	Examples
Outcome vulnerability, end-point vulnerability, top-down, bio-physical	• Focus on impacts • Search for technical adaptive solutions and mitigation	• Hazard: climate change • Scales: local to global • Methods: quantitative tools, biophysical models, economic assessment	Laux et al (2010), Luers et al. (2003), Nelson et al. (2009), Purkey et al. (2008), Tanaka et al. (2006), Tingem and Rivington (2009)
Contextual, starting-point, bottom-up, inherent, social	• Focus on causes, socio-ecological systems, actor-oriented, social networks. Political, institutional, economic and social contexts. • Aim to increase capacity to adapt	• Hazard: multiple stressors • Scales: local to regional • Methods: combine quantitative and qualitative, indicators, statistical, econometric	Adger (1999), Adger and Kelly (1999), Below et al. (2012), Cutter et al. (2003), Eriksen and Kelly (2007), Nicholas and Durham (2012), Notenbaert et al. (2013)

Source: Own elaboration based on Füssel and Klein (2006), Füssel (2007), Rothman et al. (2013)

However, the existence of different approaches does not imply that one approach is better than the other. Rather, IVA research is progressively evolving towards more integrated approaches recognising that both approaches are complementary (Rothman et al., 2013) and necessary for informing and facilitating policy-making and implementation in the field of climate change adaptation. In line with this, climate change IVA research is more and more integrated and the definitions and assessments of vulnerability and adaptation have gradually been enriched from a bio-physical perspective. This has contributed to the development of a more holistic view that takes into consideration both the bio-physical and the socio-economic dimensions.

Recent developments in climate change research (Howden et al., 2007, Meinke et al., 2009; Moss et al., 2010; Rosenzweig and Wilbanks, 2010; van Vuuren et al., 2012) advocate the integration of different approaches and types of modelling exercises and assessments that have been developed independently by different scientific disciplines and serve different purposes. Responding to the need of more integrated approaches a new climate change scenario generation process was initiated in 2006/2007, which is currently in progress. In the last decade climate change assessments have been primarily based on the emission scenarios provided by the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000) which comprise four families of scenarios, namely A1, A2, B1 and B2, developed according to socio-economic scenarios (population, gross domestic product (GDP), technology, etc.). These scenarios represent plausible future development paths framed under different global vs. regional oriented development and economic vs. environment oriented development. Climate change assessment was then organised following a linear process (Moss et al., 2010) where the emission scenarios gave rise to radiative forcing scenarios, used, in turn, as input for climate models that provide different estimations of changes in climate variables (climate change scenarios).

The climate change scenarios based on the SRES emission scenarios do not take into account climate change policies that seek to reduce greenhouse gas (GHG) emissions and mitigate climate change. However, current policy processes and the potential for mitigation set different plausible futures for socio-economic development and adaptation needs. In light of this, a new scenario generation process was put in place that jointly addresses the different possibilities, the needs for mitigation and adaptation actions along with the potential synergies and trade-offs between them (van Vuuren et al., 2013).

This integrated and coordinated process promotes the harmonised formulation and modelling of climate, socio-economic and emission scenarios. The process is articulated in three phases (van Vuuren et al., 2013) starting with the selection of four Representative Concentration Pathways (RCPs) (based on selected radiative forcing trajectories) used to assess and project the magnitude of climate change, as described by van Vuuren et al (2011a). The second phase includes the development of Shared Socio-economic Pathways (SSPs) that define alternative future socio-economic development pathways, including storylines and quantitative descriptions of population growth, governance, technology development, among other variables. These are currently being completed and described by Ebi et al. (2013). Finally, the combination of RCPs and SSPs define mitigation and adaptation needs and capacities, which together with the different assumptions on climate policy determine climate change projections which constitute the third phase of this new scenario process.

The contributions of this new approach, as highlighted by Moss et al. (2010) or van Vuuren et al. (2011b, 2012, 2013) include the facilitation of new approaches to climate change assessments that promote the collaboration between different disciplines and that produce insights on the relations between human and natural systems, contributing to policy making. Moreover, this new scenario framework is conceived to facilitate linking physical, socio-economic and decision-making processes taking place at different spatial and temporal scales (van Vuuren et al., 2013). Within the challenges for adaptation research that the new SSP try to address is the integration across scales and disciplines which has been highlighted by many studies (Meinke et al., 2009; Rosenzweig and Wilbanks, 2010; Rothman et al., 2013). In line with this, climate change assessments are increasingly based on multi-scale approaches. In developing new scenarios that jointly consider mitigation and adaptation, the need to consider different scales becomes evident. While mitigation benefits are felt at the global scale, the goals of adaptation are normally defined at the local (or national) scale. Also mitigation and adaptation actions and decisions are adopted at different scales. Many studies have addressed the multi-scale nature of climate change (Adger et al., 2005; Cash and Moser, 2000; Meinke et al., 2009; Wilbanks and Kates, 1999). Moreover, vulnerability and adaptation assessments have pointed to the multi-level nature of vulnerability constructs and adaptation (Adger, 2006, Berkes, 2007, O'Brien et al., 2004). Most vulnerability and adaptation assessments focus on one specific scale of analysis. However, the interlinked character of nature and human systems suggest the existence of cross-scale interactions that assessments should also address (Downing and Patwardhan, 2005). Therefore, advancing in climate change understanding, tackling climate change vulnerability and developing comprehensive adaptation strategies require the development of assessment methods that address these different scales.

Moreover, not only multi-scale integration but also trans-disciplinary integration is a requirement for effectively addressing climate change vulnerability and adaptation (Meinke et al., 2009). The ongoing new scenario development process represents a shift from climate change scenarios based on a step-by-step approach, in which different scientific disciplines communicated in a linear way, to a new approach in which researchers from different disciplines work in a coordinated and parallel process (Moss et al., 2010; Van Vuuren et al., 2011b, 2012). The need for integration is also evidenced by the limited adoption and successful implementation of adaptation strategies. Climate change studies on impacts, vulnerability and adaptation have traditionally focused on one specific risk and on its impact on one specific sector. However, as recognised by Meinke et al. (2009), decision-makers usually take a holistic approach to decision-making that takes into account different risks, institutional frameworks and sectors. The lack of more integrated approaches results in scientific knowledge production that responds only partially to the needs of decision-makers (Liu et al., 2008; Meinke et al., 2009; Weichselgartner and Kasperson, 2010).

Although many advances have been made in the assessment of impacts, vulnerability, adaptation, adaptive capacity and barriers to adaptation, further cross-scales and multi-disciplinary integration and development of climate change research is still needed.

In Europe, research needs have already been identified by climate sensitive sectors and their corresponding policies. Among the gaps that need to be addressed, the EU strategy on adaptation to climate change (EC, 2013a) highlights the importance of regional and local-level assessments and the relevance of developing appropriate frameworks and modelling tools to assess the impacts and the effectiveness of different adaptation measures for supporting policy decision-making and bridging the gap between science, policy and actions (EC, 2013a; Meinke et al., 2009; Varela-Ortega et al., *submitted*).

In the water domain, many challenges remain to achieve the good ecological status of all waters that is pursued by the EU Water Framework Directive (WFD) (EC, 2000) and, even more, to make it resilient to climate change (EC, 2012a, 2012b). Therefore, the success of water policies requires the internalisation of climate change adaptation and the implementation of ambitious water management measures that take climate change into consideration. For this, it is necessary to improve the knowledge of climate change impacts and adaptation on the hydrological system and its implications for water management with the development of appropriate modelling tools at scales that are relevant to decision-making (Bates et al., 2008). In the field of agriculture, recent developments to the Common Agricultural Policy (CAP) (EC, 2013b) demand the targeting of funds towards productive practices that contribute to climate change mitigation and adaptation, and for this improved knowledge on the links between climate, crop, and environmental systems and farmers' decision making is still necessary.

1.3 Objective of the research

The challenges of water management for agriculture in arid and semi arid regions of the world are likely to intensify in light of projected climate change. The previous section identified the need to address climate change from an integrated point of view that takes into consideration both the bio-physical and social aspects as well as the multi-scale nature of climate change impacts and adaptation. At the same time, current policy processes in the water and agricultural sectors (EC, 2013a, 2013b) demand the incorporation of climate change considerations and hence the development of climate robust strategies and actions.

In the case of water and agriculture, climate change assessments ideally require the consideration of crops, farms and river basins from the bio-physical point of view. On the social side, it will be key to consider different scales that are relevant to decision-making, including farms, water user associations and water authorities

For this, developing tools that are capable of considering multiple facets of climate change, water use and management options is a challenging task. In line with this, the overall objective of this research is to analyse water policies and climate change impacts, vulnerability and adaptation of agriculture, farmers livelihoods and water resources, using a methodology that allows for the consideration of different physical, institutional, structural and socio-economic contexts. Through this, we intend to improve understanding on water scarcity and climate change vulnerability with the aim of identifying appropriate adaptation options and contributing to policy making in the context of irrigation water management and climate change.

The specific objectives of the research can be summarised as follows:

- To provide a multi-scale vision of water scarcity and climate change that reflects how climate change is experienced differently at the regional, national or local scales, and how adaptation decisions are made in the various scales and contexts.
- To develop integrated methodologies capable to address the multiple facets of water management and climate change. Specifically, those methods must be able to integrate crop, farm and basin level processes and to address the different interactions that take place among them, and considering all relevant decision-making levels.
- To identify the vulnerabilities of irrigation farming systems to policy- and climate change-driven water scarcity in different case study areas and examining specific climate and policy impacts on crops, socio-economic systems and the hydrology system.
- To identify feasible and effective adaptation measures that improve water use economic efficiency and the conservation of water ecosystems and contribute to minimise the negative effects of climate change on water resources and on farmers' economic welfare. This will include the assessment of the contribution of current water policy instruments to climate change adaptation.

1.4 The areas of study: the Mediterranean region and selected case studies

The challenges of climate change research in the context of water and agriculture discussed above are illustrated by the study of case studies in the Mediterranean region that shows the complexity of water management in arid and semi-arid regions.

Table 2. Relevant indicators for 14 selected Mediterranean countries

	Country area (Km2) (2007)	Population (thousands) (2007)	Population annual growth rate (%) (2007)	GDP per capita (2000 USD) (2007)	GDP growth rate (%) (2007)	Renew. water resources per capita (m3/inhab/yr) (2002)	Water withdrawal (Km3/yr) (2002)	Water withdrawal per capita (m3/inhab/yr) (2002)	Agricultural water withdrawal (%) (2002)	Industrial water withdrawal (%) (2002)	Municipal water withdrawal (%) (2002)	Freshwater withdrawal as % of renew. resources (%) (2002)
Algeria	2381740	33858	1.50	2159	3	371	6	182	61	15	24	49
Egypt	1001450	80061	1.84	1697	7.07	817	68	973	86	6	8	97
France	549190	61938	0.95	23636	2.32	3530	32	542	14	68	18	15
Greece	131960	11193	0.40	14982	4.04	6705	9	838	91	1	9	12
Israel	22070	7180	1.78	21405	5.20	285	2	293	56	7	38	87
Italy	301340	59375	0.73	20017	1.56	3327	45	790	44	36	20	24
Jordan	88780	5719	3.22	2370	8.85	165	1	165	65	4	31	99
Lebanon	10400	4162	0.88	5399	7.49	1164	1	370	64	6	30	28
Libya	1759540	6169	2.03	7554	6	129	4	796	83	3	14	615
Morocco	446550	31224	1.19	1648	2.72	985	13	428	87	3	10	43
Spain	505370	44879	1.71	16363	3.66	2696	36	871	64	21	15	32
Syria	185180	20083	2.45	1295	4.20	990	16	965	88	3	8	97
Tunisia	163610	10225	0.96	2652	6.33	477	3	296	76	4	13	62
Turkey	783560	73004	1.26	5116	4.67	3233	42	642	75	10	15	20

Source: AQUASTAT (2013) and World Development Indicators (World Bank, 2011)

Water scarcity

Absolute water scarcity

The Mediterranean region is one of the most water scarce regions in the world (Ragab and Prudhomme, 2002; Simonet, 2011), with many of its riparian countries facing situations of physical water scarcity[1] (Table 2). Although there are considerable differences among the countries in the Mediterranean rim, they all share similar climatic characteristics that include dry and warm summers, mild winters and large rainfall variability with most precipitations concentrated in the winter. The climatic conditions allow for agricultural activity that includes the production of high added value crops including vegetables, citrus and olives. However, aridity and rainfall concentration in winter and inter-annual high variations make it necessary for agriculture to rely on irrigation.

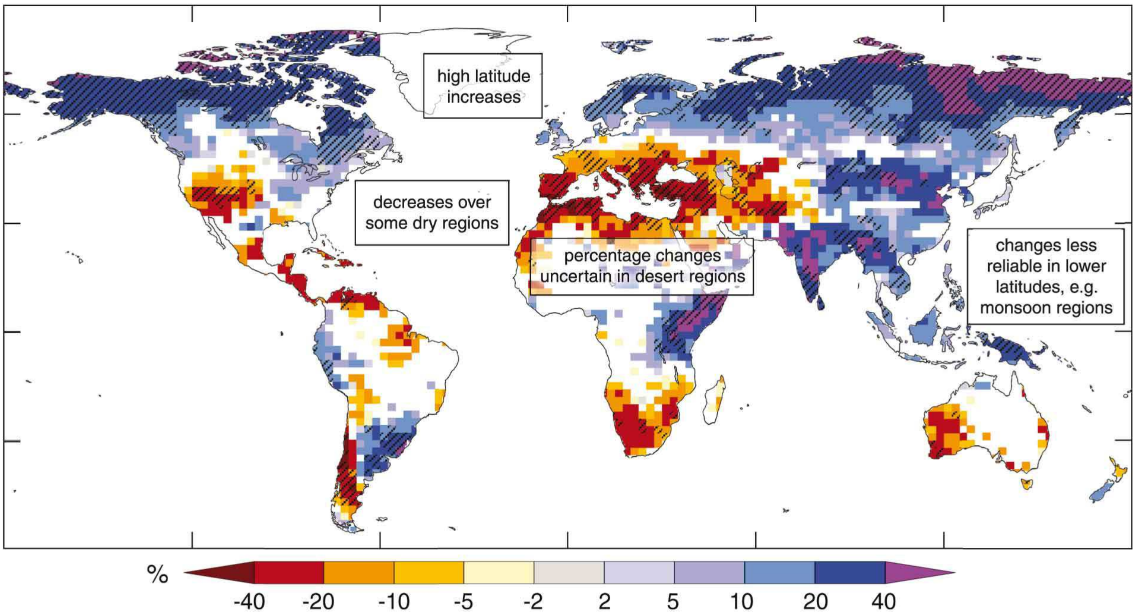
Irrigation in Mediterranean countries is responsible for around 70% of total water withdrawals (Hamdy, 2007; Simonet, 2011). Satisfying increasing water demands has been given in the past a higher priority than that conceded to the protection of water resources and water ecosystem conservation. This has led to a situation of unsustainable water use in many parts of the region (Iglesias et al., 2007). Irrigation expansion has to a great extent been based on increasing exploitation of groundwater resources in this region. Many countries are abstracting groundwater beyond sustainable levels and quality has also suffered because of pollution and saline intrusion. Country level water management policies have primarily focused on water supply improvements with remarkable infrastructure developments in some of the Mediterranean countries.

However, future climate change is projected to exacerbate water scarcity through increased water demands, mostly from irrigation, and reduced supply because of lower precipitation and surface runoff, which will further endanger sustainable development in the region (Iglesias et al., 2011; IPCC, 2007b; Simonet, 2011). Most global studies on climate change impacts and especially those focusing on impacts on water availability and water stress point to the Mediterranean region as one of the most vulnerable regions (Arnell, 2004; Bates et al, 2008; García-Ruiz et al., 2011; Giorgi and Lionello, 2008; Iglesias et al., 2011; Simonet, 2011; among many others). Population trends and expected development in the region together with climate change will significantly increase the number of people living in water stressed conditions (Arnell, 2004). Projected impacts of climate change in the Mediterranean envisage a substantial increase of aridity and warming, especially in the summer months with 25-30% precipitation decreases and 4–5 °C temperature increase by the 2050s (Giorgi and Lionello,

[1] The Falkenmark water scarcity indicator is the amount of renewable freshwater that is available for each person per year. If the value of the indicator is lower than 1000 m^3/inhab. the country is considered to be water scarce. If it is lower than 500 m3/inhab. then the country is considered to be in a situation of absolute water scarcity.

2008). This increased aridity will also manifest itself in the form of a decrease in river runoff as shown in Figure 1. According to the IPCC revision of model projections (IPCC, 2007a), modelling results consistently show runoff decreases above 20% in most areas of the Mediterranean countries.

Figure 1. Projections of relative changes in runoff by the end of the 21st century



Source: IPCC (2007a). White areas show the regions where model projections are consistent in less than 66% of the models considered, and hatched areas show the regions where more than 90% of the models reviewed by the IPCC show consistent projections on changes in river runoff.

The environmental challenge is one of the most critical in the region (UNEP, 2002). Current economic development is seriously threatening water resources, land and coastal areas and endangering the sustainability of the agricultural and tourism sectors. Climate change will exacerbate these pressures and mainstreaming adaptation to climate change in sectoral policies may therefore be crucial for the future of the region.

In the frame of the Euro-Mediterranean Partnership a Mediterranean Strategy for Sustainable Development (MSSD) was defined in 2002, which emphasises the need to achieve the sustainable management of natural resources and improve governance at the local, national and regional levels (UNEP, 2002). Among the main objectives for water resources sustainability, the strategy highlights the need to stabilise water demands, improve water productivity and promote participation and cooperation across scales. In line with this, international and country efforts are concentrated on establishing Integrated Water Resources Management (IWRM) policies and promoting water demand management with a focus on improving technical efficiency as well as economic efficiency through the use of appropriate economic instruments for water management (Blinda, 2012; GWP, 2012). However, the level of implementation of IWRM approaches in Mediterranean countries varies largely. Natural characteristics, such as the much pronounced aridity of southern and Eastern countries with respect to the Northern Mediterranean, and different socio-economic and institutional contexts determine different needs and different obstacles for water management.

1.4.1 Selection of country case studies: Spain and Jordan

The aim of the country case studies is to assess future scenarios for water demand and water balances that take into account the effect and potential contribution to climate change adaptation of specific water and irrigation policies. For this, this research attempts to illustrate the problems of water management in water constrained regions characterised by different natural, socio-economic and institutional contexts. In line with this, country selection was intended to include an EU Mediterranean country and a non-EU Mediterranean country aiming at illustrating different socio-economic and institutional settings. Within the available possibilities, Spain was selected because of its relatively greater water scarcity level, as compared to other EU Mediterranean countries. Among the non-EU countries, Jordan was chosen being one of the world's most water scarce countries with the highest population and GDP growth rates among the eligible Mediterranean countries (see Table 2). Also, the MEDPRO project that focused in these countries, and which supported fieldwork and data collection, was a key reason for the selection of these two countries. The following sections briefly introduce water problems and climate change implications in the two selected countries.

1.4.1.1 Spain

Spain is a semi-arid country and one of the most water scarce countries in the European Union considering available renewable water resources per capita together with water demand (see Table 1). In Spain water consumption is highly driven by irrigation, which is responsible for 64% of total water withdrawals (AQUASTAT, 2013). It is characterized by a Mediterranean climate that makes it more similar with respect to water and agriculture to its neighbours of southern and eastern Mediterranean countries than to other EU countries (Varela-Ortega, 2011). However, its socio-economic and institutional context is significantly influenced by its membership in the European Union, making the implementation of water and agricultural policies a challenging and special case of irrigation water management within the EU.

Agriculture in Spain occupies an area of 17.5 million hectares of which approximately 20% is irrigated (3.6 million ha in 2010) (MAGRAMA, 2012). Irrigation expands all around Spain except in the North and Northwest regions. However, irrigation is more relevant in the south and east of the country (the Mediterranean rims) which are characterised by a more warm and dry Mediterranean climate. Most characteristic irrigation crops include olives and vineyards, which cover 30% of all irrigated lands (MAGRAMA, 2012), and fruits and vegetables that, despite lower importance in terms of area, are key products in Spanish agricultural value added and exports (Varela-Ortega and Esteve, 2012).

The CAP and WFD are key policies for irrigation. Agriculture development has been significantly shaped by the EU agricultural policy over the past decades (Varela-Ortega et al., 2011). The CAP was an important trigger for irrigation expansion. CAP subsidies were formerly linked to crop production per hectare, offering important incentives to farmers to intensify agricultural production. This, coupled with national irrigation plans produced a significant expansion of irrigated land which increased from 2.4 million hectares in 1980 to 3.2 in 1990 (13% increase) and 3.7 in 2005 (an additional 16%) (MAGRAMA, 2012; MAPA, 1990, 2000).

However, current EU policies are converging towards common goals of sustainability that are inspired by the EU Sustainable Development Strategy (EC, 2001, 2006, 2009) (Varela-Ortega, 2011). In this spirit, the successive reforms of the CAP, and especially the 2003 reform that decoupled payments from production and introduced the Cross-Compliance scheme, have progressively introduced a more environmentally conscious approach to agricultural policy. Together with the removal of market distorting elements, the result has been the elimination of incentives to further intensify production and has contributed to a stagnation of the irrigated area and an apparent shift from highly water demanding crops, such as maize, to more efficient crops with higher value added (Garrido and Varela-Ortega, 2007; Varela-Ortega, 2011). The recently achieved political agreement on the post 2013 CAP reform (EC, 2013b) is a step further in the integration of agricultural and water policy goals, with the introduction of the WFD as a requisite for obtaining CAP direct payments (Cross-Compliance scheme).

The WFD is the backbone of the European water policy. It advocates IWRM with the overall objective of achieving the good ecological status of all water bodies. This Directive has led to the review of all river basin management plans to ensure that they include new elements that support the achievement of the good ecological status of water bodies and, among other requisites of the WFD, the recovery of the costs of water services, including environmental and resource costs.

Spain is still in the process of enacting the new river basin plans in line with the mandate of the WFD, with the 2009-2015 plans of the Tajo, Segura and Jucar basins not yet approved and the 2015-2021 plans' participatory processes already open for the rest of the basins. However, as highlighted by the EU Commission review of the implementation process of the WFD (EC, 2012b), the adoption of measures to recover the costs of water has been very limited across EU countries. In Spain, this is a contested issue as beyond technical constraints to implement cost recovery measures in the agricultural sector, the increase of water prices required to recover costs of water services, may cause relevant losses to farmers in areas of low technical efficiency in water deliveries. Therefore, the implementation of the WFD is a difficult task in Spain that may be further hindered by the effects of climate change.

Climate change projections for Spain envisage lower precipitations, increased frequency of floods and droughts and decreased water availability (CEDEX, 2011). Specifically, according to CEDEX (2011), river runoff could decrease by 8% from 2011 to 2040, by 11% and 16% from 2041 to 2070 and by 14% and 28% in the last period of the 21st century[2], for the SRES scenarios B2 and A2 (Nakicenovic and Swart, 2000) respectively. Southern and eastern river basins, where irrigation agriculture is more prevalent, will be more severely impacted than central and northern basins. This will require the adaptation of all economic sectors and especially of agriculture as the primary water user.

Climate change adaptation policy in Spain is coordinated at the national level by the Spanish Office for Climate Change (OECC, for its acronym in Spanish) under the competence of the Spanish Ministry of Agriculture, Food and Environment. The framework for adaptation policy is established by the National Climate Change Adaptation Plan (OECC, 2008) that establishes the priorities, coordinates cooperation among different administrative bodies and develops a framework for the assessment of impacts and vulnerability across sectors. However, given the administrative structure of Spain, with seventeen autonomous regions, and the current distribution of competences among administrations, regional governments are committed to

[2] Average of different scenarios from different General Circulation Models tested

develop specific regional plans for climate change mitigation and adaptation. The development of these plans is uneven across regions, and the absence of specific funding mechanisms and the lack of solid science-policy coordination at regional level that supports decision-making on adaptation has limited their scope (Pfenninger et al., 2010). Because of this, a deeper understanding of the potential impacts of climate change across sectors and regions is a fundamental issue for the development of adequate adaptation plans that address the climate change implications in an integrated manner as well as the required actions at different decision-making levels.

1.4.1.2 Jordan

Jordan is one of the most water scarce countries in the world (Humpal et al., 2012; Venot et al., 2007) with natural water resources availability per capita estimated at 165 m^3per year. It covers an area of 88790 Km^2, with clearly differentiated regions according to topography and climate (AQUASTAT, 2008). Average annual precipitation amounts 111 mm/year although its distribution is uneven, ranging from 600mm/year in the North-western area to around 50 mm in the eastern and southern desert regions. Climate ranges from semi-tropical in the Jordan Valley to Mediterranean in the Uplands and more continental in the eastern and southern desert area (AQUASTAT, 2008).

Jordan's total renewable water resources are estimated to be approximately 937 Mm^3, of which 682 Mm^3 correspond to internal water resources and 255 Mm^3 to external resources. Groundwater safe yield is estimated to be 275 Mm^3 (AQUASTAT, 2008), but in many groundwater basins, water abstraction is beyond sustainable levels and there is ongoing exploitation of non-renewable groundwater sources. According to Jordan's Water Strategy 2008-2022 (THKJ, 2008), non-conventional sources of water include treated wastewater (107 Mm3), reused treated wastewater (83.5 Mm3) and desalination (9.8 Mm3). Current water allocations in Jordan amount 950 Mm3 of which 63% are allotted to irrigation. However, water supply delivered is below real water demands and around 38% of water demands are not satisfied (THKJ, 2008). The growing population is a major pressure on water resources. Population in the north-western part of Jordan has largely increased in the last decades mostly because of the arrival of refugees from the neighbouring countries, especially from Palestine, Iraq and Syria (MPC, 2013). Urban sprawl, mainly in Amman, has further reduced supply reliability and currently household supply is provided only once or twice a week (KfW, 2011).

Water scarcity is a general problem for all users and sectors, with irrigation water demands satisfied at a rate of only 55% (THKJ, 2008). Agriculture covered an area of around 230000 hectares in 2008 (DOS, 2008) of which 35% was irrigated. However, frequent drought periods produce a large variation of cultivated area from year to year. Although the agricultural sector is normally relevant in the southern and eastern Mediterranean countries, water scarcity and extreme climate conditions in Jordan considerably limit the potential of agriculture, which represents only 3% of the country's GDP (AQUASTAT, 2008).

Irrigation agriculture is mainly located in the Lower Jordan river basin (the Jordanian part of the Jordan basin), which accounts for more than 80% of the country's irrigated land (Venot et al., 2007). The most relevant irrigated crops are permanent crops (47%), of which olives, citrus and bananas are the most important, and vegetables (43%), including tomatoes, potatoes, squash and eggplants (AQUASTAT, 2008; Venot et al., 2007). There are two main differentiated types of irrigation farming systems: the Jordan Valley, based on surface waters, and the Uplands, based on groundwater. The use of modern irrigation techniques is common in the country's irrigation lands, especially for the groundwater based fields. More than 80% of the area is irrigated with pressurised irrigation techniques (AQUASTAT, 2008). However, in irrigation areas that rely on surface water, the low demand reliability, the high losses in the water distribution networks and uncontrolled abstractions from the irrigation canals reduce the pressure in the systems and thereby affect the performance and water use efficiency of the irrigation systems (Shatanawi et al., 2005).

Water affairs are so intrinsically linked to agriculture that water policy and irrigation policy fall under the competence of one administrative body especially devoted to these issues: the Ministry of Water and Irrigation (MWI). This Ministry is in charge of water policy, planning and management, water supply, water infrastructure development and financing, and monitoring. Within the MWI two key bodies assist water management, namely The Jordan Valley Authority (JVA) and the Water Authority of Jordan (WAJ). The JVA is in charge of water management and socio-economic development in the Jordan Valley including irrigation development. The WAJ manages the water and sewage systems in all of Jordan, and is in charge of licensing and controlling irrigation water use in the Uplands. As shown by MWI (2013), Water Policy is based on a set of documents enacted between 1998 and 2002 which include the Groundwater Policy, the Irrigation Water Policy, the Wastewater Policy and the Utility policy, with a strong focus on water supply management. In 2006 a water demand management approach was introduced in Jordan with the adoption of the Irrigation Equipment and System Design Policy and the Irrigation Water Allocation and Use Policy. The main guiding principles of these policies are contained and summarised in Jordan's Water Strategy. The main goals of Jordan's Water Strategy 2008-2022 (THKJ, 2008) involve the control and reduction of irrigation demands, especially in the groundwater-based irrigation systems, the introduction of water tariffs that incentive water saving and enhance water use economic efficiency, improving demand reliability for drinking water, increasing supply from non-conventional sources of water and enhancing governance and improving the enforcement of water legislation. Achieving these goals remains a major challenge for water managers. Current unmet demands in irrigation, the obsolete water conveyance systems and infrastructures, and the poor socio-economic conditions of many farmers and households in the agricultural lands limit the range of possible action for water management and may require important investments and agricultural reforms (THKJ, 2008, Humpal et al., 2012).

With respect to climate change, there are not specific plans developed in Jordan for mitigation or adaptation. Although the water strategies and management plans refer to it as a future issue for water management, emphasis is currently placed on the challenges of socio-economic development and its implications for water demand and supply, as stated in Jordan's Water Strategy (THKJ, 2008).

1.4.2 A basin level case study: the Middle Guadiana Basin

The Guadiana basin is located in the southern central plateau of the Iberian Peninsula. It is a transboundary river basin shared between Spain and Portugal. It covers an area of 67143 Km^2, from which 83% is located in Spain. The basin is characterised by a remarkable dichotomy between the upper basin that relies primarily on groundwater resources and where aquifer overexploitation is considerably constraining irrigation, and the middle basin, where surface waters are more abundant.

The Middle Guadiana covers an area of 34,250 Km^2. It presents a Mediterranean-continental climate with average annual precipitation of 590 mm, and an average annual water inflow of 4270 Mm^3 (CHG, 2013a).

The agricultural sector is the most relevant economic sector in the basin in terms of water consumption (≈90%) and socio-economic importance (CHG, 2013a). Irrigation development in the region was primarily fomented by a rural development plan that was in effect from the 1950s to 1975 (Blanco-Gutiérrez et al., 2013). This plan aimed to stabilise the population in the region and was based on the development of irrigation infrastructures and irrigation districts. This plan, along with subsequent irrigation schemes and water plans, promoted the expansion of irrigated land and of storage facilities. There are currently around 140000 hectares of irrigated land and water storage capacity is approximately 8000 Mm^3.

Most relevant crops in the region include fruit trees (11%), olive trees (9%) and vineyards (4%) as well as annual herbaceous crops (75%), among of which rice, tomato and maize are the most relevant ones (INE, 2009).

Old water conveyance systems have determined low water use efficiency with significant water losses in the network and on farms. Because water is charged according to irrigation area, incentives for irrigation modernisation are low (CHG, 2008). This has promoted the excessive use of water in some parts of the basin, and especially the expansion of rice fields. Rice growing farms consume water well above the legally permitted levels (7500 m^3/ha) and this has produced confrontations between traditional and modern irrigation districts.

The implementation of the WFD in the region is problematic. Preliminary calculations of minimum environmental flows required are optimistic with respect to the current river flows in the Middle Guadiana (CHG, 2013a). However, environmental groups argue the inadequateness of the calculation methods and underscore the insufficiency of the designed flows with respect to the actual environmental needs, as stated in the allegations presented to the Guadiana basin Management Plan (CHG, 2013b). Moreover, with current and future high water demands, mostly driven by the expansion of rice fields, further pressures on water ecosystems are expected. On the other hand, the implementation of other WFD requisites such as the cost recovery of water services entails considerable difficulties. Current water delivery systems make it difficult to measure real water consumptions at farm level. In addition, low efficiency of water use, which is mainly caused by non-modern irrigation infrastructures and techniques, with more than 45% of the area still irrigated through gravity methods (MAGRAMA, 2012), which suggests the possibility of large negative impacts resulting from increased water prices and great difficulty in actually reducing water consumption, as shown by other studies carried out in Spain (Berbel and Gómez-Limón, 2000).

The high storage capacity, which has helped to mitigate the effect of drought in the past years, as well as the low fees paid that do not reflect the scarcity value of water, have produced low awareness about water scarcity issues and climate change impacts. However, the Guadiana basin is expected to be one of the river basins in Spain that will be more severely impacted by climate change, with a projected 9-12% decrease (depending on the scenario) of average runoff by 2040 (CEDEX, 2011). In line with this, concerns about the future evolution of water availability and water demands require a careful analysis of what the impact of climate change may be and what may be its effect on the implementation of the WFD.

1.5 Methodology

1.5.1 Brief review of approaches for the assessment of climate change impacts, vulnerability and adaptation in water and agriculture

Policy responses to climate change can be grouped into two broad types of actions: mitigation and adaptation (Füssel and Klein, 2006). Both policy fields build on impact and vulnerability assessments that support the identification of required actions and priority targets. As explained above, climate change research has evolved from compartmentalised scientific domains to integrated assessments that jointly analyse impacts, vulnerability and adaptation. Climate change vulnerability and adaptation research has evolved similarly to integrated assessment approaches (Füssel and Klein, 2006), and climate change as well as natural resource management research are increasingly based on the integration of quantitative and qualitative methods, stakeholder (SH) participation, the combination of simulation and optimisation approaches and the use of scenarios.

Malone and Engle (2011) highlight some commonly used methods for assessing vulnerability including, indicators, SH-driven processes and scenario-building methodologies. Indicators, usually derived from model-based quantification or statistics, are useful tools for comparisons across regions, temporal scales and also for quantifying the effect or adaptation potential of different policy measures. The main virtue of SH-driven assessments is that SH are better able to identify site-specific vulnerabilities. Also SH involvement increases the legitimacy and social acceptance of policy implications of the assessments conducted. Scenario-building, which frequently involves SHs as well, is used as a tool to explore potential futures and to understand the vulnerability of the systems involved through the careful study of plausible future developments. Many vulnerability and adaptation studies combine these three different methods in order to provide a comprehensive vision on the multiple dimensions involved, including bio-physical and socio-economic elements.

As explained above, vulnerability and adaptation assessments have been primarily developed around two approaches, namely bio-physical and socio-economic. Within these two, Smit and

Wandel (2006) identified a total of four types of vulnerability and adaptation assessments, two within the bio-physical approaches and two within the socio-economic. Among the bio-physical we find assessments based on the use of theory-based models and economic assessments that focus on the evaluation of climate change impacts and the contribution of adaptation actions to reduce those impacts. Examples of this type of assessment include Nelson et al., 2009; Nicholls and Toll, 2006; Tubiello and Rosenzweig, 2008; Tubiello et al., 2000. Second we find other types of assessments that focus on the prioritisation of adaptation measures for which cost-benefit, cost-effectiveness and multi-criteria assessment tools are frequently applied (e.g. De Bruin et al., 2009; Dolan et al., 2001).

Within the social or socio-economic approaches, there is an important body of research (Brooks et al, 2005; Guillaumont, 2009; Hahn et al., 2009; O'Brien et al., 2004) that uses indicators of social vulnerability and adaptive capacity for the identification of most vulnerable individuals. This type of research is frequently oriented towards the prioritisation of policy targets and regional comparisons. Finally, the last group of adaptation studies identified by Smit and Wandel (2006) include research works that focus on the implementation of adaptation processes by assessing adaptive capacity, identifying adaptation needs within communities or regions, and looking at decision-making processes and interactions across relevant institutions and actors (e.g.: Adger et al., 2009; Berkhout et al., 2006; Engle and Lemos, 2010, among others).

In the field of water and agriculture, most studies have focused on the bio-physical and economic aspects of climate change and have been based on theory-based modelling tools, such as bio-economic models, and typical indicators such as crop yields, crop productivity, water supply or farm income. Table 3 shows different types of climate change impacts, vulnerability and adaptation assessments, their main features and some examples on literature. These research works focus on the different dimensions relevant to irrigation agriculture, namely agronomic, socio-economic and hydrologic, and different scales from the local to the global. Most studies focus on just one dimension but integrated approaches in which two or the three dimensions mentioned are combined, are becoming more common.

Table 3. Approaches to vulnerability and adaptation assessment: main characteristics and examples from the water and agriculture fields

Vulnerability and adaptation focus	Dimensions considered	Scales / Levels	Tools	Key features and issues	Examples in literature
Bio-physical and Economic (end point vulnerability)	Agronomic	Crop	Crop, agronomic models	Usually test climate impacts on yields and different crop management approaches	Easterling et al. (1993, 2003), Laux et al. (2010), Tubiello et al. (2000, 2002), Ventrella et al. (2012), Wang et al. (2012)
	Socio-economic	Farm	Statistical analysis, econometric models, mathematical programming optimisation models, agent based models	Focus on farm-level adaptation, decisions on cropping patterns and management	Seo and Mendelsohn (2008), Reidsma et al. (2010), Risbey et al. (1999)
	Hydrologic	Global, country, (Sub-) Basin	Hydrological and water balance models	Focus on supply side solutions and technical options for adaptation. Do not account for increased crop water requirements or the dynamic nature of water demands	Christensen et al. (2004), Droogers et al. (2012), Rochdane et al. (2012)
	Agronomic, Socio-economic	Crop, farm	Sequential or integrated agronomic-economic models	Simulate climate change impacts on crops and economic effects	Butt et al. (2006), Mendelsohn and Dinar (1999), Carmona et al. (2013)
	Agronomic, Hydrologic	Global, (Sub-) Basin	Yield functions, agronomic, hydrologic and water balance models	Do not consider farm-level decision-making and adaptation, may overestimate climate change impacts	Rosenzweig et al. (2004), IMPACT-WATER (Cai and Rosegrant, 2002)
	Socio-economic, Hydrologic	(Sub-) Basin	Modular and holistic hydro-economic models, agent-based models	Address the dynamic nature of water demands and economic activities in relation to water resources. Most cases do not address the crop dimension	Hurd and Coonrod (2012), Jeuland (2010), Medellín-Azuara et al. (2008), Tanaka et al. (2006)
	Agronomic, Economic, Hydrologic	(Sub-) Basin	Integrated assessment models, hydrology modelling, crop growth functions and economic optimisation, agent-based models	Consider all relevant dimensions. In most cases do not consider feedbacks between different levels and dimensions. Usually only linear integration	Cai et al. (2003), Holman et al. (2005), MedAction PSS (van Delden et al., 2007), MP-MAS (Schreinemachers and Berger, 2011), Vano et al.(2010)

Studies focusing on the agronomic dimension (Easterling et al., 1993; Tubiello et al., 2000, 2002; Ventrella et al., 2012; Wang et al., 2012) use models that simulate the effect of changes in climate variables and in crop management on soil-crop processes and crop-growth, such as the EPIC (Environmental Policy Integrated Climate) model (e.g. Easterling et al., 2003) or the CropSyst agronomic model (Laux et al., 2010; Tingem and Rivington, 2009) These provide estimations of the likely effects of climate change in terms of changes in crop yields or water and nutrient requirements. They also assess, in many cases, potential adaptations in crop management, that contribute to mitigate the effects of climate change, such as the use of improved crop varieties, changes in planting and harvesting dates, or deficit irrigation methods.

However, the consideration of farm-level decision-making has proven to be relevant for climate change assessments. Studies that focus on farm-level decision-making (Seo and Mendelsohn, 2008; Reidsma et al., 2010; Risbey et al., 1999) use different methods such as mathematical programming models, dynamic simulation models and agent based models (van Wijk et al. 2012), often combined with statistical or econometric analysis, which usually explore resource use and allocation and changes in cropping activities. These types of studies address farm level decisions and adaptation under climatic stimuli and usually focus on the economic performance of farm holding, on food self-sufficiency or in food security (van Wijk et al. 2012).

Focusing on water resources assessment, we find studies based on the use of hydrological or water balance models at the local, regional or global levels (Christensen et al., 2004; Droogers et al., 2012; Rochdane et al., 2012). When it comes to adaptation, this type of studies usually focuses on water supply or demand management measures, their potential contribution to water supply, demand satisfaction or water efficiency and, very often, their costs.

However, as explained above, research developments have highlighted the need for more integrated assessments of climate change impacts, vulnerability and adaptation assessments (Howden et al., 2007, Meinke et al., 2009). Climate change is a physical event whose consequences are first experienced in the bio-physical dimension. However, integration of different modelling disciplines is important to understand the true magnitude and impact of climate change. Understanding how changes in temperature and precipitation will affect crops and water availability is important as it will have implications for food security. But changes in crop yields will also be determined by changes in the hydrological system, especially for those crops that depend on irrigation. Changes in water availability and crop yields will affect socio-economic welfare in rural areas and will determine farmers' decision-making in relation to water management and crop choice. These decisions at farm level will in turn affect the hydrology system as well as crop productivity. Moreover, decisions made at farm level or in a region may affect conditions in other farms and regions. Therefore methods that are able to incorporate the interactions between the agronomic, socio-economic and hydrologic dimensions and the different existing feedbacks are necessary. Given the multiple scales, both geographic and socio-institutional, of climate change impacts and adaptation, it is necessary to use multidisciplinary integrated methodologies to address these complex problems (Downing, 2012; Meinke et al., 2009).

Examples of integrated modelling approaches used for the analysis of climate change include those that combine crop models with economic models to assess the implications of climate change impacts on crops at the farm level (Butt et al., 2006; Carmona et al., 2013; Mendelsohn and Dinar, 1999). These models allow for the assessment of the impacts of climate change on crop growth as well as the internalisation of those impacts in farmers' decision-making.

Examples of models that integrate the agricultural and hydrologic dimensions include the study by Rosenzweig et al (2004), which explores the effect of climate change on crop yield and water availability in five case studies that correspond to five agricultural regions of the world. For this, they use three crop models, a hydrology model and a water balance model. They also test crop adaptation measures. Another example is the IMPACT-Water model (Cai and Rosegrant, 2002), which combines the IMPACT model (Rosegrant et al., 2012), a partial equilibrium model for the agricultural sector, with a water module. This integrated framework allows for consideration to be made of the effects of climate change on crop production as well as on water demand and supply, whilst incorporating the assessment of global food markets. However, this modelling does not address farm level decision-making, i.e. farmer autonomous adaptation. Under water limitations or decreased crop yields it is reasonable to think that farmers would adjust their cropping patterns and farming operations to adjust to new conditions. This will affect also water demand and therefore water balance.

The use of integrated hydro-economic modelling has proven to be useful for linking climate change, hydrology and socio-economic dimensions while also contributing to an improved understanding of the complexity and uncertainties inherent in water resources and climate change (Jeuland, 2010). This type of integrated model emerges in response to the shift from traditional supply side management approaches to demand oriented water management. Managing water resources involves the management of the different interactions that occur between human and economic activities and land and water resources, and the consideration of the associated potential economic, social and environmental risks (GWP, 2000). The shift from a water supply approach to a broader view of water management that integrates both supply and demand sides of water use, allows for more detailed analysis and an improvement in our understanding of the complex relations between the hydrological systems and human systems (Rijsberman, 2006). In line with this, hydro-economic modelling has been shown to be a useful tool for IWRM (Blanco-Gutiérrez et al., 2013, Harou et al., 2009). These models enrich traditional engineering-oriented water management approaches by introducing an economic dimension in hydrology models, moving from a static view of water demand, based on fixed demands, to a dynamic consideration of water demand based on the economic values provided by water resources (Harou et al., 2009). At the same time they enlarge the scope of economic analysis by addressing and including the physical environmental context characteristics in the economic modelling parameters and constraints.

Hydro-economic modelling has been widely applied with different purposes and at different scales, focusing on the economic behaviour of different sectors or on the economic principles that govern water allocation and use among different sectors. It was first applied by Bear et al. (1964) (Harou et al., 2009), who used water demand curves for the optimisation of water resources system in relation to the conjunctive use of surface- and groundwater. Gisser and Mercado (1972) are among the pioneers in using hydro-economic modelling for the analysis of agricultural water demand. Scientific literature contains many examples in which hydro-economic modelling has been used in the context of agriculture, such as in the assessment of water quality issues (Peña-Haro et al., 2009; Volk et al., 2008), the evaluation water allocation policies (Blanco-Gutiérrez et al., 2013; Rosegrant et al., 2000), and the management of groundwater resources (Varela-Ortega et al. 2011), among many others.

In the context of climate change impact and adaptation assessments, hydro-economic modelling has been widely applied for the simulation of climate change scenarios as well as different types of adaptation measures (Hurd and Coonrod, 2012; Jeuland 2010; Medellín-Azuara et al., 2008). Many of these models usually consider a fixed relation between water and yields and do not consider the effects of climate change on crop growth cycles and on the yield response to water. In this sense, water demands are not responsive to climatic changes.

Other modelling frameworks that have jointly addressed the socio-economic and hydrological dimensions include agent-based models combined with water balance or hydrology models. These have also been frequently combined with models or crop yield functions considering together the agronomic, socio-economic and hydrology dimensions (Schreinemachers and Berger, 2011).

Theory-based modelling studies have also taken into consideration the three dimensions considered here, agronomic, socio-economic and hydrology (Cai et al., 2003; Holman et al., 2005 ; van Delden et al., 2007; Vatn et al., 2006). Cai et al. (2003), for example, use a hydrology model that calculates water supply and allocation to demand nodes and links it to a crop function that estimates crop yields according to soil salinity and soil moisture (which depends on water allocation for irrigation). Then, based on crop yield the benefits achieved in irrigation demand nodes are estimated. The economic objective function is the maximisation of irrigation benefits, hydropower benefits and ecological benefits, which are calculated according to water available for environmental uses. Then this integrated modelling framework optimises water allocation for different uses. The main limitation of this approach is that it does not consider the effects of changed climate conditions on crop growth functions. But even more relevant is that it cannot consider the farm level decision-making with respect to crop production and water availability and allocation, which is a key aspect to represent climate change effects more realistically. The study by Holman et al. (2005), however, does include farm-level optimisation of profits subjected to risk, internalising the effects of climate change on crop productivity in farmers' decisions on cropping pattern. These results are used by the hydrology model to simulate water resource processes. However, the link between the economic and hydrology model is unidirectional, in the sense that the results of the hydrology model and potential water constraints for agricultural use are not translated into decision making effects at farm level.

The methodology used in the present research builds on theory-based models and tries to advance in modelling integration and to respond to the multi-dimensional implications of climate change for water and agriculture representing relevant interactions and feedbacks. The methodology developed tries to address the multiple dimensions of water, agriculture and climate change and accounts for the bio-physical effects of climate change as well as for the socio-economic implications and decision-making at farm level, river basin level and national level. This integrated modelling tool consist of a hydro-economic modelling framework that combines a hydrological simulation model, a farm decision-making optimisation model and an agronomic module that simulates crop growth accounting for temperature, soil moisture, evaporation and transpiration. In this way, all three dimensions are modelled in a climate-responsive way. This modelling framework, fully explained in subsequent chapters, is applied at different scales and complemented with other tools, including econometric assessments and socio-institutional analyses and thus provides a comprehensive view of climate change impacts and adaptation in the water and irrigation sectors.

1.5.2 Applied methodological framework: Selection of methods and multi-level coverage

In accordance with the objectives established for this research, the methods selected allow us to address the multiple levels, scales and dimensions of water use and management. The selection of the modelling tools applied describes a sequential process in which the progressive enlargement of the scales of analysis requires the incorporation of new tools capable of addressing the different dimensions of water resources management and climate change. This process consists of four phases:

1. *Analysis of water scarcity and policy impacts and farm level vulnerability: farm level agro-economic model*

The research starts with the analysis of farm level impacts and response to water conservation policies with a focus on farm level vulnerability. For this, a farm-level agro-economic mathematical programming model (MPM) of constrained optimisation is developed using a set of representative and real farms. The model reproduces farmer's behaviour under different natural, technical, and policy constraints. The output includes farmers' decisions on resource allocation (land and water) to different cropping options as well as the impacts of those choices on farm income, water use, and labour use. Income losses derived from the implementation of water conservation policies are used as indicator of farmers' vulnerability. Then, the use of an econometric model that explains income loss allows for the identification of key determinants of farmers' vulnerability.

2. *The need to consider the bio-physical dimension: Hydro-economic model*

Assessment of farm level impacts and responses to water conservation policies allows us to develop an improved understanding on farm vulnerability and the main elements that determine it. However, this vulnerability assessment is only based on farm characteristics and on farmer decision making and adaptability. Vulnerability and adaptation research has shown that vulnerability is dynamic in the sense that it is affected by processes that occur at multiple geographical scales and decision-making levels. This is especially true in the case of water resources, where the bio-physical dimension as well as the socio-economic and institutional setting determine water resource availability and allocation. A hydro-economic model is developed that combines the farm-level agro-economic MPM with the hydrology and water management model WEAP (Water Evaluation And Planning system) (Yates et al., 2005a, 2005b). The use of the MABIA (Sahli and Jabloun, 2005) calculation method in WEAP allows for the consideration of crop growth and therefore also how climate and water resources availability impact on crop yields and irrigation requirements. Consequently, this model integration addresses the agronomic, socio-economic and hydrology dimensions of water resources management and climate change. The use of these models permits the simulation of water management and climate change scenarios and the evaluation of the most effective adaptation options.

3. *The socio-institutional dimension of adaptation: social network mapping and barriers to adaptation*

Once the most effective adaptation measures are identified, the question of whether those measures can be successfully implemented remains. In order to address this question, an analysis of potential barriers to adaptation is carried out based on, first, the analysis of socio-institutional networks for adaptation in the context of water and agriculture, and second, a stakeholder-based evaluation of the strengths of the identified barriers and their effect on specific adaptation measures.

4. *Socio-economic and climate scenarios, aggregated water balances, and policy assessment*

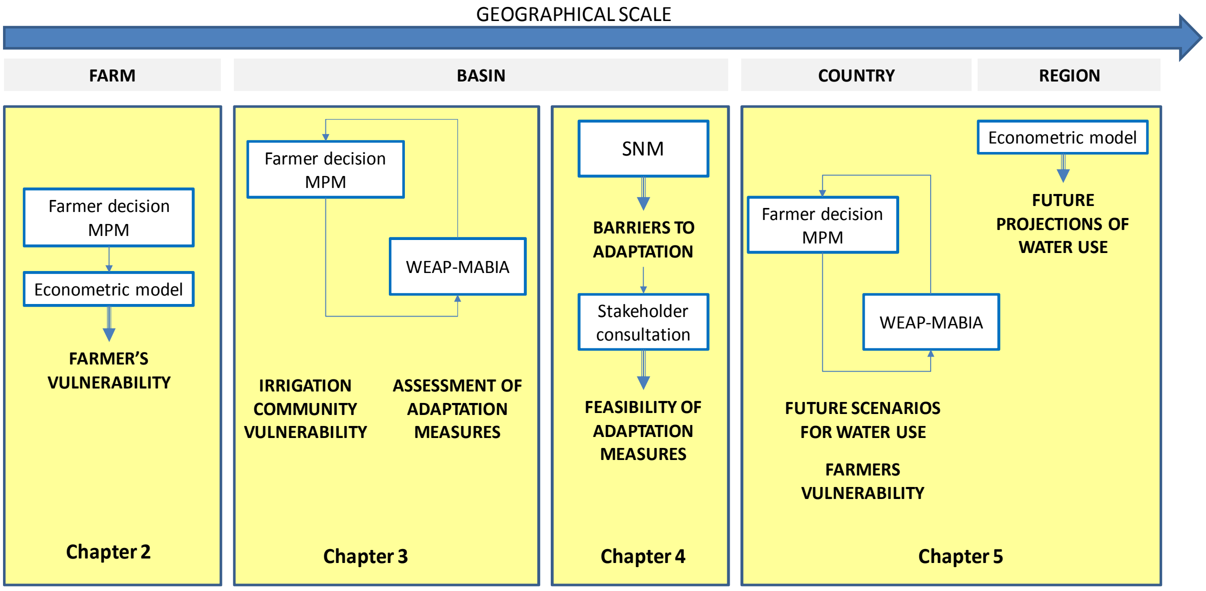
Finally, an aggregated vision on water resources and climate change is shown. For the analysis of water demand and climate change in the Mediterranean region, national level indicators are used. An econometric model for water withdrawals analyses the main drivers of water use and provides projections of water withdrawals for a set of 14 Mediterranean countries using different socio-economic and climate scenarios. This analysis is followed by a two country case study assessment, in Spain and Jordan, based on the use of an aggregated agro-economic optimisation MPM and a country level WEAP water balance model that considers urban, industrial and agricultural water demands. This model combination allows for the analysis of future water demands and the assessment of the effect of specific water policies.

Table 4 summarises the different dimensions and scales addressed in this thesis and refers to the specific chapter, and Figure 2 shows the tools used and the different scales of analysis on each chapter.

Table 4. Thesis coverage of different scales, sectors and models

INTEGRATED APPROACH			CHAPTER
Multi-scales / geographic	• Farm	• Real / representative farms →	Chapter 2, 3
	• Irrigation community	• Middle Guadiana ICs →	Chapter 2, 3
	• River Basin	• Middle Guadiana →	Chapter 3, 4
	• National	• Spain / Jordan →	Chapter 5
	• Regional	• Mediterranean →	Chapter 5
Multi-scales / decision-making	• Farm	• Real / representative farms →	Chapter 2, 3
	• Irrigation community	• Middle Guadiana ICs →	Chapter 2, 3
	• River basin	• Middle Guadiana →	Chapter 3, 4
	• National	• Spain / Jordan →	Chapter 5
Multi-facets	• Hydrology / Water sector →		Chapter 3, 4, 5
	• Socio-economic →		Chapter 2, 3, 4, 5
	• Agronomic →		Chapter 3, 5
Multi-sectors	• Water →		Chapter 2, 3, 4, 5
	• Agriculture →		Chapter 2, 3, 4, 5
	• Urban →		Chapter 3, 4, 5
	• Industrial →		Chapter 4, 5
Model integration	• WEAP-MABIA →		Chapter 3, 5
	• Agro-economic →		Chapter 2, 3, 5
	• Econometric →		Chapter 2, 5
	• SNM →		Chapter 4

Figure 2. Geographical scales and tools



MPM: Mathematical Programming Model; WEAP-MABIA: Water Evaluation and Planning System – MABIA method; SNM: Social Network Mapping

1.6 Structure of the thesis and related publications

This document is organised in 6 chapters covering the context, objectives and methodologies of the research, the application of the selected methods to different case studies and the most relevant results and the conclusions of this doctoral research.

Chapter 1. Introduction

This chapter provides an overview of the context and research framework of this PhD thesis, description of water scarcity and climate change issues and the state of the art in climate change research and impacts, vulnerability and adaptation assessments. It describes the general objectives of this doctoral research and the methods used to attain these objectives.

Chapter 2. Towards sustainable water management in agriculture: assessing farmers' vulnerability in a water scarce river basin

Chapter 2 presents a farm level vulnerability assessment in the Middle Guadiana basin. This chapter focuses on the impacts of water conservation policy at farm level and the derived vulnerability of farmers that face constraints to water use. The methodology of the study is based on the integration of a farm level MPM and an econometric model for farmer income loss. As a result, this chapter identifies key elements that may determine farmers' vulnerability with the aim of contributing to water policy decision-making.

This chapter is based on:

- Esteve, P., Varela-Ortega, C. Towards sustainable water management in agriculture: assessing farmers' vulnerability in a water scarce river basin. Submitted to: *Agricultural Water Management* (30/08/2013, Ref. AGWAT5775).

And the approach, methods and preliminary results have been also presented in:

- Esteve, P., Varela-Ortega, C. An economic modelling approach for vulnerability assessment in irrigation farms in Spain. Paper presented at the VIII Spanish Congress of Agricultural Economists. 14 – 16 September 2011. Madrid, Spain.

- Esteve, P., Varela-Ortega, C. An economic modelling approach for vulnerability assessment in irrigation farms in Spain. Poster presented at the 12th Congress of the European Association of Agricultural Economists – EAAE 2011. 30 August – 2 September 2011. Zurich, Switzerland. Published online in: http://ageconsearch.umn.edu/bitstream/114337/2/Esteve_Paloma_617.pdf

- Varela-Ortega C., Esteve, P., 2012. Environmental standards in the fruits and vegetables sector of Spain. In: Brouwer, F., Fox, G. and Jongeneel R. (Eds.) The Economics of Regulation in Agriculture. Compliance with Public and Private Standards. CABI Press, Wallingford, UK, 181-195pp.

- 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, P., De Stefano, L., Hernández-Mora, N., Zorrilla, P., 2010. The Guadiana Basin. In: Mysiak, J., Henriksen, H.J., Sullivan, C., Bromley, J., Pahl-Wostl, C. (Eds). The Adaptive Water Resource Management Handbook. Earthscan, London, UK, 103-115pp.

Chapter 3. Climate change in the Middle Guadiana irrigation agriculture: a hydro-economic modelling approach for assessment of impacts and adaptation

Chapter 3 presents an assessment of climate change impacts and adaptation in the Middle Guadiana basin, based on the use of a hydro-economic model. The paper specifically analyses the effect of different climate change scenarios on water supply and demand, looking at the impacts on unmet irrigation demand and farm income. It also analyses the effect of different water policy instruments of IWRM policies and explores their potential contribution to climate change adaptation.

This chapter gave rise to the following paper:

- Esteve, P., Varela-Ortega, C., Downing, T.E. Climate change in the Middle Guadiana irrigation agriculture: a hydro-economic modelling approach for assessment of impacts and adaptation. Under review by the authors to be submitted to: *Journal of Water and Climate Change*

And a partial presentation of its methods and results is included in:

- Varela-Ortega, C., Blanco, I., Bharwani, S., Esteve, P., Fronzek, S., Downing, T.E., (*in press*). How can irrigation agriculture adapt to climate change? Insights from the Guadiana basin in Spain. Submitted to: *Regional Environmental Change* (14/07/2013, REC-D-13-00254).
- Varela-Ortega, C., Blanco, I., Esteve, P., Bharwani, S., Fronzek, S., Downing, T.E., Juárez, E. Analyzing adaptation to climate change in the water and the agricultural sectors in the Spanish Guadiana basin. Communication presented at the European Climate Change Adaptation Conference (ECCA) 2013. Hamburg, Germany. 18 – 20 March 2013.
- Varela-Ortega, C., Blanco, I., Esteve, P., Bharwani, S., Downing, T.E., Fronzek, S. Analyzing climate change adaptation in the agriculture and water sectors: screening risks and opportunities. Communication presented at the IX Spanish Congress of Agricultural Economists. Spanish Association of Agricultural Economics. Castelldefels, Barcelona, Spain. 3 – 5 September 2013.

Chapter 4. On the social side of adaptation: Participatory analysis of determinants and barriers to adaptation in the Middle Guadiana irrigation agriculture

This chapter present an assessment of the adaptation socio-institutional context, its main strengths and weaknesses and potential barriers that may arise when implementing adaptation strategies. The analysis is based on the representation of a Social Network Map built through stakeholder involvement and validated by stakeholders and experts. In addition, the chapter presents a valuation of the strengths of different barriers and their relevance for the implementation of specific adaptation measures, based on stakeholder opinions.

This chapter resulted in the following paper:

- Esteve, P., Varela-Ortega, C., Downing, T.E. On the social side of adaptation: Participatory analysis of determinants and barriers to adaptation in the Middle Guadiana irrigation agriculture. Under review by the authors to be submitted to *Ecology and Society*

And is based on:

- Varela-Ortega, C., Blanco, I., Bharwani, S., Esteve, P., Fronzek, S., Downing, T.E., (*in press*). How can irrigation agriculture adapt to climate change? Insights from the Guadiana basin in Spain. Submitted to: *Regional Environmental Change* (14/07/2013, REC-D-13-00254).
- Varela-Ortega, C., Blanco, I., Esteve, P., Bharwani, S., Downing, T.E., Juárez, E. Analyzing adaptation to climate change in the water and the agricultural sectors in the Spanish Guadiana basin. Communication presented at the European Climate Change Adaptation Conference (ECCA) 2013. Hamburg, Germany. 18 – 20 March 2013.
- 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.

Chapter 5: A regional view on future water scarcity: water, agriculture and climate change in Mediterranean countries

This chapter provides an up-scaled vision of water resources management challenges in the Mediterranean region. Based on the use of an econometric model, the chapter identifies the main drivers for water use and explores future projections in Mediterranean countries using different socio-economic and climate change scenarios. Then, using two country case studies in Spain and Jordan, the combination of an agro-economic model and a water management model serves for the analysis of the effects of specific policies on water use and water scarcity.

This chapter gave rise to:

- Esteve, P., Varela-Ortega, C. A regional view on future water scarcity: water, agriculture and climate change in Mediterranean countries. Under review by the authors to be submitted to: *Water Resources Management*

A preliminary presentation of the methods and results is included in:

- Varela-Ortega, C., Blanco, I., Esteve, P. Socio-economic and climate change scenarios in Southern and Eastern Mediterranean countries: adaptation pathways for the water sector. Under review by the authors to be submitted to a journal.
- Varela-Ortega, C., Esteve, P., Blanco, I., Carmona, G., Ruiz, J., Rabah, T., 2013. Assessment of Socio-Economic and Climate Change Effects on Water Resources and Agriculture in Southern and Eastern Mediterranean countries. MEDPRO Technical Report No. 28/March 2013. MEDPRO Project.

Chapter 6. Conclusions

Chapter 6 presents the main conclusions obtained in this doctoral research. It also includes recommendations, reviews the main limitation of the methods and results presented and shows potential future lines of research.

2. Towards sustainable water management in agriculture: assessing farmers' vulnerability in a water scarce river basin

This chapter is the first step of the integrated analysis presented in this research. It presents a farm level vulnerability assessment based on the analysis of water conservation policy impacts and provides improved understanding on key elements that determine farm adaptive capacity and sensitivity.

2.1 Abstract

Water resources management constitutes a difficult challenge in water scarce regions that depend largely on irrigation development. Nature's protection is now a requirement for water management, which may result in less water being available for agricultural production. This fact puts policy-makers in need of improved knowledge on potential water policy impacts and the derived vulnerability of farm holdings.

In this context, this chapter aims at analysing the economic impacts of a water conservation policy intended to reduce water consumption in the water-scarce Guadiana basin in Spain, and at assessing farmers' vulnerability under the application of the mentioned policy. For this, we use a two-stage modelling approach. Firstly, and economic mathematical programming model is used to explore water policy impact at farm level, focusing on income losses. Secondly, an econometric model is used to analyse the key drivers of farmers' vulnerability.

This study demonstrates that water policy impacts at local level would depend on local contexts and specifically on farm characteristics, mainly on irrigation technology. Traditional farms are the most vulnerable ones. Tariffs and quotas can achieve equivalent water savings, but tariffs produce less negative impacts on farms with modern irrigation systems. The results of the econometric model reinforce those results and confirm that besides irrigation technology, farm management determines farmers' vulnerability. Full-time farmers and farms

with a high proportion of seasonal workers would face lower income losses than their counterparts due to their greater flexibility and capacity to adapt to changing conditions.

In sum, this study provides a useful framework for vulnerability assessment and supports policy-making helping to identify most vulnerable farms and improving knowledge on the likely impact of water management decisions on agricultural holdings. Thus, it contributes to a better planning and development of water policies.

Key Words: econometric model, farm income, irrigation, mathematical programming model, vulnerability, water policy.

2.2 Introduction: Context and objective

In many arid and semi-arid regions of the world, increasing water scarcity threatens economic activities and social welfare. This situation is likely to worsen due to climate change and in light of increasing competition between the economic and environmental uses of water. The dual challenge of the conservation of water ecosystems together with the satisfaction of human demands (Postel, 2000; Vörösmarty et al., 2010) is requiring the diversion of larger volumes of water for nature's protection.

Since agriculture is the main water-consuming sector in many arid countries, water policy is a matter of high relevance in rural areas where irrigation agriculture is the main production activity. The use of water for irrigation establishes a fragile equilibrium between ecosystem maintenance and economic development, an equilibrium that is often vulnerable to change (Downing et al. 2006). Thus, water management constitutes a difficult task for the water authority, as it affects a fragile and vulnerable balance and influences social, economic, environmental and institutional interactions.

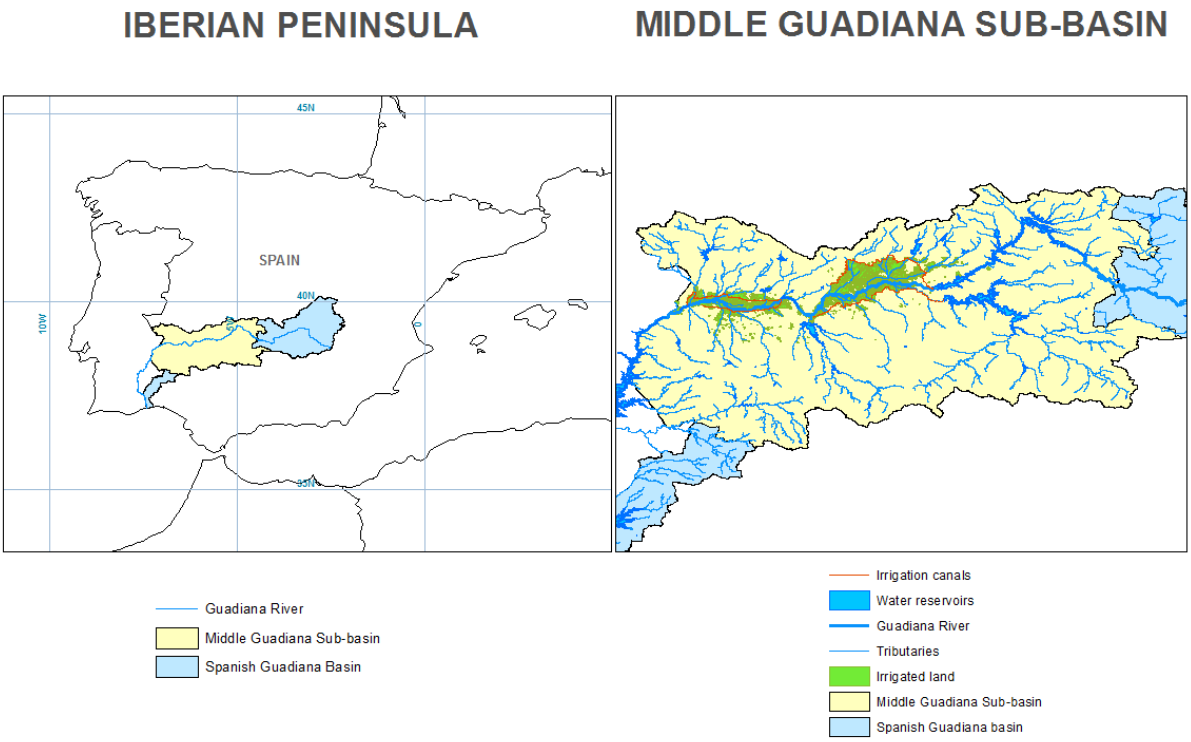
Currently, water and agricultural policies demand a more environment-oriented production in many parts of the World. Specifically, in the EU both types of policies are gradually converging to common goals of nature protection (EU Sustainable Development Strategy, EC, 2009). The latest proposal of the Common Agricultural Policy (CAP) on-going reform specifically targets water management as one of the main challenges for agriculture in the EU (EC, 2011a, 2011b) and the last policy agreement reached (EC, 2013b) specifies the incorporation of the EU Water Framework Directive (WFD) (EC, 2000) within the Statutory Management Requirements of the water and agricultural sectors, and the European Water Scarcity and Drought Policy (EC, 2012c) demands an effective and more quantity-oriented implementation of the WFD promoting a more efficient water use in agriculture using economic incentives.

However, policy impacts are not uniformly distributed and are likely to diverge across different types of farms. In consequence, there is a need to determine different vulnerability profiles that represent distinct vulnerable situations to a given impact (Downing and Bharwani, 2006; Downing and Ludeke, 2002). Then, in the context of the EU water policy, vulnerability assessment is key for the implementation of the WFD. It can inform policy-makers on the likely impact of such policy, and eventually on its potential success or failure when downscaled to local contexts (Varela-Ortega, 2011).

In irrigation areas that consume large amounts of water and where irrigation systems are technically inefficient, implementing water-conserving policies may be a difficult task. This is more acute in water scarce regions. The Middle Guadiana basin in Spain (Figure 3) is an illustrative example of such a problem and exemplifies what water authorities might face to respond to the mandate of the EU WFD. In this basin, irrigation agriculture consumes around 90% of total renewable water resources. Low irrigation technical efficiency and the lack of incentives to reduce water abstractions produce large amounts of water being withdrawn with high water losses. This may hinder the implementation of water conservation policies without inflicting substantial losses to agriculture and without generating a great opposition by the affected farmers.

Located in the province of Badajoz (south-western Spain), the Middle Guadiana basin comprises around 140,000 hectares of irrigated land, devoted to annual herbaceous crops (75%), fruit trees (11%), olive trees (9%) and vineyards (4%) (INE, 2009). The Guadiana river basin has an storage capacity of 8000 Mm^3 developed largely by a public-funded development plan along the 50's and 60's, the so-called Plan Badajoz. This plan fostered socio-economic development through the establishment of irrigation districts, the construction of dams and irrigation canals, and the application of rural development policies. Although in past decades farmers faced severe drought periods, large hydraulic infrastructures in the area have reduced vulnerability to drought (Estrela and Rodríguez, 2008; Krysanova et al., 2010). For this reason, consciousness among users about water scarcity is low.

Figure 3. The Middle Guadiana basin



Source: own elaboration

However, the application of the EU WFD, together with climate-related uncertainties, poses important challenges to Middle Guadiana water managers and users. Within the WFD main goals, good ecological status of water bodies, cost recovery of water services and the application of water pricing, seem difficult to achieve. For EU water scarce southern countries, compliance with this quality-driven directive, which only considers quantity as an ancillary element of water quality (EC, 2000), constitutes a challenging task. The need to respect environmental flows and protect water ecosystems as established by the WFD may entail the reduction of current irrigation water allotments in the basin (7500 m3/ha, or 6600 m3/ha for farmers withdrawing water directly from the river). In fact, the Guadiana basin authority has considered lowering water allotments by 10% to 30% in order to satisfy environmental requirements (Rodríguez-Cabello, 2009), but these have not been fully specified in the recently enacted Guadiana River Basin Management Plan (CHG, 2013a). On the other hand, the use of economic instruments for water demand management, such as water tariffs, also considered in the WFD, may offer an alternative approach for achieving similar water savings than the water quotas system. However, this option has not been sufficiently explored in this basin.

In this context, the purpose of this research is to analyse the effect that the implementation of the above mentioned policy, instrumented by two alternative measures (quotas and tariffs), may produce on irrigation farming in the Middle Guadiana basin, focusing on farmers' vulnerability. Based on the combination of a Mathematical Programming Model (MPM) and an econometric model, the chapter analyses the impacts and vulnerability of farmers under the implementation of a water policy that seeks to reduce water consumption for irrigation. The research focuses, first, on the assessment of economic impacts at farm level. Then, using the results on farm income losses, the chapter explores the key drivers of farmers' vulnerability and vulnerability profiles in the Middle Guadiana.

This way, this research tries to address questions relevant to decision makers such as how will a given water policy affect farmers and, in particular, how will farmers cope and respond to constraints to water use.

2.3 The approach to impact and vulnerability assessment

In this research, we look at the impacts of water policies at farm level and to farmers' vulnerability to the derived impacts of nature- and policy-driven water scarcity.

Vulnerability analysis aims to assess the vulnerability of different farms and improve our understanding of the structural, agricultural, technical and socio-economic elements contributing to this vulnerability.

The concept of vulnerability raises deep discussions in scientific literature with respect to its definition, its assessment and the elements that compose it. Consistent with the varied conceptualisations of vulnerability, there are also numerous assessment methods. It is a concept used in many different disciplines, with different purposes and under very different premises, but most times definitions of the concepts, drivers and assessment methods are vague (Hinkel, 2010).

Füssel (2007) lists the main approaches to vulnerability research including the risk-hazard approach, the political economy approach, the pressure-release model, the integrated approaches and the resilience approach. From a general perspective, this classification responds to different study focus. For example, the risk-hazard approach focuses on the assessment of the risk faced by peoples or infrastructures, determined by the hazard considered and the vulnerability of the exposure unit. The political economy approach focuses on the identification of most vulnerable people and the elements that determine that vulnerability, from a socio-economic perspective.

This research follows and integrated approach in which we assess farmers' vulnerability using economic indicators (economic losses) and then analyse the different structural, social and technical elements that determine vulnerability. The analysis performs at a micro scale and in a small region, and then we assume that all farms are under similar exposure characteristics: the same natural conditions and the same institutional and policy setting. Therefore, if we consider vulnerability as a function of exposure, sensitivity and adaptive capacity (Füssel, 2007; Smit and Wandel, 2006; among many others), differences in vulnerability here are driven by different sensitivity and different adaptive capacity, which depend on specific characteristics of the different types of farms.

According to Brooks et al. (2005), when different systems experience similar hazards, which in this case are water scarcity and the same water conservation policy, the difference in the outcome responds only to the differences in vulnerability across the systems. It means, in this case, that under similar natural conditions and under the same water policy, the different impact of restricted use of water on farm income is just a consequence of the different vulnerability. Then, vulnerability is measured here by the degree to which a given farm experiences a negative economic impact in a situation of water scarcity and restrictive water policies. In this chapter we use an economic indicator, farm income loss, as an outcome variable that allow for comparison among farms, as other studies do using economic related variables such as income or consumption, or yields, as outcome indicators of vulnerability (see Échevin, 2013; Gallai et al., 2009; Luers et al. 2003; and others).

Among the different methods available for analysing impacts and vulnerability at farm level, we propose the combination of MPM and an econometric model.

MPM is a tool that permits to simulate farmers' decision-making when the different policy options under study are implemented, assuming that farmers are rational individuals that try to maximise their welfare. Optimization MPMs have proven to be useful for analysing the effects and suitability of agricultural policies and water allocation and pricing policies. They have been applied in many international studies (Bartolini et al., 2007; Bazzani et al., 2005; He et al., 2006; Tsur et al., 2004) as well as in the context of Spanish water and agricultural policies (Berbel and Gómez-Limón, 2000; Blanco-Gutiérrez et al., 2011; Iglesias and Blanco, 2008; Varela-Ortega et al., 1998, 2011; among others). Frequently based on the use of farm types, these models allow simulating economic agents' decision making subjected to constraints of different types, based on technical, economic, environmental and policy variables and making assumptions on the decision-makers' goals.

On the other hand, empirical studies, such as statistical and econometric assessment, based on real observations, allow for considering the full range of situations and take into account social, institutional or structural elements that may be relevant for vulnerability and that are difficult to include in normative models. Moreover, for the analysis of vulnerability it is important to consider all types of real situations including marginal types of farms that are often more vulnerable than others. For these reasons, statistical and econometric methods have been frequently used in the study of vulnerability (Brooks et al., 2005; Cutter et al., 2003; Rygel et al., 2006; Wood et al., 2010; Yohe and Tol, 2002). Using statistical and econometric models, however, limits the scope of the study to past or present events and observations. Cross-sectional datasets, being very often the only source of information, may be problematic for measuring vulnerability because of the absence of information for more than one time step (pre- and post- hazard occurrence) (Hoddinott and Quisumbing, 2008).

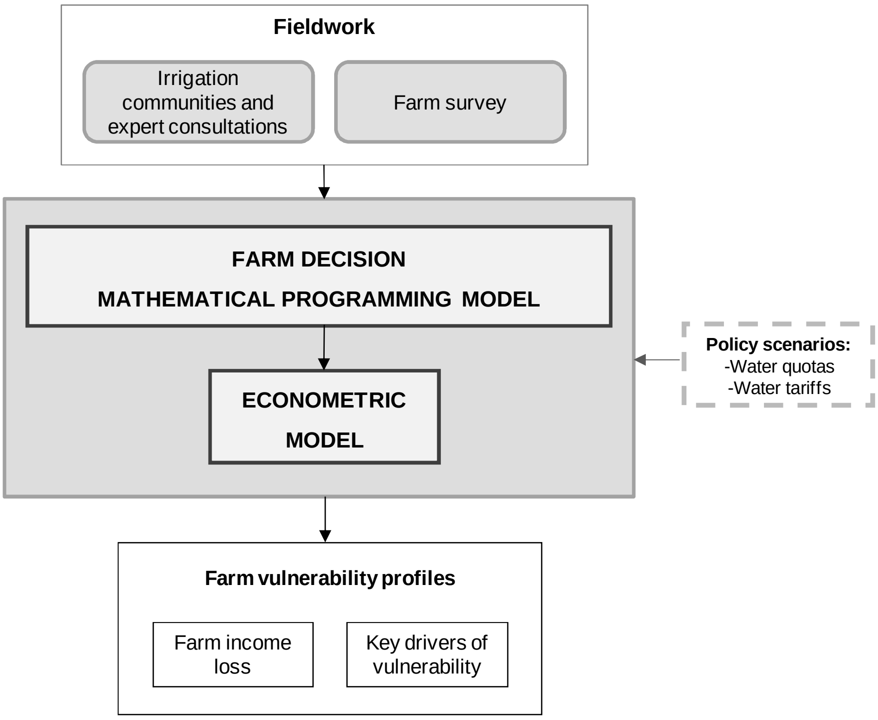
Optimisation MPM and econometric models have been combined in previous studies (e.g. Buongiorno (1996) for analysing forest products market; Antle et al. (2006) for explaining soil degradation in agricultural systems in Peru). However, in vulnerability literature, this type of combination has not been explored. In this research, we attempt to profit from the strengths of both types of methods, MPM and econometric models, for the analysis of vulnerability. This way, we can incorporate behavioural information of farmers' responses (as suggested by Buysse et al. 2007), and we can complement the econometric analysis, normally based on past behaviour, with information on adaptation to new economic or institutional conditions provided by the MPM.

2.4 Methodology

To attain the proposed objectives we developed a two-stage modelling approach (Figure 4), based on the above-explained combination of a MPM and an econometric model.

The MPM is a non-linear farm-based model of constrained optimization that simulates farmers' responses to the application of the EU water-conserving policy (in the form of quotas and tariffs), by adapting cropping patterns and farm income. Using the results of the MPM on farm income loss, we use an econometric model to identify the main elements that determine vulnerability at farm level.

Figure 4. Methodological scheme



The study is carried out in two selected irrigation communities (IC) that represent two opposite types of water management and technologies: "Tomas Directas del Guadiana" (TD), a modern IC that comprises around 20,000 ha, with pressurized irrigation systems in which farms, located all along the river, take water directly from the natural water course, and "Montijo" (MON), a traditional IC of around 10,500 ha, in which water comes from the Montijo water canal.

The scenarios simulated correspond to two alternative instruments of water policy, water quotas and tariffs, aiming at lowering water consumption. For each instrument, we simulate two levels of reduction in water use:

- Water quotas: a) 10% reduction of water allotment; b) 30% reduction of water allotment, as considered by the RBA.
- Water tariffs: a) tariff that achieves a 10% reduction in water consumption; b) tariff that achieves a 30% reduction in water consumption.

2.4.1 Model specification

2.4.1.1 Farm decision MPM

The MPM developed in the first stage of this research, builds upon previous work by Esteve (2007). It is a single-period, non-linear model of optimisation subjected to technical, structural and policy constraints. The model considers that farmers behave as rational individuals that try to maximize their utility. However, expected utility is likely to decrease because of the existence of natural and market risks. Thus, farmer's utility (Equation I) is defined by the farm's gross margin (Z) and a risk component, in which φ is a coefficient that represents farmer's risk aversion and *σ(Z)* is the standard deviation of the farm's gross margin due to climate variability (affecting yields) and market variability (affecting prices). This risk component, and particularly farmers' risk aversion, is used for the model calibration (Hazell and Norton, 1986). Equation II show the estimation of farm's gross margin (Z).

Equation I: Objective function

$$MaxU = Z - \varphi \cdot \sigma(Z)$$

Where: *U: expected utility*; *Z*: farm gross margin; φ : risk aversion coefficient; $\sigma(Z)$: standard deviation of income distribution.

Equation II: Farm gross margin

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

Where: *Z*: Farm gross margin; $gm_{c,r}$: gross margin per crop (*c*) and technique (*r*); $X_{c,r}$: Production area per crop (*c*) and technique (*r*), and decision variable in the model; $Sb_{c,r}$: CAP coupled subsidies per crop (*c*) and technique (*r*); *Sfp:* CAP single farm payment; *Mdu:* CAP modulation rate; *fco:* family labour opportunity cost; $flab_p$: Family labour availability per period of the year (p); *hlw*: hired labour wage (€/h); $hlab_p$: hired labour per period (p); wpm^3: volumetric water price; *WC*: farm water consumption; *wpha*: irrigation water fee paid per hectare; *sirrg*: irrigated area in the farm.

Cropping area is constrained by total farm land area (*surf*) (Equation III), and labour use is constrained to available family labour (*flab*) plus hired labour (*hlab*) per period (*p*) (Equation IV).

Equation III: $$\sum_{c,r} X_{c,r} \leq surf$$

Equation IV: $$\sum_{c,r} labreq_{c,r,p} \cdot X_{c,r} \leq flab_p + hlab_p$$

The key constraint in the model is the water use limitation, represented by Equation V, as water is the main limiting factor and is the driver of the simulation scenarios. Other relevant constraints in the model are CAP cropping permits and set aside requirements.

Equation V: Water availability constraint

$$\sum_{c} wreq_{c,ri} \cdot X_{c,ri} \leq sirrg \cdot wavail \cdot H$$

Where: $wreq_{c,ri}$: water requirements per crop (*c*) and irrigation technique (*ri*) (includes the technical efficiency of the irrigation method); *wavail*: water allotment per hectare; *H*: efficiency of the water conveyance system.

Fieldwork, public statistics and previous research (Blanco-Gutiérrez et al., 2013; Varela-Ortega et al., 2009) provided the technical coefficients of the model. But this research is a step further in the analysis by focusing on a large set of real farms instead of using a limited representation of farm types. This allows to capture the vulnerability of real farming systems. In the area of study, a farm database was built containing information of 60 real farms from the two irrigation communities included in the study. Real farms have been clustered into five groups according to their characteristics with respect to farm size, productive orientation and technology, within which response to risk is assumed similar.

The main outputs of the MPM are the impact on farm income, water consumption and optimal crop choice. How farmers adjust their cropping patterns, how they switch from some irrigation techniques or cropping strategies to others, or what water price they are willing to pay before changing their activities, give us good insights on farmers' willingness and capability to adapt.

2.4.1.2 Econometric model

As explained above, statistic and econometric assessments have proven to be useful for vulnerability studies. Here, we follow an econometric approach using an Ordinary Least Squares (OLS) regression model. Farm income loss is the dependent variable in the model. It measures the outcome of the instruments of water policy analysed and it is used as proxy for farmers' vulnerability. Then, the econometric analysis allows for identifying key elements of farmers' economic activity that determine their vulnerability, such as what are the most profiting crops, whether having other economic activities may reduce their sensitivity and what are the key institutional and social elements which affect them.

For this analysis, we use a real farm database obtained through a survey (Annex A) that included the completion of questionnaires containing information on 46 agronomic, technical, structural, economic and social variables. Independent variables were selected according to fieldwork, stakeholder consultations, and literature about determinants of farm income (De Janvry and Sadoulet, 2001; Rao and Qaim, 2011; Safa, 2005), vulnerability and adaptation at farm level (Adger, 1999; Apata et al., 2009; Glewwe and Hall, 1998; Jalan and Ravallion, 1999; Notenbaert et al., 2013; O'Brien et al., 2004; Reidsma et al., 2010). These variables include socio-economic, structural and technical variables such as age, education, household size, access to credit, farm size technical assistance, irrigation and rain-fed area, labour use, crop types and crop production techniques, among others.

The general form of the estimated models is:

Equation (VI)

$$Inc\_loss_i = \alpha + \beta^{st} \cdot Str_i + \beta^{s} \cdot Soc_i + \beta^{a} \cdot Agric_i + \beta^{t} \cdot Tech_i + \varepsilon_i$$

Where: Inc_loss_i: Income loss in farm *i* (%)

Str_i: Vector of structural variables for the observation *i*

Soc_i: Vector of social variables for the observation *i*

$Agric_i$: Vector of agricultural variables for the observation *i*

$Tech_i$: Vector of technological variables for the observation *i*

In this vulnerability analysis based on income loss, we use the MPM results of two out of four scenarios: the 30% decrease in water quota and the tariff that achieves an equivalent 30% reduction in water consumption. Thus, we generate two families of models: one for income losses driven by water quotas and one for income losses driven by water tariffs.

2.5 Results and discussion

This section presents and discusses the main results obtained in this research. We will look, first, at the impacts of water quotas and tariffs on farm income that will permit us to compare different farms with different structural and agricultural conditions. Second, we will reflect on farms' economic vulnerability, looking at the key drivers of farm's income loss, and we will identify vulnerability profiles in the Middle Guadiana according to those drivers.

2.5.1 Water policy impacts

Water policy simulation is carried out, as explained above, on each farm in the database. However, five farms were selected, one farm per cluster, to determine risk aversion. Analysis of water policy impacts is based on those five farms. Table 5 shows the characteristics of selected farms, three from Tomas Directas IC and two from Montijo IC.

Table 5. Farms selected for the economic analysis.

Farm Type	IC	Municipality	Size (ha)	Crops	Risk aversion
F1 – TD	Tomas Directas (modern)	Badajoz	90	maize (30 ha), tomato (40 ha), olive (20 ha)	1.05
F2 – TD		Guareña	20	rice (20 ha)	1.4
F3 – TD		Mérida	45	peach (30 ha), plum (15 ha)	0.5
F4 – MON	Montijo (traditional)	Montijo	50	wheat (10 ha), maize (20 ha), tomato (12ha), peach (8 ha)	1.35
F5 – MON		Puebla de Alcocer	10	maize (4 ha), tomato (6 ha)	1.3

The scenarios simulated, as explained above, correspond to water quotas and tariffs. The water quota system applied in the area grants equivalent water allotments to all users, and builds upon the current water allotments by decreasing them by 10% or 30%. Then, we simulated a water tariff system intended to achieve similar water savings, but increasing, at the same time, water use efficiency. The selected level of tariff for each scenario is calculated by simulating increasing water tariffs in the different farms. Then, we selected a certain tariff level for each IC so that the total water consumption in the IC decreases by the desired amount. Nonetheless, when water tariffs are implemented, water consumption will be different across farms in the same IC because each farm presents different behaviour and capacity to adapt according to their different characteristics (see water demand curves in Figure 5).

Table 6 shows the impacts of the water instruments simulated on farm income (€/ha) and on water consumption (m3/ha). Numbers in brackets show the percentage change with respect to the reference scenario.

In aggregated terms, we can see that the quota system affects both ICs in a very similar way, having 2% and 4% income loss with the 10% quota reduction in Tomas Directas and in Montijo IC respectively, and 7% and 10% income loss with the 30% quota decrease. However, this does not happen when we look at the tariff system. The tariff system is much more harmful for old irrigation systems (Montijo IC), which face 24% and 25% income losses under the two tariff levels simulated, than for modern systems (Tomas Directas IC) which are already better adapted to water scarcity conditions and have modern and efficient technologies available. These modern farms face 8% and 13% income losses for the two water price levels tested respectively, evidencing a large difference between the pressurized irrigation-based Tomas Directas IC and the non-modern gravity-based Montijo IC. As other studies show (Tanaka et al. 2006), these farms are better able to afford paying higher water prices than other farms with lower economic efficiency, and do not need to switch to rain fed production.

Table 6. Water policy impacts on farm income and water consumption

		Water Policy Scenario				
		REF	Quota -10%	Tariff -10%	Quota -30%	Tariff -30%
Tomas Directas IC (modern)	Income (€/ha)	2653	2601 (-2%)	2440 (-8%)	2474 (-7%)	2317 (-13%)
	Consumption (m3/ha)	7557	5417 (-28%)	5572 (-26%)	4377 (-42%)	4429 (-41%)
Montijo IC (traditional)	Income (€/ha)	1958	1875 (-4%)	1490 (-24%)	1764 (-10%)	1478 (-25%)
	Consumption (m3/ha)	8153	6732 (-17%)	7134 (-13%)	5236 (-36%)	4905 (-40%)
F1-TD (large, modern)	Farm income (€/ha)	2275	2275 (0%)	2083 (-8%)	2112 (-7%)	1973 (-13%)
	Consumption (m3/ha)	5851	5851 (0%)	5844 (0%)	4606 (-21%)	5839 (0%)
F2-TD (small-medium, rice farm)	Income (€/ha)	1240	1046 (-16%)	844 (-32%)	988 (-20%)	734 (-41%)
	Consumption (m3/ha)	13846	5922 (-57%)	6511 (-53%)	4606 (-67%)	2287 (-83%)
F3-TD (medium-large, modern, fruit trees)	Income (€/ha)	5928	5928 (0%)	5811 (-2%)	5928 (0%)	5744 (-3%)
	Consumption (m3/ha)	3333	3333 (0%)	3333 (0%)	3333 (0%)	3333 (0%)
F4-MON (medium-large, traditional)	Income (€/ha)	2102	2072 (-1%)	1688 (-20%)	1980 (-6%)	1675 (-20%)
	Consumption (m3/ha)	7216	6732 (-7%)	7289 (+1%)	5236 (-27%)	4356 (-40%)
F5-MON (small, traditional)	Income (€/ha)	1501	1250 (-17%)	863 (-42%)	1080 (-28%)	857 (-43%)
	Consumption (m3/ha)	11122	6732 (-39%)	6641 (-40%)	5236 (-53%)	6641 (-40%)

In the traditional Montijo IC, the tariffs that would achieve the intended 10% and 30% reductions in water consumption are almost equal (0.057 and 0.058 €/m^3, respectively). This means that in this IC farmers do not change their water consumption until the price reaches a rather high certain level, an "exit price" (Massarutto (2003), in Berbel et al. (2007)), that sharply decreases water consumption and produces a switch to rain fed production (see Figure 5).

The proposed tariff levels in Montijo IC cause severe income losses to the affected farmers, and, therefore, there would be likely difficulties for the implementation of such a policy. The main reason for such negative impacts relates to the lack of modern irrigation technologies in the farms and in the IC because of not having adequate infrastructures and not having accomplished the appropriate investments for that. Blanco-Gutiérrez et al. (2011), Johansson et al. (2002), and Varela-Ortega et al. (1998), among others, have also stressed the relevance of the link between the effectiveness of water pricing policies and irrigation technology.

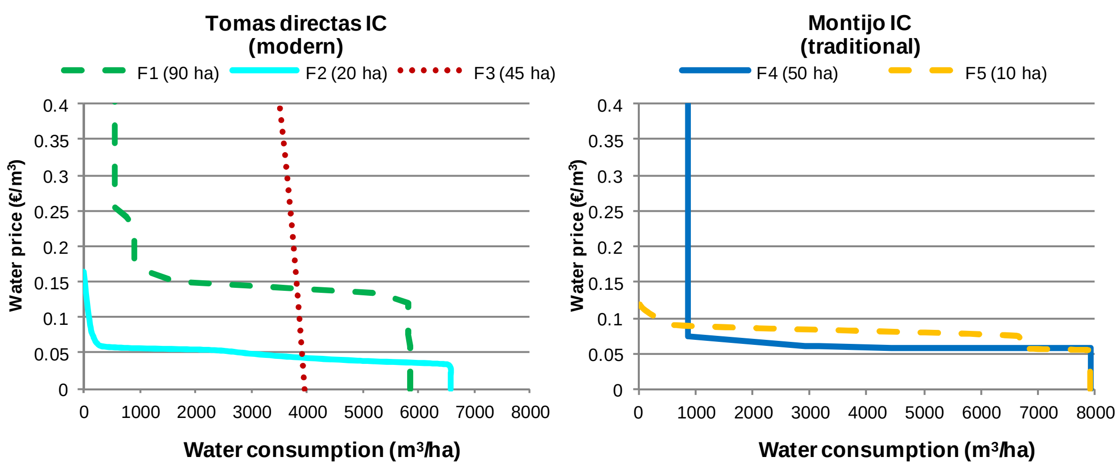
Results at farm level show similar patterns but permit to identify the effect of different elements in farm vulnerability. A 10% decrease of water quotas already affects small farms significantly as compared to the almost null impact in other farms. This may be a consequence of farm size and cropping activities in the reference scenario. Farms F2 and F5 consume large amounts of water in the current situation, so that makes them especially vulnerable not only when water allotments are reduced but also when compliance with current water quotas is controlled. When the 10% quota reduction applies, both farms must reduce their water consumption by around 40-50% to comply with the policy. Farm F2 grows rice in the reference scenario. Being in a modern IC (Tomas Directas), it can adapt to more water-efficient crops and techniques but it implies large economic losses, the substitution of rice cultivation by maize and tomato and the increase in rain fed area. Farm F5 follows a similar path but, in this case, the lack of available modern irrigation techniques drives a much larger increase in rain fed area and the sharp reduction of maize growing.

The impact of tariffs reflects again that the smallest and non-modern farms of both ICs, F2 and F5, experience the most severe income losses, coinciding with most studies on the impacts of water pricing on irrigation under the WFD (Berbel et al., 2007). For these two farms and for F4, also from Montijo IC (the traditional one), the impact of the tariff system is much higher than in the case of the quotas. In fact, farms F4 and F5 from Montijo IC experience income losses of 20% and 42% respectively for an overall water saving of 10% in the irrigation community under this tariff. In general, most authors coincide in the fact that the impacts of water tariffs at farm level depends extremely on the type of farm and on elements apart from the specific price level, such as technology and type of management. Garrido and Calatrava (2009) envisage income losses between 10% and 50% for price increase between 0.03€/m^3 and 0.10 €/m^3, depending on farming characteristics. Other studies (Berbel and Gomez-Limon, 2000; Chohin-Kuper et al., 2003; Varela-Ortega et al.,1998), evidence that in small and low-technology farms such as F2 and F5, income loss driven by a restrictive water tariff is often more than proportional to the reduction in water consumption.

Old irrigation systems prevent more water-efficient production. The lack of adequate irrigation systems in the traditional Montijo IC is difficult to solve because the water conveyance systems do not allow for pressurizing water distribution unless important reforms and investments are accomplished. This fact causes important economic damage to farms under the implementation of the water policy considered here, especially in the case of the application of water tariffs.

Water demand curves (Figure 5) illustrate how the different farms adapt their water consumption (through adaptation of cropping patterns and technology use) when water prices increase. Water demand curves are usually inelastic at low price ranges (Berbel et al., 2007; Blanco-Gutiérrez et al., 2011; De Fraiture and Perry, 2007; Gómez-Limón and Riesgo, 2004). It means there is a threshold price under which water consumption remains constant. If this threshold is too high, the tariff level that achieves the desired reduction in water consumption will drive important economic losses.

Figure 5. Water demand curves at farm level



Farms in Montijo IC and farm F2 from the modern Tomas Directas IC show, first, a short inelastic section, and then, above a price of 5€ cents/m^3, a sharp reduction of water consumption. The lack of modern irrigation techniques in those farms makes it impossible or very costly (in the case of F2) to adapt by switching to more efficient irrigation techniques. Modulation of water consumption through tariffs in this kind of farms is not possible because the lack of modern technologies limits adaptation capacity and leaves no room for gradual adjustments. The only option for these farms is to switch to rain-fed production.

Modern farms, F1 and F3 in Tomas Directas IC, show a higher adaptive capacity and they can still irrigate their crops by changing crop mixes and switching to efficient techniques. The first inelastic section in these farms is longer than in the non-modern farms, reflecting a greater water productivity (in terms of €/m^3) that makes still profitable to maintain similar levels of water consumption up to higher water prices.

In sum, three aspects seem to be relevant for the impact and success (or failure) of the water policy instruments considered: 1) technology adoption, 2) farm size and 3) initial cropping activities (that determine initial water consumption) and structure. At the farm level, we see that the smallest farms (F2 and F5), that are the ones that consume most water (above the legally permitted level) and the most traditional ones (i.e. with old irrigation systems) (F4 and F5) face the greatest income losses. This may have great implications for policy development.

2.5.2 Results of the econometric model: vulnerability drivers and profiles

As explained above, the aim of the econometric assessment was to identify key determinants of farmers' vulnerability and to represent vulnerability profiles in the Middle Guadiana. Among the different dimensions of vulnerability, we will be looking at economic vulnerability, represented by income loss experienced by farmers under the already analysed policy instruments.

2.5.2.1 Key determinants of farmers' vulnerability

Table 7 shows the results of the two families of models estimated (for income losses driven by water quotas and driven by water tariffs). For each family, two models are shown which include different sets of variables.

Table 7. Results of the estimated models for income loss and income per hectare

		Income loss – Water quota		**Income loss –Water tariff**	
Var_name	Description	(1)	(2)	(3)	(4)
R^2		0.76	0.70	0.78	0.69
dummy_ic	Irrigation community (1=TD)	**-8.44*** **	**-6.06*** **	**-29.58*** **	**-28.65*** **
dummy_atp	type of farmer (1=full time farmer)	0.54		**-43.20*** **	**-27.89*** **
dummy_corp	farm is legally constituted as a corporation	1.5		0.07	
Rent	percentage of rented land in the farm	**-0.04* **	**-0.05*** **	0.10**	
Age	farmer's age	-1.25E-03		-0.35	
dummy_tech_assist	Farmer receives technical assistance	-1.72		-5.25	
dummy_coop	the farmer is integrated in a cooperative firm	-2.17		-5.07	
Size	farm size (in hectares)	0.01		**0.16* **	**0.22*** **
fam_lab	family labour employed in the farm (num)	-0.29		-0.25	
perm_lab	permanent hired workers (num)	1.58		4.85	
season_lab_j	seasonal labour hired in the farm (working days)	-2.05E-03		**-0.01* **	**-0.01** **
dummy_insur	1= farmer has insurance	-0.18		-3.13	
dummy_credit	1=access to credit	0.43		1.3	
Press	percentage of irrigated land with pressurized irrigation systems	-0.01		**-0.15*** **	**-0.11** **
Perm	percentage of farmland under permanent crops	**-0.22*** **	**-0.23*** **	-0.17*	-0.22**
Crop_divers	Number of different crops	0.44		2.89	
Wconsumption	Total water consumption in the reference scenario	3.56E-04		**2.54E-3** **	**1.63E-3* **
_constant		23.72	24.1	99.92	70.88

**90% significance level; ** 95% significance level; ***99% significance level*

Looking at the models for income loss with water quota (1 and 2), three variables appear as the most relevant and only significant: the irrigation community (*dummy_ic*), the share of land rented (*rent*) and the share of permanent crops in the farm (*perm*). In fact, those three variables account for 70% of income loss variation. However, in the case of income losses under water tariffs (3 and 4), there are more significant elements than in the case of water quotas. Six main variables explain 70% of income variation, and they largely differ from those in the quota system. The only variable that results significant in both families of models is the irrigation community (*dummy_ic*).

The negative sign of *dummy_ic* coefficient indicates that farms in Tomas Directas IC (the modern one) experience lower income losses under the two policies considered, than farms in Montijo IC (the traditional one). This coincides with the results of the economic MPM analysis at the IC level shown in section 2.5.1. Tomas Directas is an irrigation community in which water is pumped directly from the river to the farms and, thus, farmers can use modern pressurised irrigation techniques. In addition, this irrigation community controls cropping patterns and water consumption in the farms, incentivising compliance with water allotments and water efficient crops and technologies.

In the case of water quotas, the negative sign in *rent* and *perm* coefficients indicate that farms with high share of rented land or with high share of permanent crops experience lower income losses. This result is not surprising as farmers that pay a land rent bear an additional variable cost and, therefore, should reach higher land productivities. On the other hand, permanent crops are usually associated to low adaptation capacity and high vulnerability to drought, mainly because of the multi-annual character of investments that makes it difficult to change to other crops when adverse conditions. However, this type of production has low water requirements and is highly productive and profitable in this area, where the combination of modern irrigation technology, water availability and soil and climate conditions make these crops (mainly fruit trees and olives) especially suitable. Thus, having adequate technologies and a very low water consumption, farms with permanent crops suffer softer impacts from quota reduction.

However, the share of permanent crop area is not so strongly significant for the impact of water tariffs. Instead, but also related to the low water demand of permanent crops, water consumption in the reference scenarios (*Wconsumption*), i.e. before policy implementation, is necessarily a significant variable that affects income losses under water tariffs, as either lowering consumption or consuming the same amount but at a higher cost will lead to lower income achieved. In addition, seasonal labour, related to high value added crops such as fruits and some horticultural crops, comes out as significant variable linked to lower income loss.

The significant variables that determine income losses driven by water tariffs relate largely to adaptation processes. Pressurised irrigation systems, as explained in section 2.5.1, play a key role in farm capacity to adapt to water constraining policies, minimising the negative impacts of such policies. Also, seasonal labour is more easily adjusted and implies greater flexibility in the farm management.

Farm size is a significant variable for income losses driven by water tariffs. It has a positive coefficient, indicating that big farms experience greater income losses than small farms. Large farms are often less intensive than small farms, and this would normally lead to a lower water productivity (€/m^3), leaving a smaller margin for paying per cubic meter of water. This is also linked to the potential existence of diseconomies of scale widely discussed in economic literature. Sadoulet and De Janvry (1995) explain that in highly technified farming systems labour productivity can decrease as farm size increases. Many times, farm size increase leads to lower efficiency and a reversion of economies of scale. This is largely due to an increase in transaction costs driven by the higher employment of hired labour (De Janvry, 1988). Also in relation to hired labour, Deininger and Byerlee (2012) argue that family labour will be more flexible, will have greater incentives and will be more productive, than employees that require costly supervision.

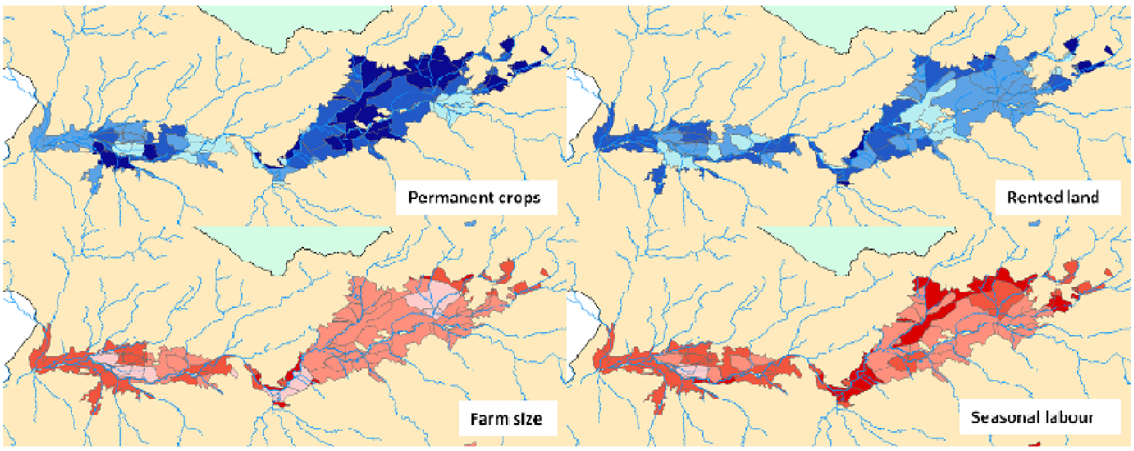
Finally, the type of farmer comes out as a relevant variable, as those farms in which the owner is a full-time farmer, experience lower income losses.

2.5.2.2 Vulnerability profiles in the Middle Guadiana

Overall, the econometric analysis of income losses under two different water policy options shows that farm vulnerability depends on diverse elements of farm structure and management. Water quotas are more equitable and homogeneous in the impacts they produce. However, water tariffs are clearly more harmful for traditional farms that present lower water use efficiency and lower adaptive capacity. This evidences the need to look at farm characteristics when selecting and designing measures for irrigation water policy. Farm characteristics will determine the potential impact of policies and the adaptation of farms to constraints in water use.

Maps in Figure 6 show the spatial distribution in the Middle Guadiana irrigation area of four of the key variables determining farm vulnerability (those for which there are available data at municipal and irrigation community level) translated into vulnerability profiles. According to the sign of the coefficient of each variable, a more intense blue colour represents higher vulnerability to water quotas, and a more intense red colour stands for higher vulnerability to water tariffs. Current data availability does not allow for building complete vulnerability profiles, but according to this preliminary representation, the upper part of the sub-basin would present a higher vulnerability to income losses driven by water policies that constrain water use. The areas coloured as the most vulnerable correspond mainly to traditional irrigation communities with poor irrigation technologies and very water intensive crops such as maize or rice.

Figure 6. Vulnerability profiles of the irrigation agricultural systems in the Middle Guadiana.



2.6 Conclusions

This research has contributed to the analysis of the effects that different water policy instruments could have on irrigation agriculture in a water-scarce basin. Making use of a novel modelling initiative, the research contributes to address several major issues of the EU WFD legislation, such as the application of water pricing, the maintenance of environmental flows and the costs incurred by specific vulnerable farms.

The chapter presents an original methodology for vulnerability assessment based on the combination of MPM and econometric modelling. Though econometric models have been extensively used in vulnerability assessments its use in combination with a MPM allows the representation of farmers' response to changes in rules of access to water resources (allotments or prices) that econometric models cannot capture.

The results of the study show that the two water policy instruments analysed affect negatively farmers' income in a different way, and highlight the important role that technology adoption plays in the outcomes and success of water policies and in general in adapting to water use limitations. Water tariffs and water quotas can achieve similar water savings, but the volumetric tariff system, produces higher income losses and is especially damaging for old and non-efficient irrigation farms. The success and legitimacy of water policies that constraint water use, especially through water tariffs, is closely related to irrigation modernisation. Therefore, implementing water tariffs would require the application of accompanying measures that support the adaptation of traditional old farms to new conditions.

The econometric model points out that farm vulnerability to water constraints depends on different variables, according to the water policy instrument selected. The negative impacts of water quotas will depend mainly on the type of crops grown in the farms, being the farms that cultivate primarily permanent crops less vulnerable than farms growing annual crops, due to their lower crop water requirements. However, the impact of water tariffs depend on different variables that relate to the farmers' flexibility and capacity to adapt. Beyond irrigation technology, variables such as the existence of part-time farming and use of seasonal labour are determinant for explaining adaptive capacity at farm level and the effects of water tariffs.

This study illustrates the existing dichotomy in the basin, where modern, competitive and profitable farms, coexist with traditional, low-efficient farms. The dichotomy found in relation to crop production and water management determines the effects of the implementation of water policy in the basin. The study identifies specific farms in which policy implementation may produce large negative impacts and that are, therefore, more vulnerable than others, and less capable to adapt to water constraints.

In sum, the results of this study demonstrate that the success of downscaling EU policies to specific regions will depend on explicit socio-economic and technical conditions that define the local contexts. This research provides an improved vision of water policy impacts and farmers' vulnerability that can contribute to water policy implementation and water management decisions across different types of farms in arid and semi-arid agricultural regions. The results of this study are policy-relevant in that they provide a better understanding about farmers' responses under the implementation of water conservation policies, in an area in which the application of such policy may have undesired socio-economic effects due to water scarcity conditions.

3. Climate change in the Middle Guadiana irrigation agriculture: a hydro-economic modelling approach for assessment of impacts and adaptation

After the farm-level analysis carried out in the previous chapter, we now include the physical dimension for studying climate change impacts and adaptation in the Middle Guadiana. This helps to improve our understanding on the interactions of crops, farms, irrigation communities and the basin. The analysis is based on the use of a hydro-economic model and a built-in crop simulation module that allows for the consideration of all relevant physical, socio-economic and decision-making levels.

3.1 Abstract

Adaptation to climate change is critical to water-scarce basins that depend on irrigation, such as the Spanish Middle Guadiana (South-western Spain). In this drought-prone basin, the large water storage capacity has permitted the development of water intensive irrigation districts. Highly technically developed irrigation communities coexist with traditional, water-inefficient irrigation communities that consume large amounts of water. However, climate change projections envisage severe reductions in water availability that may seriously affect irrigation agriculture. In this context, the aim of this research is to assess climate change impacts and to evaluate the effect of different adaptation options for water management. For this purpose, we use an integrated economic-hydrologic modelling framework that represents the bio-physical and socio-economic dimensions of vulnerability to climate change and allows for the simulation of water management decisions as well as farmers' decision-making. It also includes an agronomic module that simulates crop growth and allows for the consideration of climate change impacts on crop yields and crop water requirements. Results highlight how climate change vulnerability depends on technical characteristics, water management at the irrigation community level, spatial location and decisions in other irrigation districts. Farms located in upstream Middle Guadiana have lower water supply reliability, mainly because of the high water demand of the large rice growing areas. Traditional farms without pressurised irrigation systems face higher risks of water scarcity and bear higher costs of adaptation. Water demand management instruments have considerable potential to improve adaptation. Especially, in the case of the Spanish Middle Guadiana where awareness of water scarcity risks associated to climate change is low, economic incentives that reflect the scarcity value of water, such as water tariffs, promote more rational use in periods of water shortage and facilitate adaptation. This research contributes to the development of a better understanding of the factors affecting climate change vulnerability and adaptation by providing a more integrated view of the crop, farm, irrigation district and basin interactions that are crucial for designing and implementing adaptation strategies.

Keywords: *climate change adaptation, hydro-economic modelling, irrigation water demand, water resources management.*

3.2 Introduction and objectives

The Mediterranean region is considered a climate change “hot-spot” (Giorgi, 2006; Iglesias et al., 2011; Varela-Ortega et al., 2013), where water resources are expected to be affected in the form of increased water scarcity and frequency of floods and droughts (Arnell, 2004; Bates et al., 2008). Spain, a country characterised by a semi-arid Mediterranean climate, has a long history in dealing with water scarcity and droughts. However, climate change poses additional challenges and requires a more ambitious approach to the management of water scarcity and water supply and demand through the adaptation of human activities and economic sectors to new climatic conditions.

Climate change adaptation is perceived as one of the main global challenges for water resources management (UNEP, 2012). Agriculture, which is directly affected by changes in climate variables and is the main water-consuming sector in arid and semi-arid regions, is highly vulnerable to climate change and therefore adaptation is especially urgent. Adaptation to increased water scarcity may require the adoption of water supply as well as water demand strategies. This can include increased water storage, the use of non-conventional water sources, increased water use efficiency through technology improvements and the introduction of economic incentives. In line with this, Integrated Water Resources Management (IWRM) is an adequate framework for the implementation of adaptation processes (Bates et al., 2008) that address the multifaceted nature of climate change and water resources.

Over the last decades knowledge production on climate change has been highly fragmented. Two main streams have emerged in the study of climate change adaptation that correspond to different interpretations of climate change vulnerability: physical and economic assessments, based on natural and economic sciences, and actor-oriented social assessments based on social sciences (Downing, 2012; Wheeler et al., 2012). The first type of assessments very often focus on a specific facet, impact or sector, such as sea level rise and its implications for urban planning, heat waves and the impacts on health, etc. The social-based approaches usually consider multiple stressors and focus on the dynamic nature of vulnerability.

Most agriculture-focused studies are based on the physical-economic approach. Some examples are Moriondo et al. (2010), Tubiello et al. (2000) or Ventrella et al. (2012) that use crop models to assess climate change impacts on crop growth and simulate adaptation measures at the crop level. They do not however consider other elements, such as water availability or policy constraints that may be relevant at the farm, local or regional scales. Other studies that analyse the water system in detail, such as Joyce et al. (2011) or Rochdane et al. (2012), do not capture the effects of climate change on crop growth or the implications of farmers' decision-making.

More integrated approaches to vulnerability and adaptation assessments that address all relevant dimensions and decision-making levels are needed (Howden et al., 2007) and are important to understand the true magnitude and impact of climate change. Adaptation is a process that occurs at multiple scales, both geographic and socio-institutional (Downing, 2012; Meinke et al., 2009), and as such, it is necessary to use multidisciplinary integrated methodologies to address these complex problems.

In this research, we attempt to carry out an integrated analysis of climate change pressures in a river basin taking into account the crop, socio-economic and hydrology systems. The specific aim of this chapter is to assess climate change impacts and adaptation in the middle Guadiana basin in Spain, a river basin heavily impacted by droughts in the past. In evaluating adaptation strategies, we will focus on the impact and effectiveness of each strategy in terms of its contribution to reduce the gap between water supply and demand and its impact on agricultural income. We will also investigate to what extent current water policies contribute to adaptation.

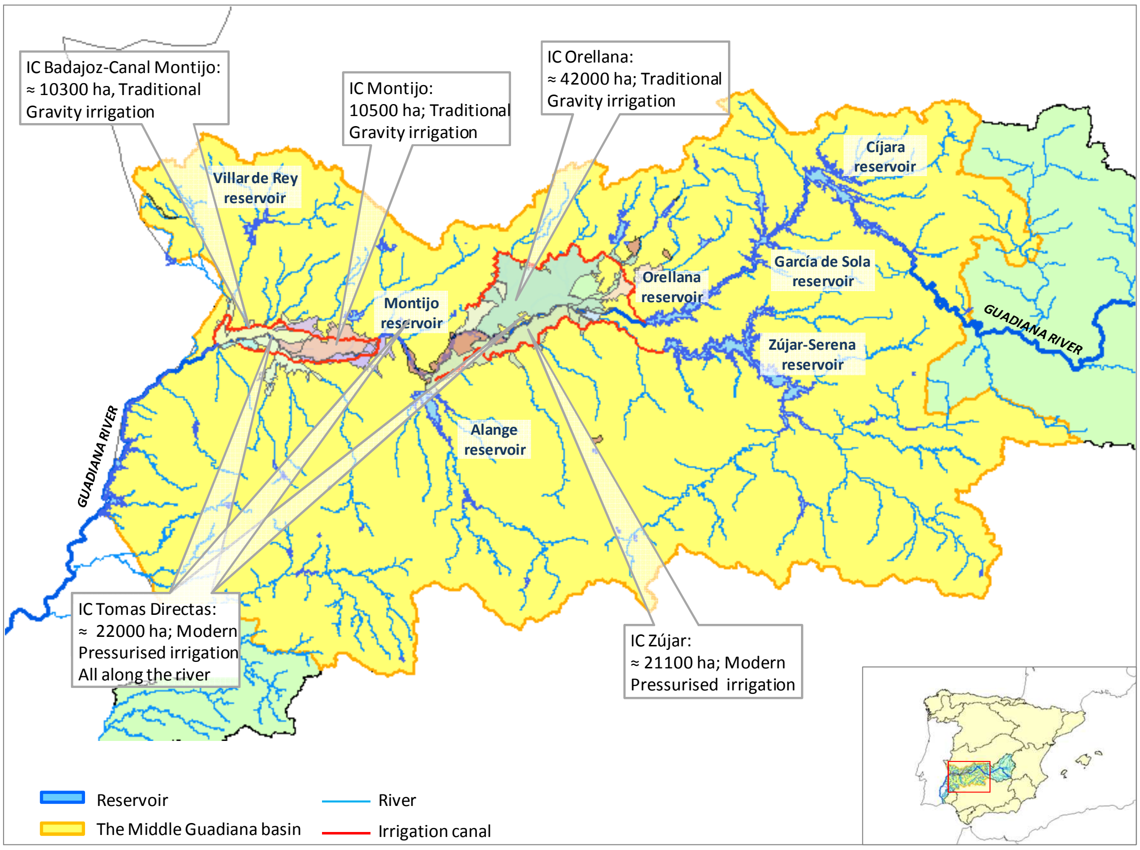
The methods developed to address this challenge include the linkage of two different models: an agro-economic model and a hydrology model that represent the social and natural systems and some of their interactions, and consider the various entities relevant to decision-making. We use these models to assess farmers' vulnerability to climate change and to test the effectiveness of different policy options including instruments of current policies for water demand management.

3.3 Water, agriculture and climate change in the Middle Guadiana

The Middle Guadiana basin, in the South-Western Spanish central plateau, presents many of the complexities and challenges of adaptation in water scarce basins that rely on irrigation. The Guadiana River is one of the most regulated rivers in Europe with a large storage capacity of which 85%, about 8000 Mm3, is located in the middle part of the basin (CHG, 2008). The Middle Guadiana basin (Figure 7) covers an area of about 34000 Km^2 characterised by a continental Mediterranean climate with a marked dry season, an average annual precipitation of 500 mm and a semi-arid humidity regime (CHG, 2008). Rural development policies during the 50's and 60's and more recent National Irrigation Plans have fostered the development of irrigation districts, primarily based on the development of hydraulic infrastructures. These infrastructures have been crucial for irrigation and rural socio-economic development and have mitigated the damaging effects of the many droughts that affect this region.

Irrigation relies on surface water and covers an area of 140000 hectares with 75% of this area devoted to herbaceous crops (mainly maize, rice and horticulture), 11% to fruit trees, 9% to olive trees and 4% to vineyards (INE, 2009). Farmers are organised in irrigation communities (IC) that are in charge of managing water distribution to all farms, collecting water fees and controlling water use and irrigation. The type of irrigation community plays an important role in several issues affecting irrigation farms, including technology adoption and type of water management on the farm. There are 12 main irrigation communities along the Guadiana River in its middle section, of which the most important ones are shown in Figure 7.

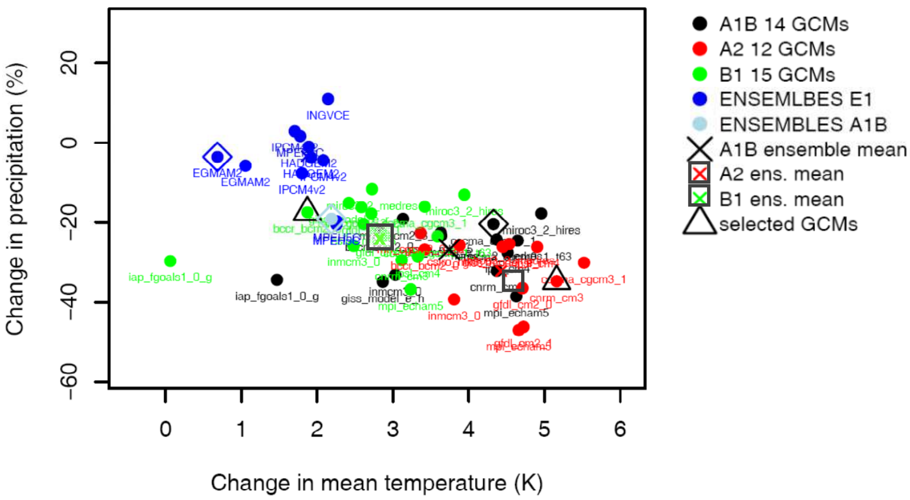
Figure 7. The Middle Guadiana basin and its main ICs



Source: own elaboration based on Blanco-Gutiérrez et al. (2013), Junta de Extremadura (2009), MAGRAMA (2013)

Agriculture in the Middle Guadiana is threatened by climate change impacts on water resources availability, changes in meteorological and agronomic conditions and climate-driven extreme events. Model outputs from the Third Coupled Model Intercomparison Project (CMIP3, Meehl et al. 2007) for the Middle Guadiana area (Figure 8), show mean changes in annual temperature and precipitation of around +2.7° and -22% respectively for the B1 scenario and +4.4° and -33% for the A2 scenario (Varela-Ortega et al., *submitted*) in the last period of the 21st century. These values hide important inter-seasonal variations and more extreme values are projected for spring and summer when most agricultural activities take place.

Figure 8. Changes in temperature and precipitation for an ensemble of models and scenarios from the CMIP3. 2070-2099 period (mean annual values).



Source: Varela-Ortega et al. (submitted)

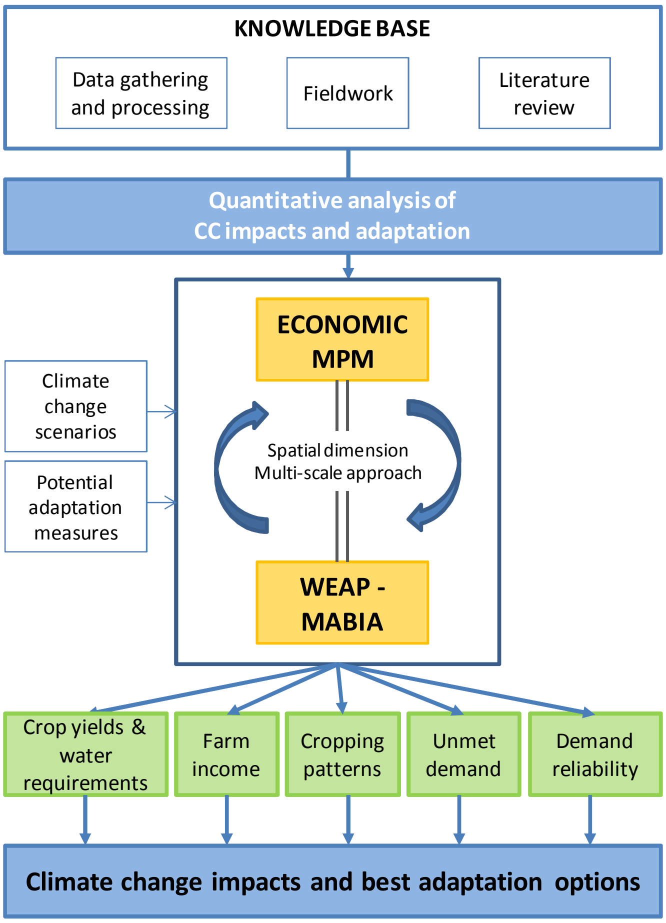
Based on these climate change projections water scarcity is likely to be exacerbated in the basin. Several studies identify the Guadiana basin as one of the most impacted river basins in Spain. First estimations of climate change impacts on water resources in Spain (MMA, 2000) determined that the Guadiana basin could experience reductions in water availability between 11% and 24% by 2030, depending on the scenario. A more recent report (CEDEX, 2011) estimates runoff decreases of 9% and 12% for the 2011-2040 and 2041-2070 periods respectively under a B2 scenario, and 11% and 27% for the same periods under an A2 scenario. However, how those changes in physical variables will affect the whole water system (hydrology, infrastructures, water management) and socio-economic systems, and what water management and farm management measures can support adaptation to change have not yet been thoroughly explored.

3.4 Methodology: Hydro-economic modelling as a tool for assessing climate change impacts and adaptation options

In this research we developed an integrated modelling framework that will allow for the assessment of climate change impacts and adaptation in agriculture and for the exploration of its physical and economic dimensions. This responds to a need for this type of integrated approach in which climate change and its effects at different levels are analysed.

Figure 9 presents the scheme of the research with the methods utilised. A quantitative modelling appraisal is developed for the analysis of impacts and vulnerabilities to climate change based on the joint application of a hydrology and an economic model. The combination of these modelling tools will allow us to simulate different adaptation measures and assess their effectiveness for mitigating the impacts of climate change-driven water scarcity.

Figure 9. Scheme of the research



Water scarcity has traditionally been approached from a supply side/engineering point of view in which water policies have focused on supply management through infrastructure planning and development. However, increasing water scarcity problems and the emergence of conflicts over water use all around the globe force us to look at elements apart from natural availability that determine water scarcity. These elements refer to the socio-economic dimension of water management and include how water resources are made available to people, what people's needs are and how are they defined (Rijsberman, 2006).

Managing water resources therefore involves the management of the different interactions that occur between human and economic activities and land and water resources. In addition, it requires the consideration of the associated potential economic, social and environmental risks (GWP, 2000).

Methods that are able to integrate these different aspects, such as hydro-economic models, are especially suitable for the assessment of the water resources system and for informing policy-making (Blanco-Gutiérrez et al., 2013; Harou et al., 2009; Heinz et al., 2007). They are also appropriate for the assessment of the multiple facets of climate change and its impacts on water and agriculture. These methods are therefore especially appropriate for the purpose of this chapter, in which we analyse climate change adaptation options based on IWRM policies, such as the EU Water Framework Directive (WFD).

Hydro-economic models represent physical/hydrological water balances (supply and withdrawals) and economic demands with a specific spatial distribution. They are usually represented as a set of linked water flows, demand nodes and water infrastructures (dams, conveyance systems, canals...). They incorporate rules for operation and allocation, such as supply and demand priorities or water storage and release rules. These models also take into account economic water demands of one or several economic sectors or water users or an aggregate demand for a specific location or region (or even a country). In addition, they can include the optimisation of an economic outcome, such as the maximisation of socio-economic benefits or agricultural income, etc.

Hydro-economic modelling has been widely applied with different purposes and at different scales, focusing on the economic behaviour of different sectors or on the economic principles that govern the water allocation and use among different sectors. Focusing on agriculture, scientific literature contains many examples in which hydro-economic modelling has been used to address management problems related to water quality and agriculture-driven pollution (Peña-Haro et al., 2009; Volk et al., 2008), water allocation and irrigation policies (Blanco-Gutiérrez et al., 2013; Rosegrant et al., 2000), groundwater management and over-exploitation (Varela-Ortega et al., 2011). Within climate change research, some examples of studies that have used hydro-economic modelling are Hurd and Coonrod (2012) or Jeuland (2010).

In this chapter we present a modular hydro-economic model, i.e. a model in which there are two sub-models, economic and hydrologic, that run separately and in which one model's outputs are the other model's inputs. Specifically, we use an economic mathematical programming model (MPM) of constrained optimization and the Water Evaluation And Planning (WEAP) model (Yates et al., 2005a, 2005b). Blanco-Gutiérrez et al. (2013) used a similar hydro-economic modelling approach based on WEAP and an economic MPM, to assess the impacts of EU water policies under current climate conditions in the short term. Here we attempt to go a step further in the analysis by broadening the scope of the study to include climate change scenarios and potential adaptation options in the basin. Furthermore, crop growth analysis is also included in the assessment. Through the use of the MABIA method (Sahli and Jabloun, 2005), which calculates crop evapotranspiration and growth based on Allen et al. (1998), we also consider the effect of climate change on crop evapotranspiration and growth and, consequently, on irrigation water requirements and yields.

3.4.1 The hydrology model WEAP

The WEAP model is a decision support tool for integrated water resources management, developed by the Stockholm Environment Institute. This is a water-balance-based platform that enables the consideration of both the bio-physical/hydrologic system and the socio-economic/management system. From its first application for the analysis of water development policies in the Aral Sea (Raskin et al. 1992), it has largely evolved towards its current version, WEAP21, incorporating a Graphic User Interface, an improved robust algorithm for water allocation, and new components for simulation of rainfall-runoff processes, groundwater hydrology and water quality modules. For a detailed explanation of the components and characteristics of WEAP see Yates et al. (2005a, 2005b).

The WEAP model has been largely used in scientific research (Purkey et al., 2008; Rosenzweig et al., 2004; Varela-Ortega et al., 2011; Yilmaz and Harmacioglu, 2010; among many others) and also by water managers and policy makers (e.g. Jordan Ministry of Water and Irrigation for the Jordan National Water Master Plan, or the Massachusetts Department of Environmental Protection for the Massachusetts Watershed Initiative).

Specifically, we can find a vast number of studies in which WEAP is used to study climate change impacts and adaptation in different basins around the world. Purkey et al. (2008) and Joyce et al. (2011), for example, analyse the probable effects of different climate change projections in the Sacramento river basin, in California. They also explore different possible adaptation options in agriculture, such as improved technology adoption and changes in cropping patterns. Also in California, Young et al. (2009) study the effect of climate change on snowmelt streamflows in 15 watersheds in the Sierra Nevada range area. Using WEAP, Hall and Murphy (2010 and 2011) studied the likely impacts of climate change in a river basin in western Ireland, assessed the vulnerability of water supplies and explored potential adaptation options. Rochdane et al. (2012) use WEAP to assess climate change effects on the hydrology and water management system of a river basin in Morocco and use stakeholder-driven storylines and scenarios to identify future water demand and adaptation options.

In Spain WEAP has been applied in scientific research in several basins as well. Moneo (2008) used WEAP for the analysis of drought management policies for irrigation in the Tietar and Alagón basins, within the Tagus Basin, in the Northern central Plateau. Varela-Ortega et al. (2011) applied WEAP to the Upper Guadiana basin for the evaluation of irrigation water conservation policies in an area of overexploited aquifers. Finally, Blanco-Gutiérrez et al., 2013) developed a hydro-economic model for the Middle Guadiana basin, combining the use of WEAP with an economic MPM for the integrated assessment of EU water and agricultural policies in the short term. This last research work served as a reference for this study in which we try to advance the application of WEAP for the assessment of climate change impacts in the basin. This is achieved by focussing more on irrigation communities and farm vulnerability, and through a detailed analysis of the climate change impacts on crops.

WEAP is a water-planning model that operates on the principle of water balance accounting, and represents different sub-catchments, demand nodes, infrastructures, water flows and water transmission links that are interconnected. Using climate time series, WEAP calculates the components of the hydrological cycle through a module that simulates rainfall runoff processes. WEAP offers different catchment calculation methods. In this research, we use two of these methods: the Soil Moisture Method and the MABIA Method. A watershed unit can be divided in several different land use areas for each of which a water balance is computed under assumed uniform climate within the sub-catchment.

For each sub-catchment, the Soil Moisture Method represents a two-bucket scheme in which, for the upper bucket or soil layer an empirical function is used to describe evapotranspiration, runoff and shallow interflows as well as changes in soil moisture. Then, in the deeper soil layer, changes in the soil moisture and baseflow routing to the river are simulated. Deep percolation conveys to a surface water body as baseflow or is transmitted to groundwater storage if the specific link from the catchment to the groundwater node is created.

The MABIA method, developed by Sahli and Jabloun (2005), simulates transpiration, evaporation, irrigation water requirements and irrigation scheduling, crop growth and yields, evapotranspiration and soil water capacity for irrigation catchments. This module uses the "dual K_c" method (Allen et al., 1998), in which the crop coefficient is divided in two coefficients K_{cb} and K_e, that represent crop transpiration and soil evaporation respectively. The dual Kc approach provides a better reflection of the effect of environmental conditions on water use, especially in dry areas and when evaporation from irrigation is high (e.g. surface based irrigation) (Rajaona et al., 2012), than the traditional single K_c approach used in models such as CropWat (Smith, 1992). The time step for MABIA is daily while the time step for WEAP is, normally, monthly. Therefore, for each WEAP monthly time step, MABIA is run on a daily base and then aggregated to the monthly time step. Sieber and Purkey (2011) and Jabloun and Sahli (2012) show a more detailed explanation of the Soil Moisture method and the MABIA method.

3.4.1.1 Model development and calibration

Model development is based on the watershed delineation used in Blanco-Gutiérrez et al. (2013). For each of the 15 catchments, we classified the surface into different land uses, using data from Geographical Information System (GIS) layers from the CORINE Land Cover 2006 update (IGN, 2006).

Irrigation catchment characterisation responds to the location and characteristics of irrigation communities. Each irrigation catchment is identified with one irrigation community or irrigation aggregated area. In this research, we try to represent all irrigation demands so that we can fully depict actual water use and management. At the same time, it is necessary, whenever possible, to reduce the complexity, especially considering that the daily time step of the MABIA simulation may produce model runs that are impractical due to their length. Across the different irrigation communities and farm types we selected three irrigation communities of different characteristics that represent the diversity of agricultural water management in the basin. The remaining irrigation area, which belongs to different irrigation communities, are then aggregated into two irrigation catchments, one in the upper part, *Vegas Altas*, and one in the lower part, *Vegas Bajas*. The three irrigation communities represented are:

- Zújar IC: a modern irrigation community of around 21100 hectares, located in the upper part, in which most irrigation systems are pressurised and in which water users pay the normal water charges per hectare plus a low volumetric water tariff. It is represented by one catchment that contains two farm types.
- Montijo IC: a traditional irrigation community of 10500 hectares, located in the lower part, in which water distribution is gravity based and furrow irrigation is the most frequent irrigation method. This irrigation community is represented by one catchment that includes two farm types.
- Tomas Directas IC: a modern irrigation community in which farmers pump water directly from water courses. It is located all along the river so it comprises more varied agricultural production systems. Around 22000 hectares of irrigated land belong to this community. Two irrigation catchments, one in the upper part (Tomas Directas 1) that contains two farm types, and one in the lower part (Tomas Directas 2) that contains one, represent this irrigation community.

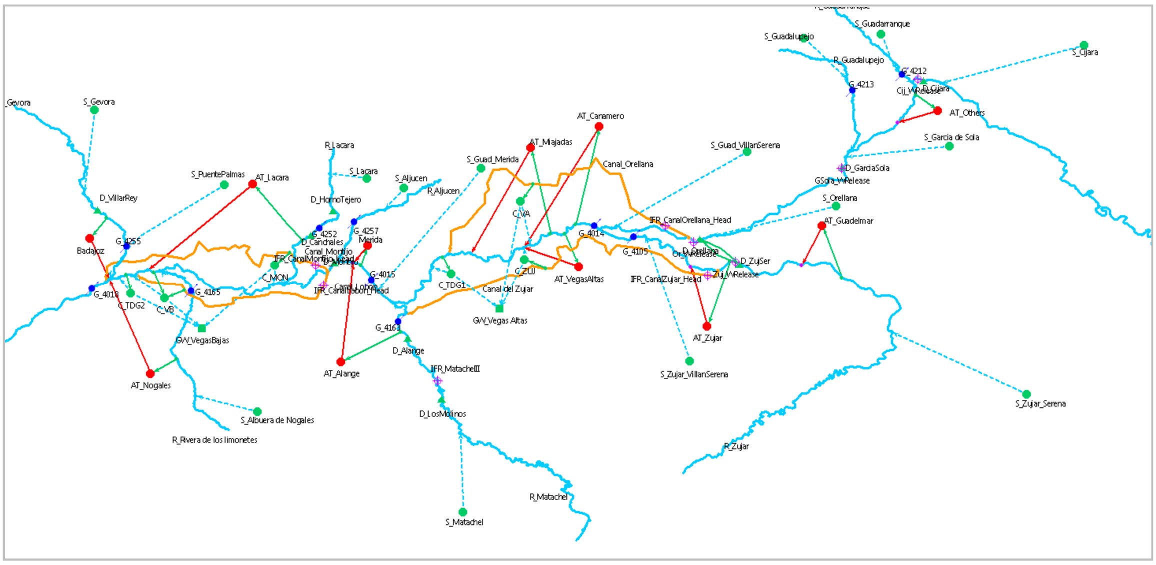
We used GIS crop and land use maps from MARM (2009a), irrigation communities delineation from Blanco-Gutiérrez et al., (2013) and data from the Regional Department of Agriculture (Junta de Extremadura, 2008), for the specification of crop areas in each irrigation community. Farm types within irrigation communities, explained in section 3.4.2, were defined according to crop area, statistics, field visits and stakeholder consultations.

Rainfall runoff processes are simulated using climate data including temperature, precipitation, humidity, wind speed and solar radiation. For this, we used the CRU-TS 3.10 Climate Database (Jones and Harris, 2011), which is a monthly data database. For the irrigation catchments, daily climate data were needed. However, daily climate data from meteorological stations for the whole period considered (1973-1990, for the calibration, and from 1990 onwards) were only available for one station. Thus, we used the monthly CRU-TS 3.10 database, compared variations in climate variables across the catchments and applied the observed variations to the monthly dataset to produce estimated daily data for all irrigation catchments.

Soil characteristics are needed to calculate soil water capacity and were obtained from the Extremadura Soil Catalogue (UNEX, 2000). Crop and irrigation parameters are based on Allen et al. (1998), on Doorenbos et al. (1979), and adjusted with data from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2005). Finally, the River Basin Authority provided technical data for water infrastructure operation and management.

Figure 10 shows the schematic view of the Middle Guadiana basin as represented in WEAP. Blue lines represent the Guadiana river and its most relevant tributaries. Red dots represent urban water demands, and green dots represent natural catchments and irrigation catchments that in this work are equivalent to irrigation communities or aggregation of irrigation areas. Green triangles represent reservoirs and dark blue dots are flow gages.

Figure 10. WEAP schematic view of the Middle Guadiana basin



The parameters used for the model calibration are those that specify the rainfall/runoff model and that are more sensitive, namely: crop coefficient, soil water capacity, runoff resistance factor, conductivity and flow direction.

Table 8 shows the calibration parameters and Figure 11 illustrates the monthly observed and simulated streamflows in four sections of different rivers in the basin. Model accuracy is measured using two widely used indices (Weglarczyk, 1998), the Nash and Sutcliff's (1970) efficiency coefficient[3] (E) and a standardised Bias score[4] (B). Results for the four river tranches presented in Figure 11 show a good level of accuracy with an E coefficient between 0.69 and 0.87 and a bias (B) of less than 20%.

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

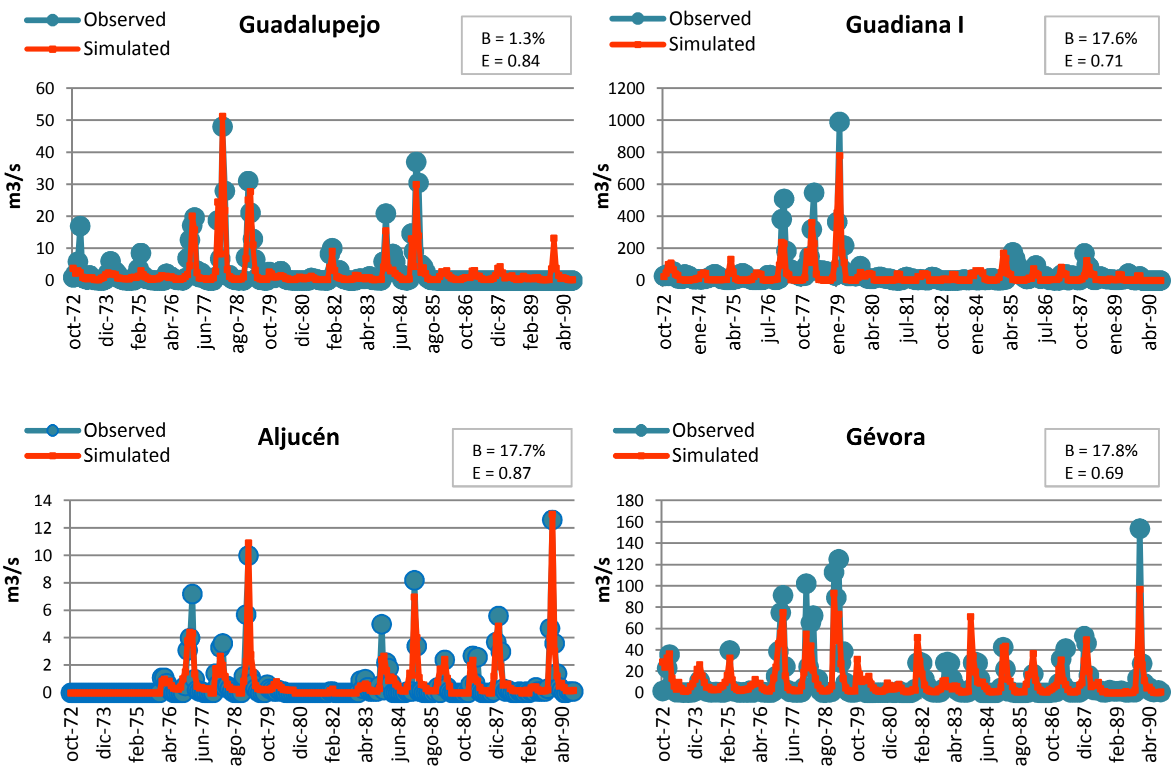
[4] $B = 100[(\overline{Q_c} - \overline{Q_o})/\overline{Q_o}]$, where $\overline{Q_c}$ and $\overline{Q_o}$ are the computed and observed average water flows.

Table 8. WEAP calibration parameters

PARAMETER	VALUE
Crop coefficient, Kc	1.1
Soil Water Capacity (mm)	Ag=130; Fo=115; Pa=140; SNat=75
Deep water capacity (mm)	1400
Runoff resistance factor	Ag=8; Fo=15; Pa=8; SNat=4
Root zone conductivity (mm)	75
Deep conductivity (mm)	50
Preferred flow direction	0.8

**Ag: agriculture; Fo: forest; Pa: pasture; SNat: semi-natural area*

Figure 11. Observed and simulated streamflows in four different river sections



3.4.2 The Economic model

MPMs have been widely used in the analysis of agricultural management of resources and crop decision-making (e.g. Bazzani et al., 2005; Blanco-Gutiérrez et al. 2011; Garrido, 2000; Howitt, 1995; Iglesias and Blanco, 2008; Qureshi et al., 2013; Varela-Ortega et al., 1998;

Varela-Ortega et al., 2011). MPM is well suited for analysing agriculture and natural resource problems. This is because MPM allows us to represent the link between economic elements, such as costs and revenues related to production, and physical and environmental elements on the farm, such as natural resource limitations or pollutant outputs of crop production (Buysse et al., 2007).

In this research, the model developed is a static farm based non-linear optimisation model that maximises farmer's utility subject to technical, structural and policy constrains. The model, programmed in the General Algebraic Modelling System (GAMS), is characterised by a stochastic approach that considers farmer's behaviour towards risk. The decision variable in the model is land allocation to different crops and techniques ($X_{c,r}$). The model finds the optimal combinations of land allocation to cropping activities that maximise farmers' utility under constraints. The model is similar to the one developed in the previous chapter and its general form is defined by equations 1, 2 and 3.

Objective function: $MaxU = Z - \varphi \cdot \sigma(Z)$ (1)

Constraints: $g(X) \in S_1$ (2)

$X \in S_2$ (3)

The objective function (1) is the maximisation of expected utility (*U*), which is calculated as a function of expected gross margin (*Z*), and a risk component that includes a farmer's risk aversion coefficient (φ) and the standard deviation of farm gross margin ($\sigma(Z)$) (Hazell and Norton, 1986), considering market and climate variability that affects yields and prices. The risk aversion coefficient serves as a calibration parameter for the model. Model calibration involves finding the value of the risk aversion coefficient that produces a better fit between the simulated and the observed cropping patterns.

Utility maximisation is subjected to constraints that include limitations on resource use (land, water, labour), availability of technology (irrigation systems) and policy requirements (water allotments, cropping area limitations, set aside). Policy elements are included either through constraints or, in the case of subsidies, taxes or tariffs, in the objective function.

The basic unit of analysis in the model is the farm. For this, a farm typology for the Middle Guadiana basin was developed based on public statistics (Junta de Extremadura, 2008) and the agricultural census (INE, 2009) as well as GIS crop and land use maps from MARM (2009a). In addition, fieldwork was carried out in 2009 in the context of the SCENES project and included a survey addressing irrigation communities (3) and individual farmers (107), through incidental sampling. The farm types selected (Table 9) represent the current farm typology, the variety of farm sizes, the most common crops and crop mixes, and the different types of farm irrigation systems and water management in the selected ICs. The remaining irrigation area, belonging to different ICs, are represented by two aggregated farm types, one in the upper part, *Vegas Altas*, and one in the lower part, *Vegas Bajas*.

Crop coefficients, including input costs, crop water requirements and yields, were obtained from MAPA (2005), MAPA (2007), and field work described above. For future scenario simulations, input costs projections are based on Varela-Ortega et al. (2013), which projects past trends into the future. Annual crop prices were projected according to past price trends using data from FAOSTAT (2012).

Table 9. Representative farm types selected for simulation with the MPM

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

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

3.4.3 The modelling scenarios

The purpose of this chapter is to analyse climate change impacts on irrigation agriculture and to test the effectiveness of different adaptation actions to reduce those impacts. For this purpose, we will use two types of scenarios: climate change scenarios and adaptation scenarios.

Climate scenarios to 2070 correspond to the scenarios selected and downscaled for the Middle Guadiana basin by Varela-Ortega et al. (*submitted*), obtained from three General Circulation Model simulation of SRES scenarios, namely of B1, A1B and A2. The three scenarios used were selected in order to cover a wide range of uncertainty, with BCCR-BCM2.0/B1[5] in the lower range of temperature and precipitation changes, CCCMA-CGCM3.1/A1B[6] in the lower range of precipitation change but high range of temperature change, and CNRM-CM3/A2[7] a dry and warm scenario at the end of the covered period. These scenarios provide changes in mean temperatures and precipitation as well as changes in relative humidity and wind speed. The changes were applied to the 1971-2000 available climate dataset to obtain two 30-year datasets for the two periods considered in the WEAP simulations: 2011-2040 and 2041-2070.

Adaptation scenarios include three planned adaptation situations (baseline + two planned adaptation strategies) and one autonomous adaptation scenario. Planned adaptation refers to those adaptation actions that are adopted by the government as a policy decision while autonomous adaptation is a private initiative triggered by actual or expected changes in welfare, market or natural conditions (Smit and Pilifosova, 2001; Fankhauser et al., 1999)

Within the planned adaptation scenarios, we propose three scenarios that address different elements contained in the WFD (EC,2000). These include the maintenance of minimum environmental flows and the use of water pricing for the promotion of efficiency and introduction of economic principles in water management, as well as the most typical adaptation actions considered in IWRM policies and which are considered in the Regional Adaptation Plan for the water sector (Gobierno de Extremadura, 2013):

a) _Baseline:_ The baseline scenario corresponds to 2007 cropping activities and includes the implementation, between 2010 and 2012, of the EU´s Common Agricultural Policy Health Check reform that introduces the total decoupling of crop subsidies within the single farm payment scheme.

b) _*Environmental and agricultural demand strategy (ENV):*_ Environmental flows + compliance with current water allotments. The strategy involves the implementation

[5] BCCR-BCM2.0 model from the Bjerknes Centre for Climate Research, Norway, with SRES B1 scenario

[6] CCCMA-CGCM3.1 model from the Canadian Centre for Climate Modelling and Analysis, Canada, with the SRES A1B scenario

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

of the following actions: (i) setting adequate environmental flows, (ii) controlling and monitoring environmental flows, and (iii) controlling water consumption at farm level.

c) *Economic incentives strategy (ECON):* Water tariffs + irrigation modernisation. This strategy involves (i) adequate water pricing that recovers total costs of water, and (ii) controlling water consumption at farm level or at least at the irrigation community level. Within this strategy, we first simulate a cost recovery tariff that includes a financial + resource (+ environmental) costs, and assumes compliance with the current quota system. In addition, this strategy includes irrigation technology modernisation.

Autonomous adaptation (AA) refers to changes in cropping patterns that are undertaken at the farmers' initiative because of observed changes in climate and water availability. This scenario is simulated for the period 2041-2070together with each planned adaptation scenario for a total of six adaptation scenarios.

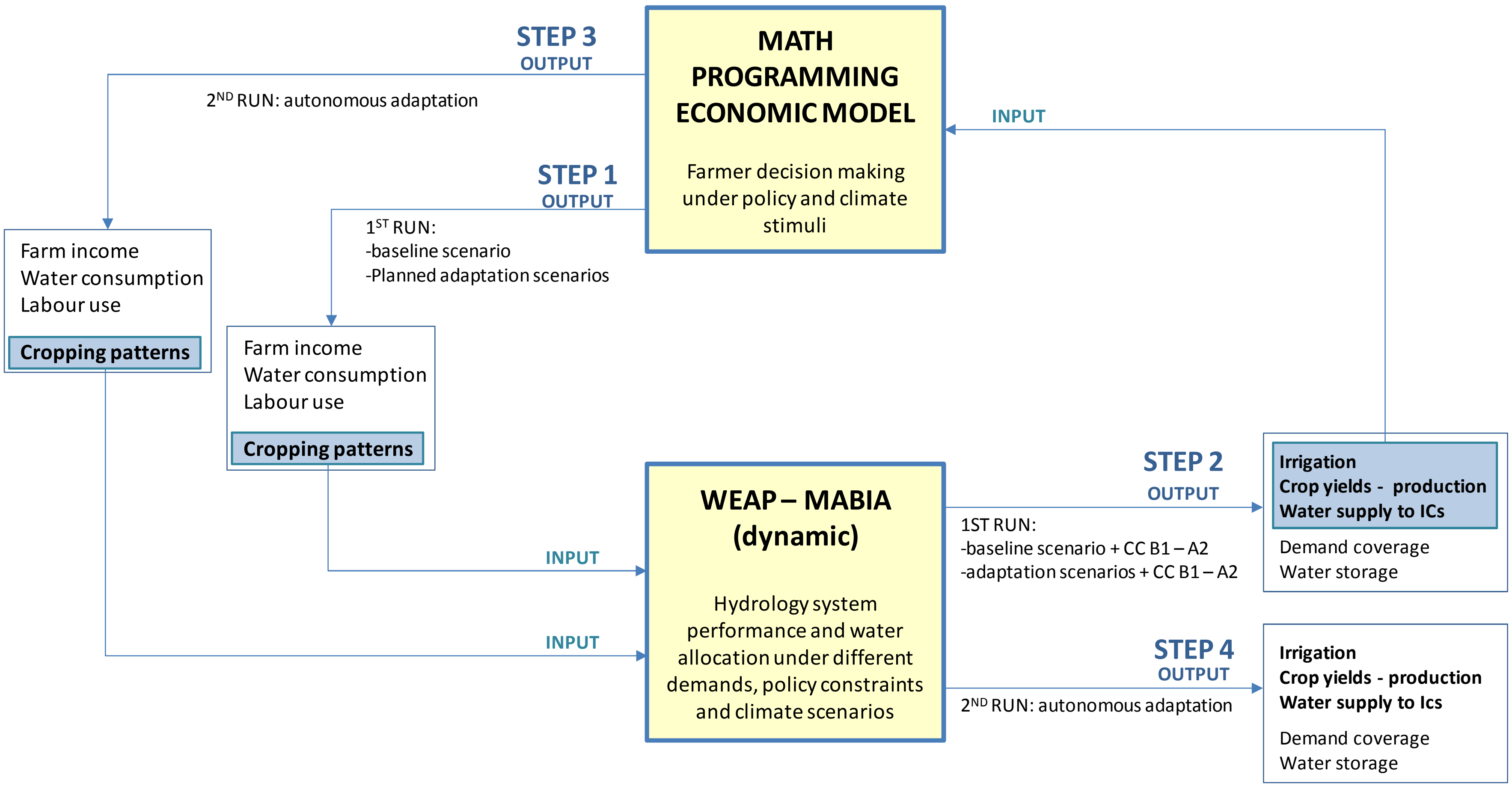
3.4.4 The model linkage and scenario running

Figure 12 shows how the models are connected and how the model iterations take place.

The hydro-economic modelling simulation is primarily driven by the agro-economic model. In the Middle Guadiana basin, water used by farmers is determined by water policies and not by physical water availability. Thus, model simulation starts with the economic model run, in which the MPM optimises cropping patterns under the corresponding scenario. The optimal cropping pattern obtained is the one that maximises farmers' utility according to policy constraints and expected crop water requirements, crop yields and water availability. Then, cropping patterns are used to specify the irrigation catchments in WEAP. Using cropping patterns as an input, WEAP calculates monthly flows and water diversions from rivers, dams and irrigation canals to satisfy the irrigation demands. Using the MABIA method, WEAP calculates irrigation water requirements and allocates water to crops depending on water availability and established priorities, and then uses this to determine crop yields.

After this first economic-hydrologic model simulation, in a second iteration, the economic model uses WEAP results on water supply delivered, crop yields and crop water requirements under climate change to simulate farmers' adjustment of cropping patterns to new optimal land allocation. Then, new adapted cropping patterns are used again by WEAP to calculate water allocation, demand satisfaction and irrigation and crop production under the new conditions.

Figure 12. Model linkage and iteration procedure



3.4.5 Limitations of the modelling exercise

Although the models presented here are useful for the intended purpose of this study, they also present some limitations.

Among these, the different spatial and temporal scales of analysis of each separate model constitute a challenge for integration.

Farm based economic models usually consider small regions, such as municipalities, provinces, or as in this case irrigation communities, while hydrology and water balance models are usually computed at the basin level. Using 9 representative farms to represent irrigation agriculture in the whole basin constitutes a simplification, but it permits us to look at basin level water policy and climate change implications through their representation in the hydrology model. The hydrology model developed is able to represent farms and reproduce them and the optimal crop mixes obtained from the economic model for the whole irrigation area in the basin, thereby bridging the different spatial scopes of each model separately.

The temporal scale of the different components of each model also varies. On the one hand the hydrology model runs on a monthly time step base, while the agronomic module MABIA operates on a daily base. WEAP aggregates MABIA results to the monthly step and is able to provide aggregated annual results which constitute an input for the economic annual model. The WEAP-MABIA simulations take into consideration the water that is available for crops in each growth stage, which is a determining factor for crop yields. However, when the outputs of WEAP-MABIA are used in the economic model the detail of those results is partially reduced as the model uses annually accumulated values of water availability and average crop yields. The economic model uses the crop yields calculated within MABIA as an input but it only partially reflects the relations between water and yields.

As the economic model is an annual model, some constraints arise when dealing with multiannual decisions such as long-term investments and permanent crops. Permanent crop area is considered fixed in the model. This is a reasonable assumption in short-term analyses, but is less likely when dealing with long-term climate change scenarios. However, the analysis of climate change scenarios aims at assessing the impacts of climate change on current agricultural systems and, even if constant permanent crop area is not realistic in the long run, it is nonetheless useful for the intended analysis.

Other constraints arise with respect to the intrinsic construction of the models. With respect to WEAP optimisation of water allocation, an important limitation is that it is not possible to prioritise between crops within the same irrigation catchment. WEAP does not consider the human dimension of water allocation to crops. When a drought occurs farmers will prioritise some crops over others as a strategy to minimise the economic impacts. For example, farmers tend to prioritise permanent crops over annual crops as they entail multi-annual investments and economic outcomes. This limitation could only be resolved by dividing irrigation catchments or by introducing economic optimisation algorithms, such as economic MPM, or other types of algorithms that are able to introduce decision rules into WEAP as shown by Kemp-Benedict et al. (2010).

The climate change scenarios used in this research do not consider changes in climate variability or in the frequency and severity of extreme events. Instead, we use changes in mean values for temperature and precipitation and consider the variability observed in past decades. The results of the model simulation may therefore underestimate the occurrence and impact of droughts in the basin.

Finally, the MABIA method calculates changes in evapotranspiration, irrigation requirements and yields without considering the potential beneficial effect of increased CO_2 concentrations on crop yields. Several studies (Carmona et al., 2013; Giannakopoulos et al., 2005; Nelson et al., 2009) suggest that in some cases irrigated crop yields may increase under climate change scenarios. However, there is great uncertainty of these projected changes. On the other hand, Howden et al. (2007) highlight that studies that predict yield increases generally assume no constraints in irrigation water availability to meet increased crop water requirements. In this research, MABIA calculates increased evapotranspiration and irrigation requirements and WEAP satisfies crop water demands in light of available water resources (which are diminished by climate change) and policy constraints. Thus, it is more realistic as it includes the spatial dimension in the analysis of crops and considers water availability for the specific locations, which depends on natural water availability and water storage. However, negative impacts on crop yields may be overestimated because the effects of increased CO_2 concentrations on crop yields are not considered.

3.5 Results and discussion

This section analyses the results of the simulation of climate change scenarios in the Middle Guadiana river basin. The scenarios simulated cover the spectrum of potential impacts of climate change, from the least to the most hazardous and thereby takes account of the high level of uncertainty that is inherent in climate change analysis. We then assess adaptation options, looking at their performance under different levels of climate change.

3.5.1 Climate change impacts and vulnerability in the Middle Guadiana basin

The baseline analysis of climate change scenarios is based on current agricultural systems in the middle Guadiana basin. These irrigation farms are mainly constrained by their own structural characteristics (farm size, availability of irrigation technologies), water policy (water allotments and water tariffs) and agricultural policies. Farmers' decision-making on resource allocation, land and water, is then simulated using the economic MPM described above. The baseline scenario represents current cropping patterns in the basin, which are used for the simulation of agricultural irrigated area within the hydrology system and climate change scenarios using the WEAP modelling platform. Results are presented aggregated at the irrigation community level. Table 10 shows the results of the economic performance in each irrigation community as considered in the baseline scenario.

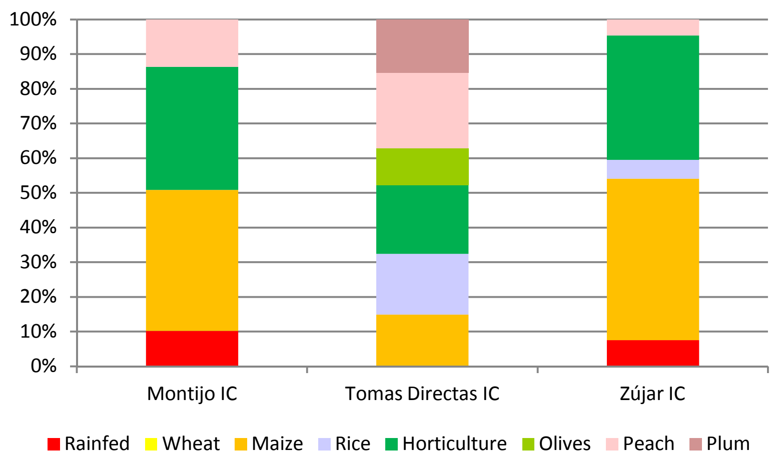
Table 10. Economic performance at the irrigation community level in the baseline scenario.

		Farm income (€/ha)	Water consumption (m3/ha)	Water cost (€/m3)	Water marginal value (€)	Total labour (total days)
Montijo IC (traditional)	Baseline	1970	9423	0.011	0.029	6221650
Tomas Directas IC (modern, uptake from river)	Baseline	4086	6247	0.040	0.010	39293325
Zújar IC (modern)	Baseline	1708	7102	0.040	0.014	4765225

**Economic results for the irrigation areas of Vegas Altas and Vegas Bajas are not presented here, as they are not irrigation communities but an aggregation of irrigated land without decision-making equivalent to farm types and irrigation communities. The reader can find the results for Vegas Altas and Vegas Bajas in Annex B*

Montijo IC is a traditional irrigation community in which most irrigation is based on gravity and furrow irrigation and whose main crops are maize and tomato. Zújar is a modern irrigation community in which maize is the main crop together with modern irrigated horticultural crops, and small areas of permanent crops and rice. Tomas Directas is a very modern irrigation community where pressurised irrigation systems prevail and where a large variety of crops are grown including profitable olive groves and fruit trees together with horticulture, maize and rice. As shown in Table 10, in Tomas Directas IC farms reach higher income levels per hectare than other ICs. This is attributable to the prevalence of permanent crops – which consume less water and are highly profitable –, and the high technology adoption that improves efficiency. Montijo and Zújar ICs reach similar levels of income, between 1700 and 2000 €/ha with higher water consumption, especially in Montijo (the traditional one) where average water consumption per hectare is 25% above official water allotments. Water costs paid by farmers in Tomas Directas and Zújar ICs (modern) are four times higher than those paid in Montijo, which leads to lower water marginal values (the value obtain by using one extra unit of water). Labour use is highest in Tomas Directas because of more area devoted to fruit and horticultural production. Figure 13 shows the cropping patterns in the selected irrigation communities in the baseline scenario.

Figure 13. Cropping patterns in irrigation communities in the baseline scenario



Using these cropping patterns and land use characteristics, WEAP simulates the water system performance and water allocation in the long term under different climate change scenarios. Of the hydrology model simulation results, we will look specifically at unmet demand, water storage and demand reliability, which are relevant indicators that explain vulnerability of irrigation agriculture to climate-driven (variability and change) water scarcity.

The impact of climate change on the hydrology and agricultural systems is simulated using the climate change scenarios explained above, namely BCCR-BCM-2.0/B1, CCCMA-CGCM-3.1/A1B and CNRM-CM3/A2. From now on, we will refer to these scenarios as B1, A1B and A2, respectively.

Figure 14 shows the results of the simulation of CC scenarios on total unmet demand in the basin. Results show that in the first CC simulation period, 2011 - 2040, there are already problems of water demand satisfaction, especially in the last decade of this period where unmet water demand peaks in all scenarios. Differences across scenarios for this period are small, with A2 slightly more negative than the other scenarios, especially during drought years. However, for the second CC period simulated (2041 – 2070), more significant changes in water resources availability take place, and water storage fails to mitigate the effects of drought more frequently, especially in scenario A2, where hydrological droughts extend over periods of several years (2042-2047, 2050-2054, 2062-2066 are the longest drought spells). These results illustrate the need to adapt water demands and economic activities dependant on irrigation.

Figure 14. Total unmet demand in the baseline scenario

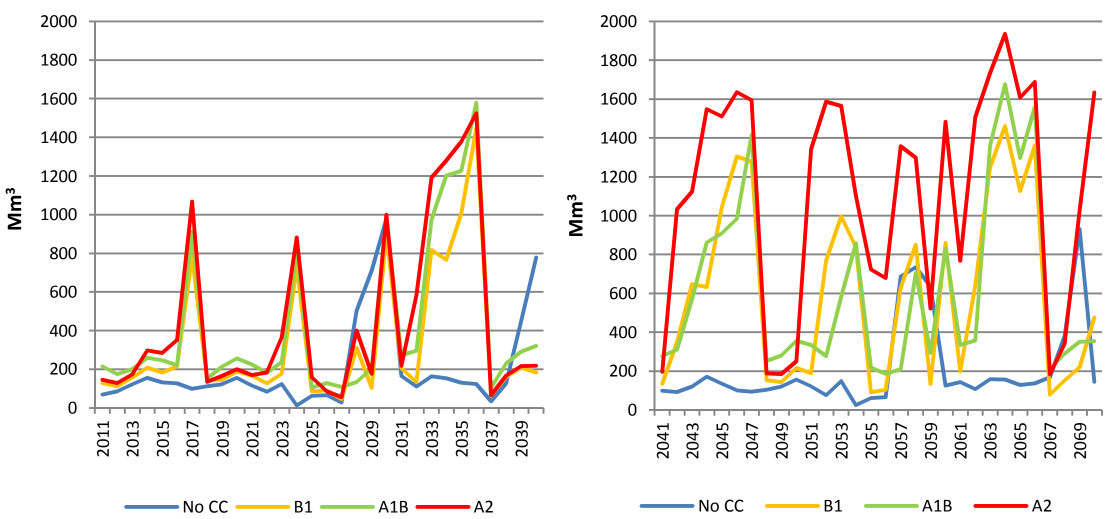
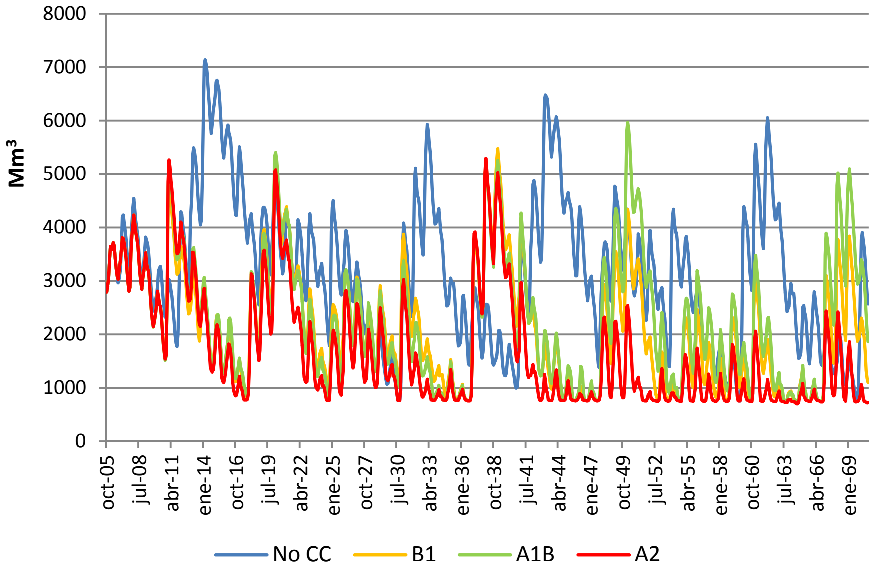
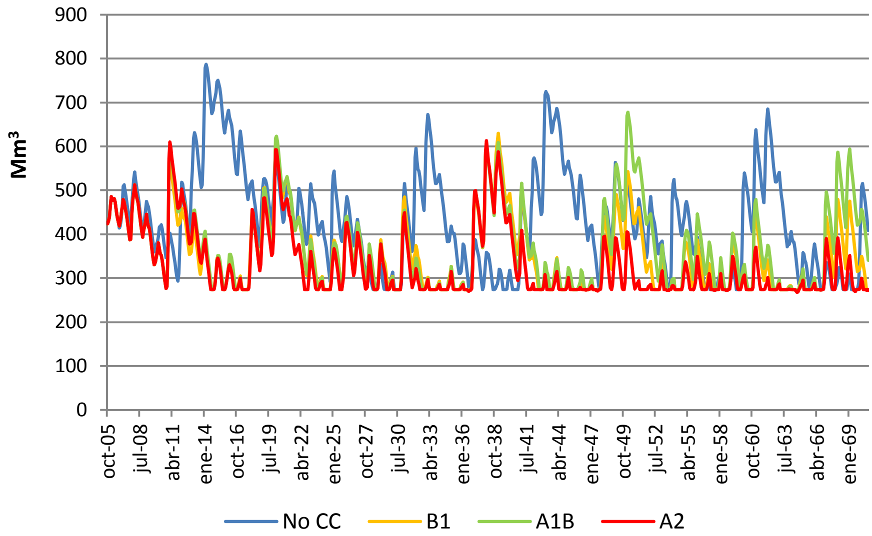


Figure 15. Reservoir water storage in the Middle Guadiana basin

a) Middle Guadiana Total



b) Orellana reservoir (upstream)



c) Alange reservoir (downstream)

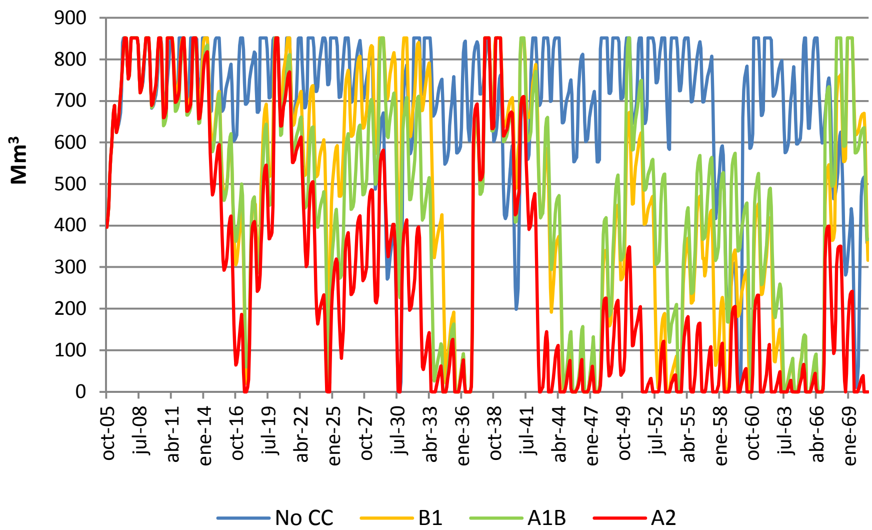
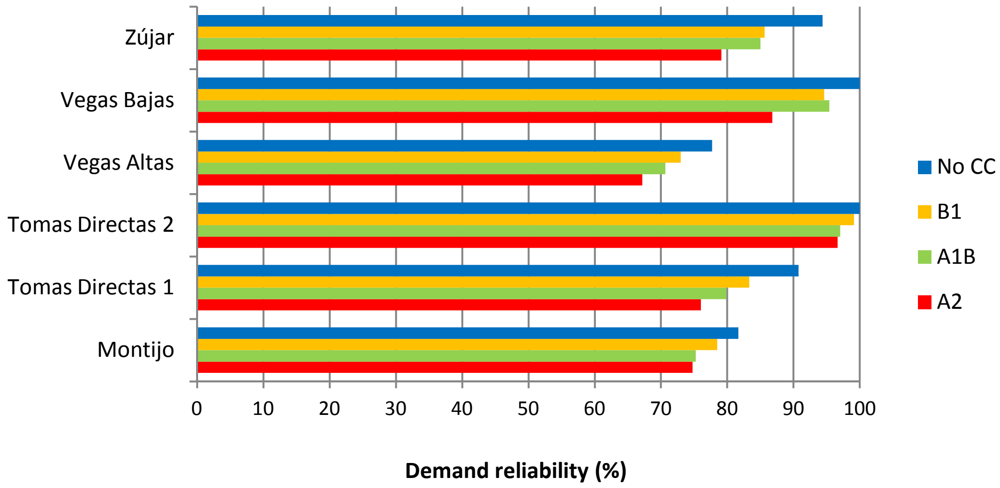


Figure 15 shows the total water storage in the Middle Guadiana (a) and in two reservoirs: Orellana dam (b) in the upper part, and the Alange dam (c) in the lower part. Scenario A2 presents a catastrophic situation, in which unmet demand is very high in the second simulation period (up to 2070), crop production fails in numerous years and water storage drops to inactive levels. If we compare the Orellana (b) and Alange (c) dams, we can observe that upstream water storage fails in more years, and therefore irrigation farms in that area will be more vulnerable than farms downstream. This may be counter-intuitive, as it is generally recognised that downstream water users are negatively affected by upstream activities, both with respect to water quantity as to water quality. However, in this basin, the high level of fragmentation due to numerous infrastructures – including many dams and irrigation canals – make downstream users less dependent on upstream activities. At the same time, the high concentration of rice fields upstream drives a very high water demand that contributes to the exhaustion of stored water resources during dry periods.

This is confirmed by looking at Figure 16, which presents the demand reliability for different irrigation communities or irrigation areas in the Middle Guadiana. Demand reliability refers to the percentage of time (timesteps in WEAP, i.e. months) that water demands are satisfied. We can see that downstream demands (Montijo, Tomas2, Vegas Bajas) have a higher reliability than upstream demands (Zújar, Tomas1, Vegas Altas), coinciding with the results presented by Blanco-Gutiérrez et al. (2013). The main reason for this is the much higher demand of upstream irrigation districts as compared to downstream districts. Orellana and Zujar-Serena dams, which supply water to Vegas Altas and Zujar IC respectively, are communicated through a pipeline that transfers water from one dam to the other. This pipeline was built to guarantee water demands in Vegas Altas and is a risk-sharing infrastructure. In years of drought, when water supply decreases, the Zujar IC bears higher risk than it would face without the pipeline because of high water demands in Orellana irrigation area. This illustrates the dynamic and multi-level nature of vulnerability and adaptation (Leichenko and O'Brien, 2002; Reidsma et al., 2010; Westerhoff and Smit, 2008; among many others), showing how decision made in one irrigation district (Vegas Altas) together with policy decision on infrastructures (pipeline) increases vulnerability in other irrigation districts (Zújar) in spite of the greater water use efficiency and the lower water demand in the last.

Figure 16. Demand reliability in irrigation communities under the A2 scenario



With respect to the effect of irrigation technology, if we compare demand reliability in irrigation communities and districts located in the same area, such as Tomas Directas 2 (modern, downstream) and Montijo (traditional, downstream), or Zújar (modern, upstream) and Vegas Altas (traditional, upstream), the graph shows that demand reliability is lower in traditional irrigation communities than in the modern ones, as also shown in Blanco-Gutiérrez et al. (2013). This indicates that traditional irrigation communities and farms are more vulnerable to water scarcity than the modern ones.

The hydrology model simulation shows that water inflows to the area under most severe climate change assumptions (A2), would decrease around 15% in the period 2011-2040 and 35% in the period 2041-2070. However, water distribution, location, supply preferences, water storage and demand priorities result in a differential impact on supply at the irrigation community level. Supply delivered to ICs in the same simulation period is on average a 48% lower in the A2 scenario with respect to No CC scenario. Table 11 shows the average changes in supply delivered to the different irrigation districts for the period 2041-2070 under the A2 scenario, which include a significant number of dry years. Table 12 illustrates the effect of the A2 climate change scenario on crop yields and irrigation water requirements for the same period.

Table 11. Climate change impact on supply delivered

	Average supply delivered 2041 - 2070		
	No CC (Hm3)	A2 (Hm3)	Diff. No CC-A2 (%)
Montijo IC	90	78	-13.7
Tomas Directas IC 1	65	33	-49.5
Tomas Directas IC 2	29	33	15.6
Vegas Altas	509	197	-61.3
Vegas Bajas	195	127	-34.7
Zújar IC	73	34	-53.7
TOTAL	**962**	**502**	**-47.8**

WEAP simulates climate impact on crops considering the boundary conditions present in the region and in the different irrigation districts which include climate parameters and water availability. These impacts on yields and water requirements are average results of the MABIA crop growth simulations subjected to water availability. This implies that given a higher water availability crop yields could be higher as well and therefore the impact of climate change on yields would be lower (with a greater impact on irrigation water requirements). Therefore, the results shown here represent one combination of irrigation water and crop yield in the water-yield functions of crops.

Table 12. Impact of climate change on crop yields and water requirements for the period 2041-2070 under the A2 scenario

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

**relative to No CC scenario in the same period 2041-2070*

As explained before, the simulated changes in crop water requirements and crop yields do not consider the effect of fertilisation produced by increased CO2 concentration in the atmosphere. Some studies that have addressed this issue include Carmona et al. (2013), which analyses climate change impacts on crops in the same region, Giannakopoulos et al. (2005) for the Mediterranean region or Nelson et al. (2009) which provide average estimations at global level for developed and developing countries. For the A2 scenario and with CO2 fertilisation, Carmona et al., (2013) projects a 20-30% increase of irrigated cereal yields in the Middle Guadiana basin for the 2080-2090 period. For the same scenario, Giannakopoulos et al. (2005) anticipate, for southern Europe (Spain, Italy and France), changes in cereal yields of between -10% and -1% without and with CO2 fertilisation respectively, and between 0% and +4% for maize under similar assumptions. Nelson et al. (2009) present similar results to those obtained in this research. They compare crop yield projections using two models with and without CO2 fertilisation. They do not reach conclusive results as, depending on the model, crop yields increase or decrease when CO2 fertilisation is considered. When there is no CO2 fertilisation both models show yield decreases for maize (between -1.2% and -8.7%, depending on the model), rice (between -3.5% and -5.5%) and wheat (between -4.9% and -5.7%) under irrigation conditions in developed countries. However, with CO2 fertilisation results are uneven. The results presented here (Table 12) do not consider the effect of increased levels of CO2 in the atmosphere, but on the other hand they represent the water system's limitations that frequently are not considered in crop model based assessments. Thus, our analysis may be more realistic with respect to assumptions on water management and constraints, but should be seen as a pessimistic scenario with respect to CO2 fertilisation, which would present a more optimistic realisation of climate change effects on irrigation agriculture.

The AA scenario tested assumes that after the first simulation period (2011-2040) farmers' are aware of changes in climate and water availability and adapt their activity to the expected decrease of water availability and changes in crop yields and irrigation requirements. Autonomous adaptation has only been simulated using the A2 scenario crop conditions for scenarios B1 and A2. Scenario A1B is not considered for now in order to reduce the number of scenarios simulated. Instead, scenarios B1 and A2 consider the less and the most negative plausible futures respectively.

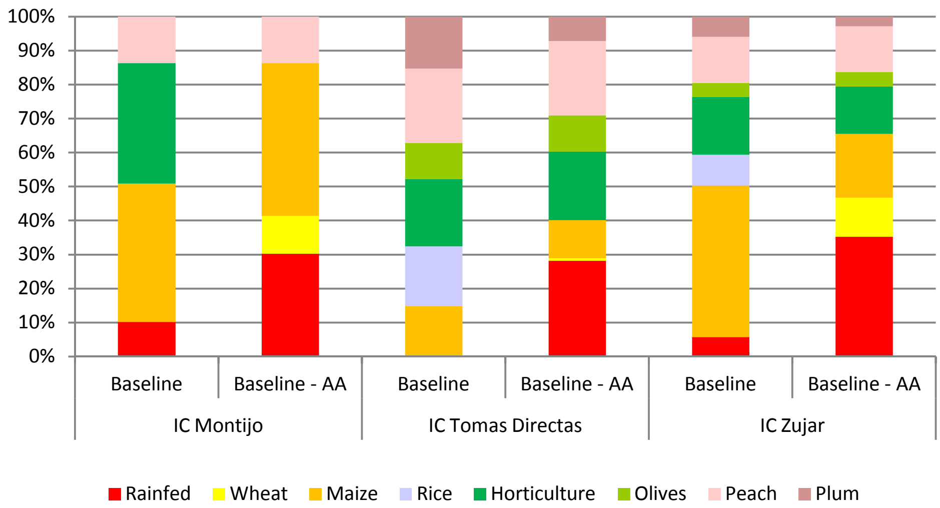
Table 13 shows the economic impacts of such adaptation process at the IC level and Figure 17 shows the shift produced in cropping patterns as a consequence of that. Farm income decreases between 10% and 20%, with Zújar IC and the upper section of Tomas Directas IC the most affected areas because of lower water availability. According to Reidsma et al. (2010), climate change impact on crop yields does not translate into similar impacts on farm income, as farm level and regional level adaptation actions partially mitigate the effects of extreme climate variations on crops. In this case, we are dealing with impacts on crop yields, crop water requirements and water availability at farm level. The results of the simulation of autonomous adaptation are indicative of the potential for adaptation at the farm level. Farms facing reductions in water availability between 10 and 50%, reductions in crop yields of up to 20% and increases in crop water requirements of up to 20%, face income losses of between 10 and 20%. These results show the importance of carrying out an analysis of farm level decision-making. This is because crop model results do not capture the complexities of the farm system and farmers' decisions and may therefore overestimate the potential negative impacts of climate change. Also, as highlighted by Reidsma et al. (2010), farm characteristics are relevant to climate change adaptation. In the case of our analysis, traditional farms in Montijo IC experience water reductions of around 14% and income reductions of 12%. Modern irrigation communities (Tomas Directas IC and Zújar IC) face water supply reductions 2 to 4 times greater than Montijo IC while income loss is less than double.

Table 13. Economic impact at the IC level of autonomous adaptation

		Farm income (€/ha)	Water consumption (m3/ha)	Water cost (€/m3)	Water marginal value (€)	Total labour (total days)
Montijo IC	Baseline	1970	9423	0.011	0.029	6221650
	Baseline - AA	1728 (-12%)	8132 (-14%)	0.013	0.031	5732606
Tomas Directas IC	Baseline	4086	6247	0.040	0.010	39293325
	Baseline - AA	2935 (-18%)	4348 (-30%)	0.046	0.050	36400912
Zujar IC	Baseline	1708	7102	0.040	0.014	4765225
	Baseline - AA	1346 (-21%)	3288 (-54%)	0.056	0.039	4102070

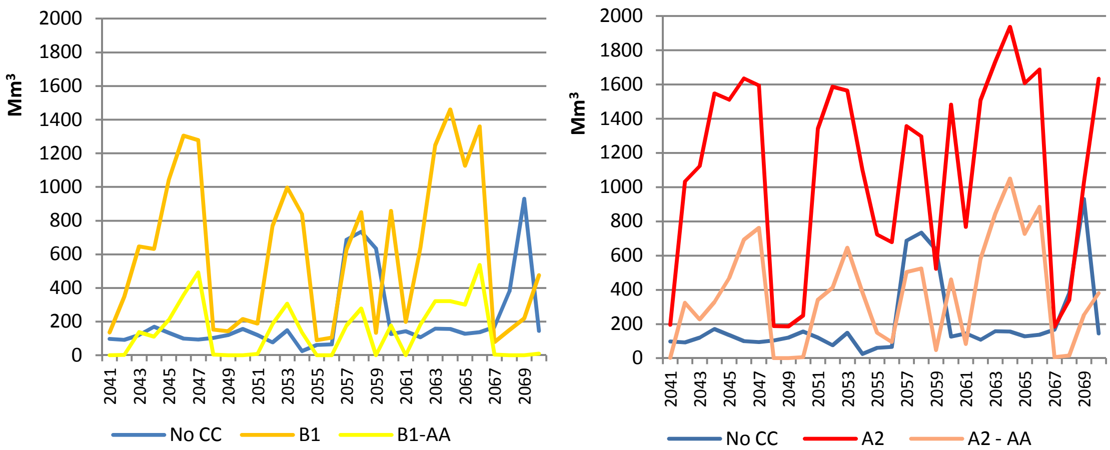
According to the model simulation, under autonomous adaptation, farmers would try to reduce their water demand and would adjust their cropping patterns changing to more water efficient crops or to rain-fed production. This increase in rain-fed area is more likely for the traditional Montijo IC as having no access to pressurised irrigation technologies they have less options for adaptation. In fact, the share of rainfed area in Montijo and Zújar ICs is similar while water constraints are much higher in Zújar than in Montijo. Although the lower water consumption translates into lower expected farm income, irrigators are in a less risky position as having lower water demands results in an increase in demand reliability.

Figure 17. Cropping patterns before and after private adaptation to climate change



These changes in land use would substantially reduce water demand, affecting the overall functioning of the water system. Maximum level of unmet demand in the A2-AA scenario (period 2041-2070) reaches 1100 Mm3 (Figure 18) in a severe drought year, which is around 45% lower than unmet demand without autonomous adaptation for the same year. However, even if autonomous adaptation diminishes water demand, in extreme drought years there is still a large unmet demand as water storage fails. Thus, policy-driven adaptation strategies are still needed.

Figure 18. Total unmet demand in the baseline scenario with autonomous adaptation at farm level



3.5.2 Analysis of potential planned adaptation options in climate change scenarios

Given the impacts of climate change on water availability, demand satisfaction and crop production, the need to implement policies to adapt to climate change is evident. Here we explore the potential of several adaptation measures to reduce farmers' vulnerability.

The strategies simulated, as explained in section 3.4.3, are:

1. Environmental strategy (ENV): Maintenance of environmental flows + compliance with current irrigation water allotments
2. Economic incentive strategy (ECON): Cost recovery through volumetric water pricing + irrigation modernisation

In the simulation of strategy 1 we test the impact of the establishment and compliance with minimum environmental flows, as required by the WFD, and the effective enforcement and control of current water policies, which grant farmers a maximum water allotment of 7500 m^3/ha, or 6600 m^3/ha in the case of farms that draw water directly from river courses.

The simulation of strategy 2 includes the application of a tariff system for the cost recovery of water services that aims to improve efficiency and reduce water consumption, and thereby attainment of higher rates of productivity per cubic meter of water. According to the Guadiana River Basin Management Plan (CHG, 2013a), the financial costs of surface water in the Guadiana basin amount to 0.034 €/m3. Resource cost, defined as the scarcity value of water or its opportunity cost, was estimated through the weighted average of the marginal value of water, i.e. the value provided by one additional unit of water, for each farm type, when financial costs are already paid (provided by the MPM, through the dual value of the water constraint). Estimated resource cost ascend to 0.021 €/m^3. Environmental costs are internalised by means of the constraint of farm water allotments, which in theory ensures that environmental water demands are met. Thus, total water costs are 0.055 €/m^3.

Both strategy 1 and strategy 2 lead to lower water demands, and, consequently, to lower supply delivery (Table 14) under normal climate conditions. However, in the case of the A2 climate change scenario, a substantial decrease in water supply is projected.

The average change in water supply delivered is used for the simulation of farmers' autonomous adaptation. Economic results across the different planned and autonomous adaptation scenarios are shown in Table 15.

Table 14. Impact of adaptation strategies on water supply delivered to irrigation catchments under different climate scenarios (average for period 2041-2070).

	ENV strategy			ECON strategy		
	No CC (Hm3)	A2 (Hm3)	Difference No CC-A2 (%)	No CC (Hm3)	A2 (Hm3)	Difference No CC-A2 (%)
Montijo IC	73	71	-2.5	39	44	14.4
Tomas Directas 1 IC	32	20	-37.2	20	18	-13.2
Tomas Directas 2 IC	29	33	16.6	28	33	15.5
Vegas Altas	400	164	-59.1	294	132	-55.2
Vegas Bajas	177	113	-36.0	40	42	6.3
Zújar IC	77	42	-46.3	56	38	-32.4
TOTAL	**788**	**443**	**-43.8**	**477**	**306**	**-35.7**

Water supply delivered under the ECON strategy is lower than under the ENV strategy because of lower demand. Thus, irrigation communities are already better prepared to face water scarcity, and this is confirmed by the results of water supply delivered under the A2 climate scenario. If we compare A2 scenario with the No CC scenario we see that under the ECON strategy the reduction of supply is smaller than in the ENV scenario (-35.7% and -43.8% respectively).

Table 14 shows the distinct vulnerability of the irrigation districts that is attributable to differences in their spatial location and in the technologies that are used. As shown in the baseline scenario, irrigation areas in downstream Middle Guadiana (Montijo, Tomas Directas 2 and Vegas Bajas) are less vulnerable than those in upstream Middle Guadiana. In addition, irrigation areas without modern irrigation techniques (e.g. IC Montijo) are more vulnerable than the modern ones (Tomas Directas 2). Supply delivered under the A2 climate scenario decreases for IC Montijo with the ENV strategy, but increases with the ECON strategy, which includes modernisation in the Montijo irrigation community. The reason for this is that water demand in Montijo IC decreases largely as a consequence of improved technical efficiency, and, thus, there is more room for satisfying the increasing irrigation demands of crops under the A2 CC scenario. These results are also confirmed when we look at the economic impacts for this irrigation community. Table 15 shows how the implementation of irrigation modernisation in the Montijo IC (ECON strategy) results in a decrease in water consumption and a corresponding farm income increase. This is attributable to new, more water efficient and productive cropping options that become available to farmers in this irrigation community. Many authors have reported on the role of irrigation technology, among other factors such as farm size and crop diversification, in determining the effect of water pricing policies (Berbel and Gómez-Limón, 2000; Berbel et al., 2007; Varela-Ortega et al., 1998) and it is recognised that having modern irrigation systems enables more profitable cropping alternatives. This results in a smaller impact of water tariffs on farm income. Kahil and Albiac (2012) consider irrigation modernisation to be an adaptation measure that produces positive effects for farm income and social welfare. They also report how irrigation modernisation incentivises horticultural and permanent crops as these are highly profitable and can therefore justify the required investment costs. However, it should not be forgotten that the mentioned effect of improved irrigation technologies may reduce the effectiveness of water tariffs with respect to the aim of reducing water demand.

Table 15. Economic impact of planned adaptation strategies and autonomous adaptation

		Farm income (€/ha)	Water consumption (m3/ha)	Water cost[8] (€/m3)	Water marginal value (€)	Total labour (total days)
IC Montijo	Baseline	1970	9423	0.011	0.029	6221650
	Baseline - AA	1728 (-12%)	8132 (-14%)	0.013	0.031	5732606
	ENV	1931 (-2%)	7500 (-20%)	0.014	0.028	5734009
	ENV - AA	1701 (-14%)	7313 (-22%)	0.014	0.032	5731828
	ECON	2017 (+2%)	3822 (-59%)	0.073	0.000	6773780
	ECON - AA	1801 (-9%)	3712 (-61%)	0.071	0.000	6175219
IC Tomas Directas	Baseline	4086	6247	0.040	0.010	39293325
	Baseline - AA	2935 (-28%)	4348 (-30%)	0.046	0.050	36400912
	ENV	4063 (-1%)	4977 (-20%)	0.041	0.011	39450920
	ENV - AA	3166 (-23%)	4033 (-35%)	0.045	0.051	40166137
	ECON	3859 (-6%)	3808 (-39%)	0.123	0.000	39984372
	ECON - AA	3253 (-20%)	3659 (-41%)	0.166	0.051	42811604
IC Zujar	Baseline	1708	7102	0.040	0.014	4765225
	Baseline - AA	1346 (-21%)	3288 (-54%)	0.056	0.039	4102070
	ENV	1702 (≈0%)	7102 (0%)	0.040	0.014	4805801
	ENV - AA	1379 (-19%)	3814 (-46%)	0.052	0.039	4117067
	ECON	1564 (-9%)	5778 (-19%)	0.064	0.000	4708134
	ECON - AA	1355 (-21%)	4801 (-32%)	0.064	0.025	4145244

[8] Water costs largely vary accross irrigation communities and across scenarios. This is due, first, to the fixed part of water fees (€/ha) that result in an increase in the cost per cubic meter when water consumption decreases; and, second, because initial tariffs paid in each irrigation community vary because of differences in management and infrastructure. The part of the tariff corresponding to the resource cost is applied equally in all irrigation community independently of the fees already paid.

Similarly to the case of Montijo IC under the ECON strategy, Tomas Directas 2 IC, the downstream section of Tomas Directas IC, shows a higher supply delivered under the A2 scenario. This means that under severe climate change, crop water demand increases and that, on average, it is possible to increase supply delivered with respect to the normal climate scenario. However, this does not imply that water demand is fully covered. For this, we should look at demand coverage and reliability (Figure 21).

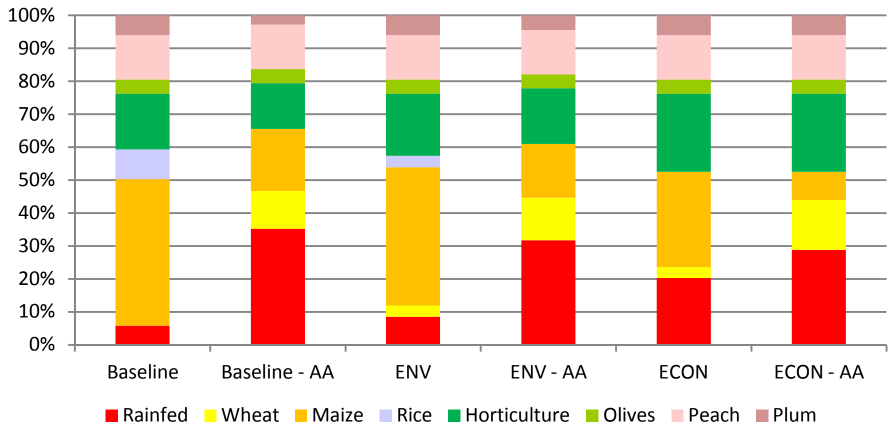
Zújar and Tomas Directas ICs (both with modern irrigation) show quite similar results under the ENV scenario. However, the impact on the traditional Montijo IC is slightly more negative than the impact observed for the other ICs. With the implementation of environmental flows and the control of compliance with water allotments, this irrigation community experiences income losses of around 2%. The two modern irrigation communities are already complying with the legal water allotments, but Montijo IC consumes more water partly due the weak control of water use at farm level and to the non-modern water conveyance and irrigation systems. These entail reduced technical efficiency and significant water losses in the distribution network.

The impact of the ECON strategy (cost recovery + irrigation modernisation) is more varied across irrigation communities than the impact of the ENV strategy. Tomas Directas and Zújar IC show income losses of 6 and 9% respectively, while Montijo IC shows a 2% income increase as a consequence of irrigation modernisation. Both strategies produce a significant reduction on water consumption, specially the ECON strategy. This translates into lower unmet demands (Figure 20) and greater demand reliability (Figure 21).

In all three ICs analysed, the reduction of water use, especially under the ECON strategy, is linked to an increase in the unitary cost of water paid. The ECON strategy also reduces the marginal value of water. However, in all three AA scenarios the marginal value of water increases, reflecting the higher scarcity value of water when climate change impacts on water availability are internalised by farmers. Scenario effects on labour use are small although reductions in labour use are observed more clearly under AA scenarios, mostly due to the reduction of irrigation area.

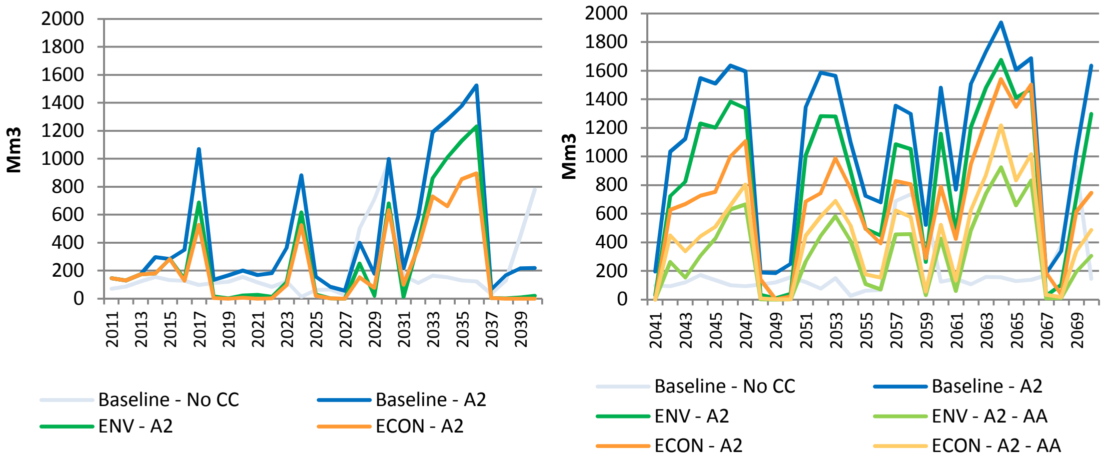
Figure 19 shows the evolution of aggregated cropping patterns across scenarios. The main trends shown include a decrease in the area of rice cultivation and an increase of the area of rain-fed crops. The adaptation strategies simulated pursue the reduction of water demand, which makes rice production increasingly infeasible. However, in the short term, rice production disappears only in the ECON strategy scenario, which imposes cost recovery. In the long run (AA scenarios), the maize area decreases in favour of wheat. This is mostly due to the lower irrigation water requirement of wheat but also because of projected price trends in the future which are more positive for wheat than for maize. As physical and policy water constraints are implemented, the rain-fed area increases and water is allocated to the most water efficient and profitable cultivars such as horticultural crops.

Figure 19. Aggregated cropping pattern changes in the Middle Guadiana for selected ICs across scenarios



The ultimate goal of each adaptation strategy simulated is to close the gap between supply and demand. We can see in Figure 20 how each adaptation scenario reduces unmet demand. The ECON strategy is the one that reduces unmet demand to a greater extent, but at the same time it results in greater economic impacts for the irrigation communities. The ECON – AA scenario (economic incentive plus autonomous adaptation) is the most negative in economic terms. Farmers would face a reduction of expected income of around 20%, except for the traditional Monijo IC where irrigation modernisation is implemented. Considering that cost recovery is a requirement already included in the Water Framework Directive, we can conclude that WFD already promotes adaptation to CC-driven water scarcity.

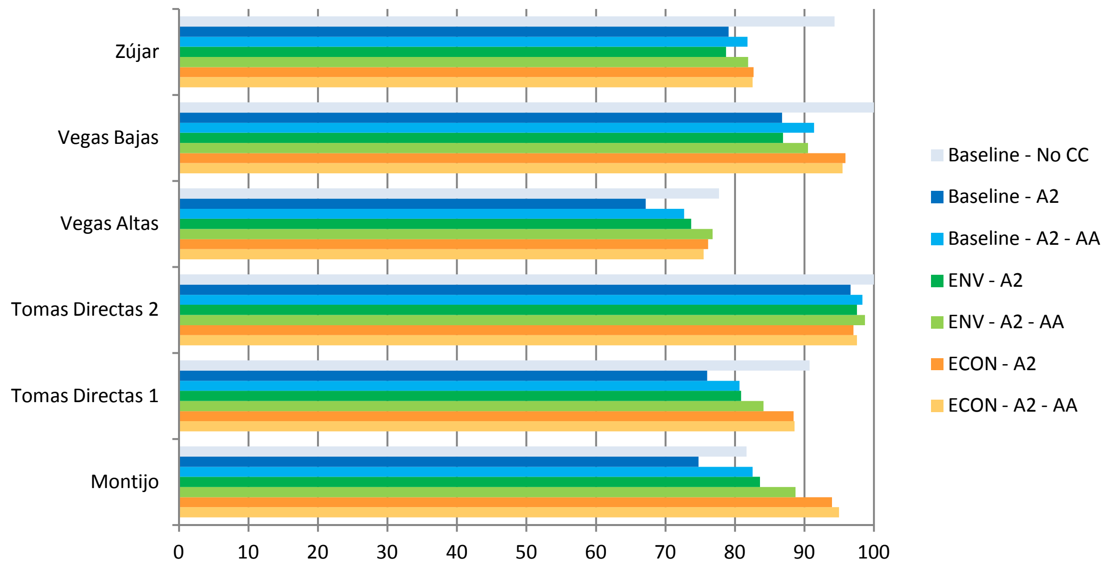
Figure 20. Impact of planned adaptation strategies and autonomous adaptation on unmet demand



The reduction of the gap between supply and demand of water presented above (Figure 20), translates into increased demand reliability at the level of the irrigation community (Figure 21). As demand reliability increases, risk[9] for the irrigation community decreases. We can see how the different planned and autonomous adaptation options highly reduce risk in the Montijo IC, especially when irrigation modernisation is implemented. The general trend is that irrigation communities that initially consume large amounts of water (frequently above permitted levels) are the ones that benefit the most from adaptation strategies in terms of risk reduction. Both the ENV strategy and the ECON strategy contribute to reduce vulnerability in the different irrigation communities. Results show that relatively inexpensive autonomous adaptation strategies at the farm level such as changing to more efficient technologies and expanding the area of high value crops, already contribute to reducing water demand and improving reliability - this has also been illustrated by other authors (e.g. Tanaka et al. 2006). At the same time, changes in water management, such as the policy stretegies simulated here, are still necessary for achieving effective adaptation, as shown in other studies (Joyce et al., 2011).

[9] Risk is defined here in probabilistic terms as the percentage of time in which water demand is not satisfied. Risk = 100 – demand reliability (%)

Figure 21. Demand reliability (%) across scenarios (percentage of WEAP time steps, i.e. months, in which water demand is fully covered)



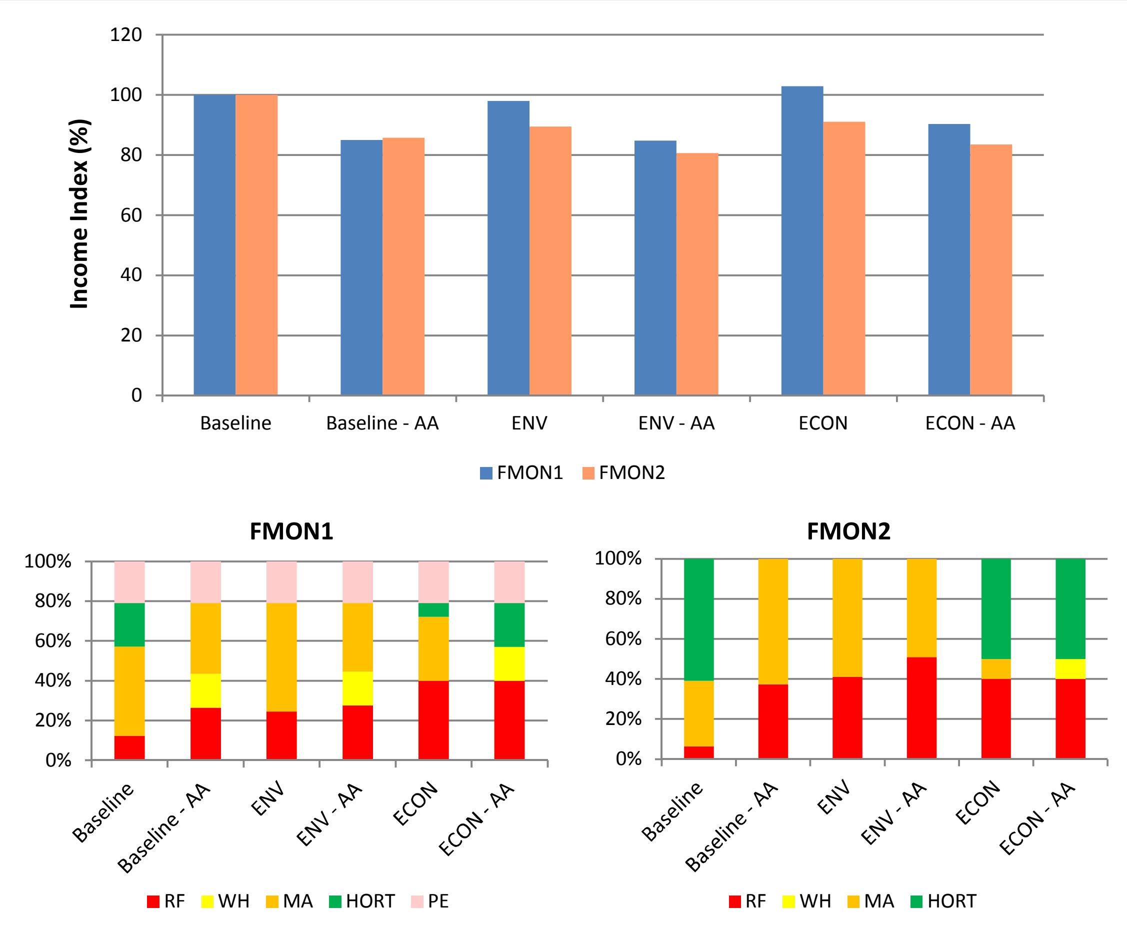
Results at farm level are provided in Annex B. However, as an illustration of the potential of the methodology to indentify farm vulnerability profiles, we present an example of the results at farm level for the two farm types in Montijo IC (Figure 22).

Results at farm level in Montijo (downstream traditional irrigation community) show that the bigger farm, FMON1 faces lower income losses than the smaller farm FMON2. This can be explained by the size of the farm - larger farms tend to have greater flexibility - and due to the presence of permanent crops in farm FMON1, which require lower water volumes and achieve a higher profitability than other crops. These results coincide with the results presented in the previous chapter and are also reflected in research such as by Berbel and Gómez-Limón (2000), Berbel et al. (2007) or Chohin-Kuper et al. (2003). These studies show that small farms with low technology adoption face greater income losses than their counterparts. In this case, the small farm FMON2 faces greater income losses than FMON1, which has similar technical characteristics but also a small area of pressurised irrigated permanent crops.

Constraints to water use will, in the long term, result in the loss of horticultural crops as farmers do not have access to efficient modern irrigation systems. In addition, this is a consequence of the full decoupling of CAP payments, which removes the partially coupled subsidies for tomato and integrates them in the Single Farm Payment. Similar results of the impact of full decoupling on the area of vegetables in the Middle Guadiana are shown in

Blanco-Gutiérrez et al. (2013). However, an analysis of the full effect of the decoupling of CAP payments is beyond the scope of this study.

Figure 22. Results of the simulation of adaptation strategies for the farm types of Montijo IC: impacts on income (above) and impacts on cropping patterns (below)



3.6 Conclusions

In this research, we assessed climate change impacts at irrigation community and basin scales, and evaluated the effect of different adaptation options. The integrated modelling approach applied is based on a hydrology model with an agronomic module and a farm-based economic model of constrained optimisation. This approach is shown to be a useful method that supports adaptation policy-making by providing a better understanding on the likely impacts of climate change, multi-scale vulnerability and the effect of different adaptation options. By combining a biophysical model that represents the water system and agronomic processes and an agro-economic model that simulates farmer's behaviour, it contributes to closing the gap between outcome-oriented biophysical impact and vulnerability assessments and socio-economic vulnerability and adaptation studies.

This research highlights the value of hydro-economic models not only for IWRM but also for climate change impact, vulnerability and adaptation assessment. While economic models are crucial for understanding water demand and the behaviour of economic agents and water users, hydrologic modelling provides insights into the spatial and physical dimensions of water resources. These are crucial for climate change assessments and, more specifically, for representing the supply side of water management.

In fact, hydro-economic model simulations show how in the Middle Guadiana basin, spatial location outweighs the technical characteristics and management of farms and irrigation communities. Zújar, a modern irrigation community located upstream in the Middle Guadiana, experiences a large reduction of water supply even if water storage capacity is greater in this area than it is downstream. This is a consequence of the high demand for water of the neighbouring rice growing water districts. Thus, the lack of implementation of rules or control methods for limiting water uptake from those irrigation districts increases vulnerability of Zújar IC.

Despite this, technology adoption is also a relevant element that determines the vulnerability and adaptive capacity of farms and irrigation communities. Traditional ICs tend to be less efficient in water use because of lower adoption of modern irrigation technologies. They have higher water losses and a smaller range of cropping options than modern farms, as they cannot cultivate crops that require modern techniques. Therefore, the limitation of water availability at farm level results in considerable costs (foregone income). Moreover, results show that the implementation of water pricing policies, that normally would have disastrous impacts in these type of irrigation communities (as shown in the previous chapter), does not inflict large income losses on traditional irrigation communities when they are introduced with a modernisation plan. This modernisation plan would however require additional financial support for farmers and irrigation communities, increasing public costs.

Public statistics show that in the Middle Guadiana region (and in Spain), there is a trend to increase the area devoted to irrigated permanent crops. This research showed that in normal climatic years (no drought), permanent crop farms show very low vulnerability because they have low water requirements and relatively high profitability. These are crops of high value added and high water productivity (€/m^3), characteristics that promote economic efficiency in water use. However, it is important to consider that permanent crops may be more vulnerable to drought than annual crops as crop failure in one year will affect the following years. Permanent crops are associated to multi-annual investments that are often linked to credits and drought can therefore have a long-term impact.

The results of this study highlight the multi-scale and interrelated nature of vulnerability and adaptation. Vulnerability and adaptation in one irrigation community depends on farm cropping and technical characteristics, water management at the irrigation community level, decision-making in neighbouring irrigation districts and spatial location in the basin (which determines climate variables and water infrastructures). The integrated modelling platform developed in this research provides an appropriate framework for analysing climate change impacts, vulnerability and adaptation taking into consideration the multi-scale nature and complexity inherent in vulnerability and adaptation processes.

The measures included in the adaptation strategies analysed in this chapter are mostly measures included or related to the WFD (especially, environmental flows and water pricing for cost recovery). This study shows that the WFD constitutes an important impulse to adaptation. By introducing economic incentives in water management, it contributes to a more rational water use and favours moderate water use in periods of water shortage, reflecting the scarcity value of water. Cost recovery (a WFD requisite) is the only measure that drives the phasing out of rice cultivation in the short term. Considering its importance in the area, this is not an appropriate farming option for water saving and water conservation purposes.

By simulating WFD-related scenarios, this research demonstrates that the implementation of the WFD supports adaptation under the most negative CC scenarios and that it can therefore reduce vulnerability. However, drought periods are more frequent and intense than in the past and further ad-hoc adaptation measures are required together with ambitious drought management plans. This illustrates the relevance of the mainstreaming of climate change adaptation in natural resource management policies. The WFD and Drought Management Plans, effectively implemented are already facilitating adaptation.

The results of the hydro-economic model demonstrate the need to combine quantitative impact assessment methods with more social-oriented methods that are able to consider socio-institutional elements and the human dimension of natural resource use. The hydrology model WEAP, allocates water according to previously defined priorities. However, it cannot represent decisions made by farmers when there is water shortage. Similarly, the economic model assumes profit maximisation as the ultimate goal of farmers' activity. However, when water shortage is experienced or water constraining policies are implemented, additional elements may constrain farmers' decisions on changing production methods or, for example, discontinuing the cultivation of tomato or rice crops, which are both socially relevant crops in the Middle Guadiana basin with a large industry developed around those cultivations. Thus, there may be other criteria, apart from economic ones, that govern decision-making and ignoring them may lead to an underestimation of vulnerability. Therefore, further analysis of vulnerability and adaptation processes seems necessary. This should be done by applying methods that capture social and institutional elements that determine the up-take of adaptation measures and the use of approaches that focus on actors, their circumstances and their needs and preferences.

In sum, this research provides a more integrated view of the interaction between crops, farms, irrigation communities and sub-basins. This contributes to improve our understanding of climate change vulnerability and is crucial for policy-making and the adequate design and implementation of adaptation strategies.

4. On the social side of adaptation: Participatory analysis of determinants and barriers to adaptation in the Middle Guadiana irrigation agriculture

This chapter offers a complementary view to the climate change adaptation assessment provided in the previous chapter. The assessment of climate change adaptation in the Middle Guadiana yielded relevant conclusions on vulnerability in different irrigation communities and areas in the basin and analysed different strategies that may contribute to adaptation. However, whether these strategies can be effectively implemented has not been explored. In this chapter we analyse the socio-institutional context of adaptation in the Middle Guadiana in order to identify potential barriers that may impede adaptation and evaluate the relevance of those barriers when implementing specific adaptation actions.

4.1 Abstract

Climate change has already been observed in many parts of the World, including Spain. In the last decade, increasing awareness on the need to adapt to climate change has fostered the development of international protocols and national strategies for adaptation. However, there are few examples in which adaptation has been successfully implemented, partly because of the existence of socio-institutional barriers to adaptation. While most research on climate change adaptation focuses on the bio-physical and economic impacts of climate change and adaptation, there is a need for improving understanding of the socio-institutional context in which adaptation processes take place. In this chapter, we analyse social networks in the Middle Guadiana to elicit the principle barriers that may impede the implementation of adaptation strategies. For this, we involved stakeholders in the development of a social network mapping exercise to identify barriers to adaptation. Based on expert and stakeholder consultations, we assessed the relevance of each barrier identified and the strength of this in determining the successful implementation of specific measures. Results show that there is a need for creating and strengthening relations between water users, and specifically farmers, and the scientific community in order to take advantage of local and new knowledge to create flexible adaptation strategies. In the Middle Guadiana basin, the government plays a central role in this task and other actors are connected through the administration. Because of this, the coordination of different levels of government and the leadership from public institutions are crucial in order to facilitate the adaptation processes. The lack of awareness and common understanding as well as limited acceptance of planned adaptation initiatives are the main barriers to overcome in this basin. Specifically, water constraining instruments such as water quotas and water tariffs are adaptation options that may be the most difficult to implement. On the other hand, irrigation modernisation and the adoption of different cropping patterns are viewed as the most accepted and feasible measures. This research contributes to adaptation planning as it identifies key elements and characteristics of the socio-institutional context that determine adaptation processes and links them with specific adaptation measures. In addition, the study contributes to adaptation assessments as it provides a better understanding of the social realm of adaptation processes and the feasibility of specific measures with respect to the barriers to implementation that they present.

Key words: adaptation assessment, barriers, climate change, social networks

4.2 Motivation

Despite the fact that the effects of climate change have already been noted in many parts of the world, including in Spain, (EEA, 2012) and even if many international institutions and the scientific community urge governments to plan and implement adaptation strategies, there are few cases in which adaptation processes have been effectively completed (Moser and Ekstrom, 2010). This may be partly due to the relatively recent development of knowledge on climate change impacts and vulnerability that up until now has limited the scope for action on adaptation. In addition, there are barriers or constraints and limits to adaptation as demonstrated by impacts caused by extreme events such as floods and droughts (Berkes and Jolly, 2001). Stakeholder (SH) participation, institutional coordination, efficient communication and public awareness have been highlighted in various adaptation studies (Adger et al., 2007, Biesbroek et al., 2010; Lorenzoni et al., 2007) as key elements, among others, that determine adaptation planning and implementation effectiveness. These elements are in turn determined by different aspects that relate to the relations and interactions between different actors, how decisions are made and how information and financial resources are distributed amongst groups.

In this research, we attempt to improve the understanding of the socio-institutional setting and actor relationships in the adaptation context in the Middle Guadiana to draw conclusions on the main barriers that may arise when implementing adaptation strategies. Following on from the previous chapter on climate change impacts and adaptation in the Middle Guadiana, we aim to further characterise adaptation in the basin by looking at the social interactions and barriers that may influence adaptive capacity and determine the success of adaptation processes.

4.3 Context and Methods

4.3.1 Socio-institutional networks and barriers to adaptation

Adaptation research has developed around different study focuses as identified by many authors (Downing, 2012; Eakin and Luers, 2006; Füssel, 2007; Füssel and Klein, 2006; Smit and Wandel, 2006; and many others). Those streams of adaptation research can be grouped around two main axes, the first one oriented towards the quantification of impacts and measurement of the effects of adaptation actions, and the second one addressing the social dimensions of climate change vulnerability and adaptive capacity. Within the first, the most frequent methods used include biophysical models and economic assessments (e.g. Nelson et al., 2009; Nicholls and Toll, 2006; Tubiello and Rosenzweig, 2008; Tubiello et al., 2000) and methods that contribute to prioritise adaptation measures, such as cost-benefit and cost-effectiveness analyses or multi-criteria assessment methods (e.g. De Bruin et al., 2009; Dolan et al., 2001). Within the second, two different types of assessments can be distinguished. On the one hand, a number of studies look at identifying the most vulnerable individuals, communities, countries and regions. For these, different sets of indicators of social vulnerability and adaptive capacity are used, based on initial assumptions made by the authors about the drivers of adaptive capacity (e.g. Guillaumont, 2009; Hahn et al., 2009). On the other hand, we find a less numerous group of adaptation studies whose primary objective is to contribute to the implementation of adaptation processes by assessing adaptive capacity and identifying adaptation needs within communities or regions by looking at decision-making processes and values and perceptions among the involved actors (Smit and Wandel, 2006). This type of assessment is usually based on the involvement of SHs and relevant actors within the community that allow for an analysis of how decisions are made and implemented and characterise adaptive capacity and barriers to adaptation. In this chapter we focus on this type of adaptation assessment to look at the main characteristics of the Middle Guadiana adaptation context with the aim of understanding potential barriers to adaptation and the feasibility of specific adaptation measures for the Middle Guadiana irrigation sector.

Adaptation to climate change is a dynamic process that occurs at multiple temporal, geographical and decision-making scales (Agrawal, 2010; Berkes and Jolly, 2001; Downing, 2012; Smit and Wandel, 2006; Tompkins and Adger, 2004). Adaptation processes often involve short-term actions as well as long-term processes that imply economic, social and institutional changes. These take place at the local level and have implications at the regional level (and vice-versa), and involve actions of individuals, communities and decision-makers that frequently are interconnected or need to be coordinated.

There are many different types of adaptation actions. For example, in agriculture, Smit and Skinner (2002) list four types of options including technological developments, government programs and insurance, farm production practices and farm financial management. All of these as well as other options will involve links and relationships between different actors at diverse scales. Implementing new technologies at the farm level require not only the farmer's willingness to adopt these new technologies but also financial support from the government or dissemination and support from extension services. Government programmes and insurance systems require social acceptance and legitimacy for which the inclusion of actors in the design and implementation of programmes may be necessary. Changes in farm production practices may require technology and knowledge for which information flows between farmers and scientists or agricultural input industries are needed. Finally, farm financial management may entail the development of new economic activities involving actors from different economic sectors or the development of governmental programs for income stabilisation, among other factors.

These high dependency of adaptation actions on different types of actors and social and institutional relations is indicative of the fact that the outcome and eventual success of adaptation processes will be determined by multiple and overlapping social processes (Jones and Boyd, 2011). In addition, socio-institutional networks will play an important role in building adaptive capacity and facilitating adaptation.

A social network is the set of actors and the ties between them that define a system. Social networks include all relevant actors in a system and the relations established between them through different types of socially relevant links such as information exchange, financing flows and other mechanisms. Various studies illustrate how social networks are relevant to natural resource management and climate change adaptation, and infer conclusions on how different aspects of socio-institutional relations may determine the effectiveness of adaptation processes. Scheffran et al. (2012) emphasise the role of social networks in improving resilience and facilitating adaptation in the case of migration as an adaptation process. Tompkins and Adger (2004) analyse the relevance of social networks and institutions in improving resilience in social and ecological systems and point out the benefits of co-management in climate change adaptation in a case study in Trinidad and Tobago. Berkes and Jolly (2001) describe a case study in Arctic Canadian communities in which co-managed institutions facilitate multi-scale interactions among individual communities. They also provide an analysis of the different levels of government and their role of in providing access to information and the creation of opportunities for new adaptive responses. Folke et al. (2005) stress the role of formal and informal social networks in generating social learning, facilitating knowledge transfer, developing social capital, and supporting capacity and financing flows for improving management of resources and adaptation. In line with this, as discussed in the adaptive management literature (Pahl-Wostl et al. 2005; Tompkins and Adger, 2004), enhancing social learning and promoting actions at all levels from the individual to governments, increases the capacity of socio-ecological systems to respond to long-term climate change risks. For this, SH participation and engagement at multiple levels of decision-making, multiple scales of management, and improved control and monitoring for informing decision-making are key elements. In fact, although climate change adaptation will most frequently affect activities and management at the local level, interactions between actors and institutions at different scales will facilitate improved responses to change (Folke et al., 2005; Tompkins and Adger, 2004).

Social Network Analysis (SNA), rooted in graph theory (Freeman, 1979; Scott, 2000), is the systematic analysis of social networks that maps the relations between actors using different types of metrics to quantify them. We can find quantitative and qualitative SNA (Bharwani et al., 2012). Quantitative SNA usually makes use of mathematical analysis and different statistics to describe the overall structure of social networks. Qualitative SNA, also called social network mapping (SNM), does not quantify the relations and relevance of actors but studies the shape of the networks and draws conclusions on a system's functioning based on network topologies. Bharwani et al. (2012) describe the potential of SNA in enhancing understanding of how the different institutions and actors in a system interact and how information, financing or capacity flow among them. They use this information to identify barriers that may arise in developing adaptation processes. Bodin and Crona (2009) study how social networks affect natural resource management. Specifically, they elaborate on how in SNA, network characteristics such as centrality, cohesion or number of ties, determine a system's performance with respect to leadership, common actions, shared values and visions, which are cross-cutting elements that are likely to create barriers at every stage in the adaptation process (Moser and Ekstrom, 2010).

The Intergovernmental Panel on Climate Change (IPCC) identifies different elements that determine the scope of adaptation, including economic resources, technology, information and human capital, infrastructures and institutions (IPCC, 2001). Similarly, these same elements can create barriers for adaptation. Jones and Boyd (2011) recognise the existence of three general types of barriers, namely natural, human and informational, including knowledge, technical and economic barriers, and social. Among these, most studies have focused on the natural, technical and economic barriers, with less attention being paid to social barriers. However, understanding these types of barriers is a key step in overcoming them and contributing to the success of the adaptation process.

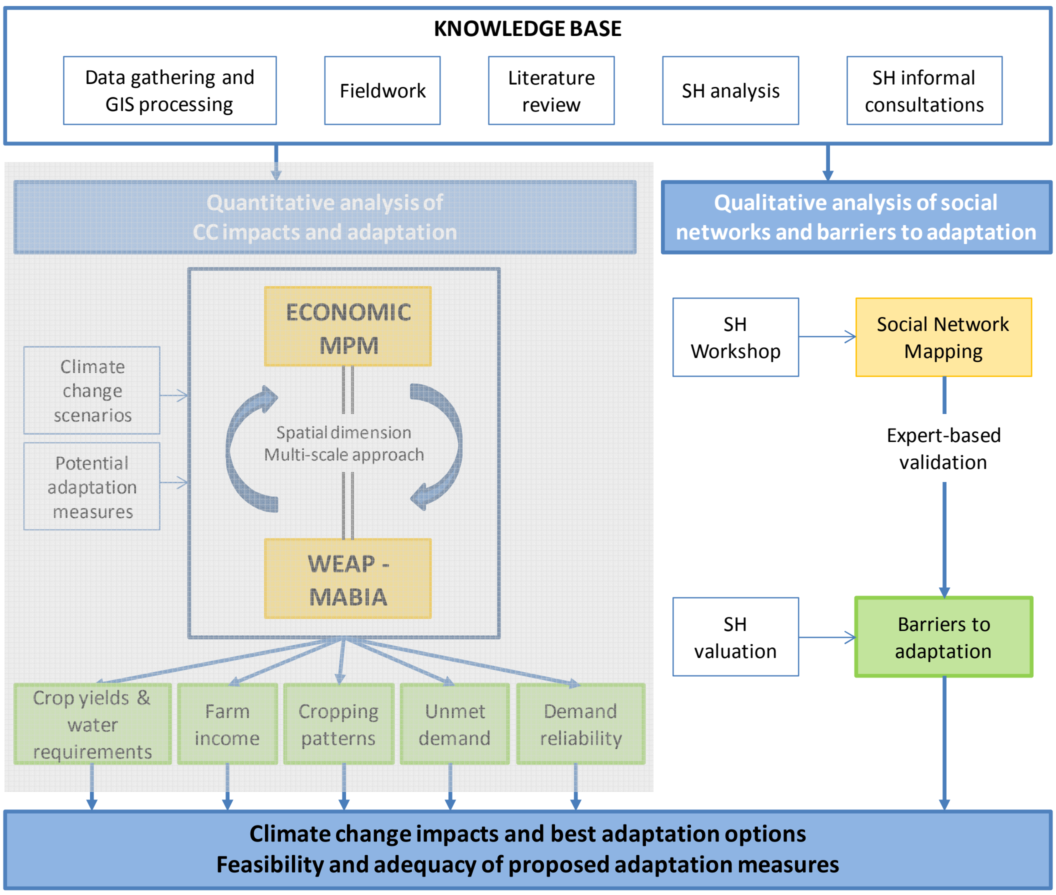
Among the studies that focus on social barriers we find the work by Adger et al. (2009), which elaborates on different aspects that impede and limit adaptation including the relevance of individual and social goals, perceptions, values and beliefs that often create subjective and malleable barriers. Moser and Ekstrom (2010) propose a framework to identify barriers along the different stages of the adaptation process and ways to overcome these barriers. This framework was applied by Kuruppu et al. (2012) to the study of adaptation in Australia at the local level and allowed for the identification of key barriers related to the trade-offs between long-term and short-term actions, uncertainty, political will or lack of knowledge, among others. Nielsen and Reenberg (2010) studied barriers to adaptation in northern Burkina Faso based on SH consultations and interviews, and found that the adaptation of livelihoods varies in different communities because of cultural barriers. Krysanova et al. (2010) compared climate change adaptation in different river basins of the world by mapping the implementation levels of common adaptation measures and assessing the relevance of different technical, economic, social and institutional barriers according to SH opinions.

In this research, we aim to identify the main crosscutting barriers that may impede adaptation using social network mapping. We then assess the relevance of the key identified barriers to determine specific adaptation options based on SH consultations. In this way, we attempt to complement the adaptation assessment carried out in the previous chapter by providing a more complete picture of not only the effectiveness but also the feasibility of adaptation strategies in the Middle Guadiana basin.

4.3.2 Participatory assessment of barriers to adaptation

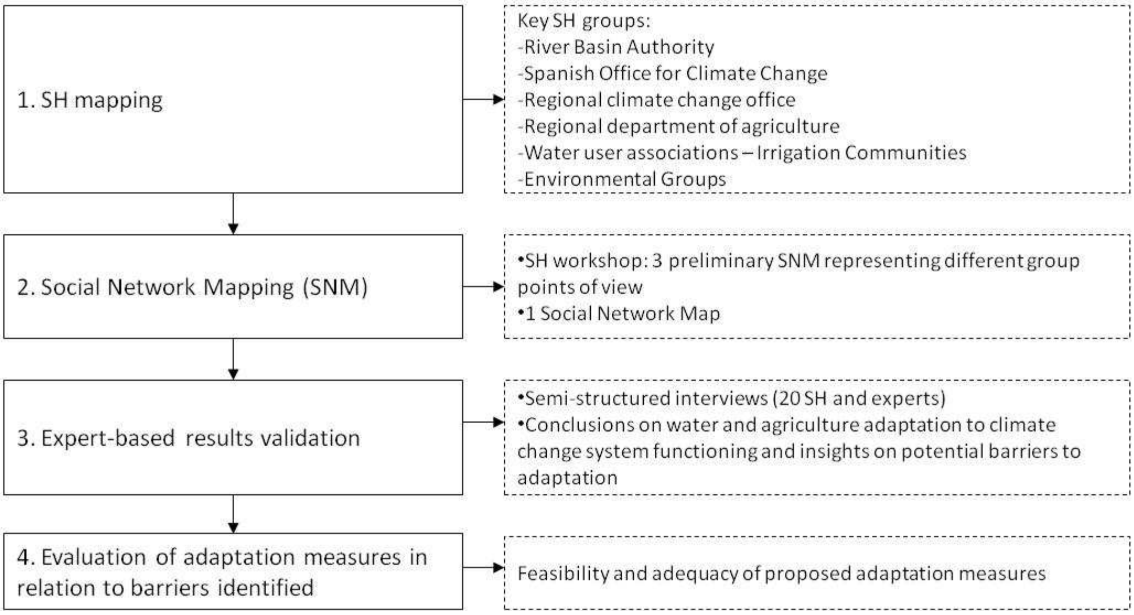
Figure 23 shows the methodological framework developed for the assessment of adaptation in the Middle Guadiana basin. The left hand side of the scheme, shaded in grey, shows the quantitative model-based analysis of impacts and adaptation carried out in the previous chapter. The right hand side of the scheme shows the SH-based qualitative analysis of barriers to adaptation which includes a SNM exercise and the semi-quantification of barriers to adaptation. The analysis of barriers to adaptation, therefore, contributes to produce and enlarged view on adaptation in the Middle Guadiana complementing the model based assessment of adaptation options.

Figure 23. Scheme of the research



The process followed for the analysis of barriers to adaptation comprised several stages summarised in Figure 24.

Figure 24. SH process for the analysis of barriers to adaptation



The first stage involved the SH mapping and selection of key SH groups, including the Guadiana River Basin Authority (RBA), the Spanish Office for Climate Change (OECC), which depends on the Spanish Ministry of Agriculture, Food and Environment (national government), the Regional Office for Climate Change (regional government), the Regional Department for Agriculture (regional government), water user associations (irrigation communities, IC) and farmers, and environmental groups.

The second stage consisted in the construction of a SNM that represents the socio-institutional context for adaptation in the Middle Guadiana basin. For this, a SNM exercise was developed in the MEDIATION project[10] (Bharwani et al., 2012; Varela-Ortega et al., *submitted*), based on the NetMap approach by Schiffer and Hauk (2010), that studied the relations between different relevant actors, their role, their goals and the main strengths and weaknesses in the

[10] MEDIATION (2010-2013). Methodology for Effective Decision Making on Impacts and AdaptaTION. FP7. Small Collaborative Project. European Commission. DG Research. Project nº 244012

adaptation decision-making and implementation context. A SH workshop was organised for this purpose, in which SH worked in three different groups, policy-makers, farmers and environmental groups, and produced three different SNM (for details about the SNM exercise see Annex C). After the workshop, these maps, containing the views from the different SH groups, were integrated into one SNM.

In a third stage the integrated SNM and the derived insights on barriers to adaptation were validated with SHs. For this, semi-structured interviews were carried out with key selected experts and SH that enriched and validated the conclusions drawn from the analysis of the SNM. Potential barriers to adaptation to climate change in the Middle Guadiana basin were then identified.

Finally, the fourth stage of the process consisted of the valuation of barriers using a questionnaire in which SHs rated the strengths of each barrier with respect to the implementation of selected specific adaptation measures.

The following table summarises the diversity of SH groups and experts involved in the different stages of the process, totalling 20 persons from nine different institutions or SH groups.

Table 16. SH involvement in the participatory analysis of barriers to adaptation.

Actor	Number of participants (total)	SNM building	Validation of SNM	Evaluation of Adaptation measures
Guadiana river basin authority	2	X	X	X
Spanish Office for Climate Change	3	X	X	X
Regional Dept. of Agriculture and Environment – Irrigation Service	2		X	X
Regional Dept. of Agriculture and Environment – Environmental Protection	2	X	X	X
Irrigation communities (ICs)	3	X	X	X
WWF (NGO)	2	X	X	X
Adenex (regional environmental protection group, NGO)	1		X	X
New Water Culture Foundation (NGO)	1		X	X
Experts on water, agriculture and climate change adaptation (scientists)	4	X	X	X

4.4 Results and discussion: the adaptation decision-making context and barriers to adaptation

In this section, we present the analysis of the socio-institutional adaptation context and potential barriers to adaptation in the Middle Guadiana basin. Then, we explore the feasibility of the adaptation measures evaluated in the previous chapter with respect to the barriers for their implementation.

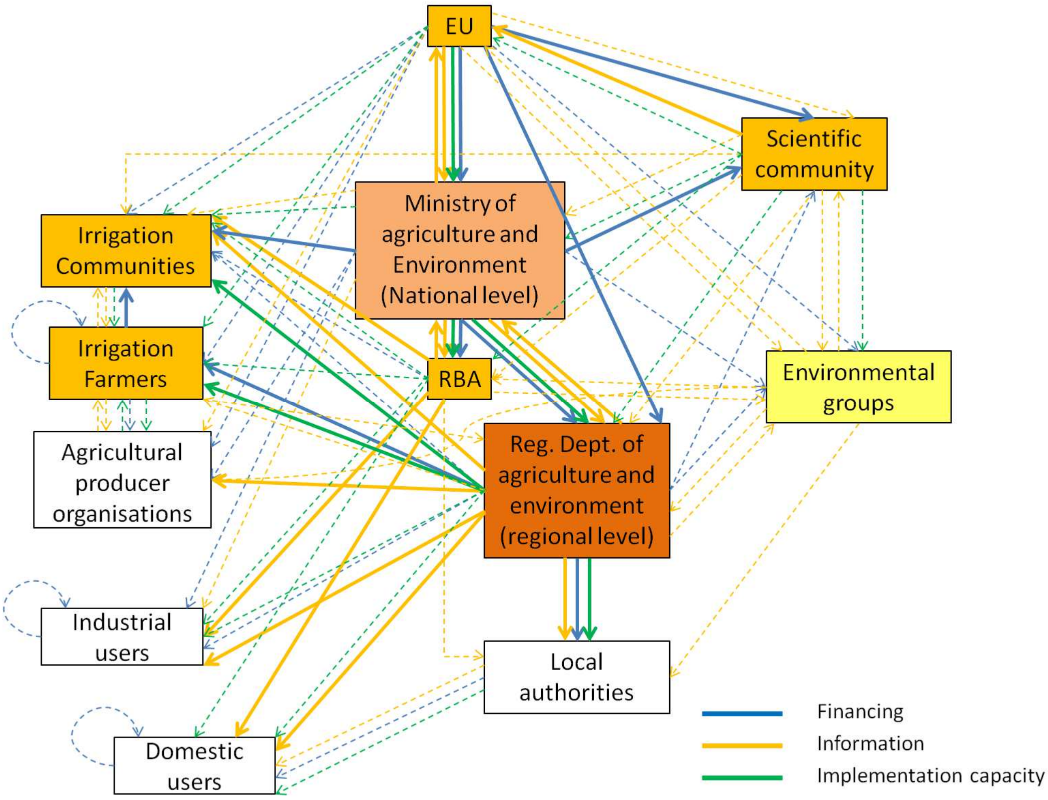
4.4.1 Social Network Map analysis

SNM is a useful tool for laying the groundwork for an in-depth analysis of the relation between different institutions and actors involved in a given system (Bharwani et al., 2012), in this case, the water system. Social networks provide insights on the key elements and links that need to be strengthened in order to allow for a better functioning of the system considered, and therefore are useful for identifying barriers and the best way to overcome them. In the context of the MEDIATION project a socio-institutional network mapping exercise was performed in a SH workshop. SH were divided into three groups: water administration, farmers and environmental oriented groups. Then, groups identified the key institutions and actors involved in adaptation in the water and agriculture sectors, and established the links between them in terms of financing, information and implementation capacity flows. Bharwani et al. (2012) and Varela-Ortega et al. (*submitted*) describe the workshop development and discuss the results obtained. The three SNM are presented in Annex C.

The analysis of these networks provides useful information. First, it provides insight on how each group perceives its own role within a system and what the main knowledge gaps and potential barriers regarding understanding, awareness, leadership and consciousness about its own capacity and responsibility for accomplishing adaptation are. Second, it provides an overall picture and allows for the development of a single model (one aggregated SNM) of the system, making it easier to identify key barriers for adaptation, and possible ways to remove them.

Building on the three networks developed by the different actors and taking into account not only what they represented in the maps but also what was identified as missing in their networks according to the author’s expertise on the region and previous research carried out in the basin (Varela-Ortega et al., 2009), a new integrated SNM is built in order to summarise the most relevant elements and capture the key structural aspects. Then, this integrated SNM was presented to experts and SHs and it was validated and further refined with them (see validation questionnaire in Annex D). The final SNM is shown in Figure 25.

Figure 25. Social Network Map that represents the water sector adaptation system.



** Colours represent the number of ties of each actor, giving an idea of the most influential actor in the system. Dark orange represents a maximum level of influence with respect to lighter orange and yellow, while white actors are the least influential ones.*

*** Blue, yellow and green arrows represent financing, information and capacity flows respectively. Bold lines represent formal and/or strong flows while dashed lines represent informal and/or weak flows.*

The network structure shows a medium level of cohesion, with different subgroups easily identifiable. First, there is a vertical axis, which is central in the network and corresponds to the different governmental levels. Then, we see, in the right side of the network, the scientific community and the environmental groups, which are connected to the administration but also connected to each other. In the left side of the network, we have the different water users, and we find that industrial and domestic users are isolated from other users and only tied to national and regional, and regional and local administrative levels respectively. Ties between different users are limited and domestic and industrial users are peripheral actors in the network. Finally, agricultural users form a subgroup with the ICs and producer organisations with links between themselves and with the governmental bodies at different levels. The fact that industrial and domestic users are marginal actors is consistent with the fact that, in terms of water consumption, agriculture is the key actor. With 90% of total water withdrawals and resulting high vulnerability, the need for adaptation is particularly high for this sector.

The network shows a clear centrality of governmental bodies, within which the regional department of agriculture and environment and the Ministry of Agriculture and Environment (national level) are the most influential actors, more so than the River Basin Authority (RBA) which is also a key player. The administrations at different levels are the key actors transferring information, financing and capacity, mainly to water users. The different governmental bodies act as a bridge between water users and the scientific community and environmental groups. These last two groups of actors are important sources of information but have little interaction with water users. In the case of environmental groups, the confrontation of the goals pursued by them as compared to those of water users is perceived as a key issue that impedes the development of further connections between them. The lack of connections between the different users and between users and the scientific community and environmental groups is indicative of possible low levels of awareness about climate change concerns in relation to water. This may be a factor that prevents the development of a common understanding by the different users, reducing the likelihood of joint actions in the basin (Bodin and Crona, 2009). Stakeholders agreed on this and confirmed the lack of a common understanding and awareness among users, and emphasised the key role that scientists should play by improving information and communication flows. The scientific community is perceived by SH as a key actor in providing knowledge and information as it does not have conflicting objectives with other actors in the systems. In this sense, and following Folke et al., 2005, combining new scientific knowledge with local knowledge of agricultural water users would open unexplored paths for adaptation. However, this group has very limited interactions with other actors, and their contribution to facilitating adaptation is therefore more restricted than desired. Current information streams are dependent on government, which should be strengthened through official participation channels. At the same time, new flows must be created in order to facilitate direct connections between users through formal dissemination and research consultations and validation processes.

The network shows multiple and strong links between the different administrations in a mostly linear way, indicating a well established hierarchy in terms of financing, capacities and information. This network structure may offer a good opportunity for the implementation of adaptation processes. Although adaptation options are most often adopted locally, the consulted experts highlighted the important role of coordination, flexibility and integration at different organisational and institutional levels in order to build adaptive capacity, as suggested in the climate adaptation and adaptive governance literature (Engle, 2011, Ivey et al., 2004). Therefore, strong leadership from the institutions, political will and effective coordination between different administrative levels are needed to facilitate adaptation in the basin and to ensure that barriers are reduced.

The distinction between farmers and ICs is relevant as these communities (water user associations) have a different and strategic role with respect to information, capacities and participation in policy- and decision-making processes, as compared to individual farmers. In this network, irrigation farmers do not appear to be as isolated as they are represented in the MEDIATION process networks (Annex C) (showed in Bharwani et al. (2012) and Varela-Ortega et al. (*submitted*)). They receive financing flows from different governmental bodies and also information and capacities from both the administrations and the ICs and agricultural producer organisations. The ICs are recognised here as separate actors, with different capacities from farmers and serving as a bridge between the RBA and Reg. Government and farmers. In fact, ICs can facilitate interactions and the representation of the most vulnerable small farmers whose views would otherwise rarely be taken into account in management and policy-making. Most vulnerable groups are frequently not included in planning and adaptation processes (Tompkins and Adger, 2004), making them more exposed to climate change impacts than others. In the Middle Guadiana, for example, this is illustrated by the role of the biggest IC in Vegas Altas (upstream). This IC consumes large amounts of water because of rice irrigation and has great influence in decision-making though their high water demands make other smaller irrigation districts in the same area more vulnerable as shown in the previous chapter.

With respect to specific flows, the financing flows considered here are from actions that may facilitate adaptation, including funds from agricultural and water policies. There are clear formal flows (bold arrows) of financing that correspond to official fixed flows of money included in the budgets of the different policies. These are payments from the Common Agricultural Policy (CAP) (single farm payment committed to farms, rural development funds committed to countries), budget for water supply systems maintenance and fees paid by farmers to the irrigation communities for common investments, etc. Informal financing flows (dashed lines) are those that are not committed "by law" or by specific policies. This funds are less reliable as they might be highly reduced or even disappear under economic stress conditions or as priorities and criteria change. These are, for example, funds committed by users for private adaptation actions, such as investments in efficient irrigation and production technologies, or specific financial support from diverse non-secured sources.

Most of the ties between farmers and ICs and governmental institutions correspond to financial flows. This may entail a risk for the adaptation process if financial flows are weak due to economic crises or if there are changes to the policies that provide such funds. Moreover, high dependency on financial flows from the administration makes farmers less pro-active and may reduce farmers' incentives to adapt, thereby making them more vulnerable. During the consultation and validation process, SHs highlighted the relevance that other financial flows, not represented in the current system, may have on farmers' adaptation. These can include flows such as those from markets and consumption, which may encourage crop production activities more adapted to new climate and water availability conditions. This type of financial flow, mentioned in the workshop only in the environmental group map, might compensate for the high influence of public funds and subsidies on farmers decisions and illustrates the link between farmers and industry, which is also not represented in the current network.

Information flows include information that may support adaptation, mainly related to climate change impacts, available adaptation options, etc. There are numerous formal and informal information flows but according to SH opinions many of these are weak or ineffective. These flows are mainly created and maintained as a requirement of different EU and national policy development processes that impose SH information and participation at different stages of the policy-making cycle.

The scientific community and environmental groups are relevant actors that provide information. However, most of their links with other actors are informal, and, more importantly, links to water users are limited. This fact may minimise the impact they have on the whole system. As highlighted by the EU Commission Report on the status of implementation of the Water Framework Directive (WFD) (EC, 2012b), there is a need for improved communication by the scientific community of the results of research so that policy-makers have access to resources for effective policy development and in order to increase legitimacy and SH acceptance.

The scientific community, the EU and the different governmental levels are the source of flows of implementation capacity. This implementation capacity flow refers, first, to the knowledge generated by the scientific community that provides policy-makers and users with an improved understanding of the system and the uncertainties associated with the climate change adaptation process. Second, the capacity flow corresponds to policies and institutional rules, mainly created by the EU and the national government, which provide decision makers with legal, technical and financial resources to implement adaptation actions.

The formal capacity flows considered in the network emanate from the EU in the first instance and then go to the National government, the RBA and the Regional government, and finally to users. These formal flows correspond mainly to adaptation policies, which are guided by international agreements and by the EU policy on climate change adaptation, as well as the National Adaptation Plan and the regional Adaptation strategy, which includes specific actions for adaptation. The National Government contributes to building capacity for all other governmental bodies, mostly through the adoption of plans and strategies and other new institutional arrangements. The RBA and the Regional Government, through the elaboration of water management and adaptation plans, also provide farmers and other water users with the capacity to adapt, as these plans determine the rules for water use and create incentives for actions on adaptation.

When we look at the three types of flows and each actor's influence on the system, it is clear that the Regional Government is a key player in all three types of flows. This underscores its role as responsible body in adaptation policy. However, the fact that this governmental body is in charge of agricultural, environmental and climate change policies in the region may hide internal coordination conflicts. Among the expert consultation process the issue of regional policy coherence was mentioned as a concern in water management. In particular, it was stated that the development of adaptation plans for water and agriculture, undertaken by the Environment Department, was not fully coordinated with the Agricultural Department, clearly a key actor affected by those plans. This indicates potential problems of coordination in the implementation of the adaptation process.

The RBA, although a central actor with respect to information and implementation capacity, is not a relevant actor in terms of financing. This suggests the need for good coordination between the RBA and the Regional Government, so that the RBA's capacity is effectively translated into actions that need public financing and the Regional Government actions are in line with the RBA's water policy priorities.

Most of the issues arising from this network analysis have been identified by several authors as potential horizontal barriers to adaptation. For example, Moser and Ekstrom (2010) recognize leadership, resources (financial, technology, information, human resources, time...), communication, information, values and beliefs as elements that may create barriers at every stage in the adaptation process. Orr et al. (2008) also identify “contextual barriers” which are elements that may impede any type of adaptation measure due to the social, economic and institutional contexts. Priority contextual barriers, among others, include the lack of leadership, the lack of a consistent policy framework, poor coordination across different organisations and actors, and deficient knowledge and awareness in terms of climate change impacts.

Thus, according to the above analysis, we can infer some of the potential barriers to adaptation, the actors that may be crucial in the adaptation process and specific actions that can be implemented to improve the process. The preeminent potential barriers identified are: (i) insufficient or inefficient coordination across different governmental levels, lack of political will and leadership that might lead to ineffective control; (ii) low awareness among water users and lack of common understanding among the different actors due to weak public participation and poor relations between different users and between users, scientists and environmental groups; and (iii) high dependency of agricultural users on public funding that may reduce their incentives to adapt, making them more vulnerable.

These key issues, especially multi-level coordination and SH participation, are also reported to be among the most relevant challenges concerning water management (UNEP, 2012). Stakeholders agreed on the potential problems of coordination between government bodies. Development of a common understanding in the basin and coordination across different administrations are key obstacles that must be overcome in order to allow for the success of the climate change adaptation process, as highlighted in the report of the EU Commission (EC, 2012b). These are also key elements in the development and implementation of policies for natural resource management.

Regarding strategic actions to overcome these barriers, stakeholders stressed the need to create new formal and informal links between the scientific community, environmental groups and different types of water users that would increase knowledge transfer and capacity building and would enhance the role of all the different actors in the adaptation process. This can be promoted through policy-driven interaction forums or through specific research driven dissemination, consultation and validation processes. For this, and in order to improve coordination across institutions and between actors, political will is a key requirement. Clearly defining competences, improving information flows and taking advantage of synergies are also necessary tasks for improving the performance of key institutions.

4.4.2 Analysis of barriers to adaptation and feasibility of adaptation measures

Once we identified the main potential barriers, a set of specific barriers was selected in order to quantify their relevance based on experts' opinions. The strength of each barrier was quantified in relation to the implementation of the specific adaptation measures considered in the previous chapter: water pricing, improved control and decrease of water allotments, modernisation of conveyance and irrigation systems, the maintenance of environmental flows, and the adaptation of cropping patterns.

Participants were asked to rate the strength of each potential barrier identified from 0 to 5, where 0 is utilized to designate barriers that are not relevant or do not affect the specific measure and 5 is used to indicate those barriers that strongly affect the planning and implementation of the measure (see questionnaire in Annex D). Table 17 shows the overall ranking of the different potential barriers identified in terms of their relevance for adaptation in the Middle Guadiana basin, according to the aggregation of SH valuation of barriers across measures. The strength of each barrier is expressed from 0 to 100 representing the range between the lowest and the highest score that each barrier could obtain.

Results show that SH and experts perceive that there are sufficient technologies and knowledge to implement adaptation in the Middle Guadiana. In line with this, the difficulty for establishing appropriate thresholds for the different measures and controlling their adoption and implementation is not perceived to be a strong barrier to adaptation. The lack of an adequate regulatory framework and concerns regarding institutional coordination are perceived as low to medium barriers in the Middle Guadiana basin. Financial resources however, are perceived as more relevant for the implementation of adaptation measures, especially for those related to water and irrigation infrastructures and technologies. The lack of them is perceived as a moderate barrier to adaptation. Finally, the low awareness on climate change related risks and on the need to adapt, the lack of a common understanding among stakeholders in the basin, and stakeholders' opposition to the implementation of specific measures (especially those related to increasing constraints on water use by farmers) are the strongest barriers to overcome in order to ensure success of adaptation processes in the Middle Guadiana, according to SH views.

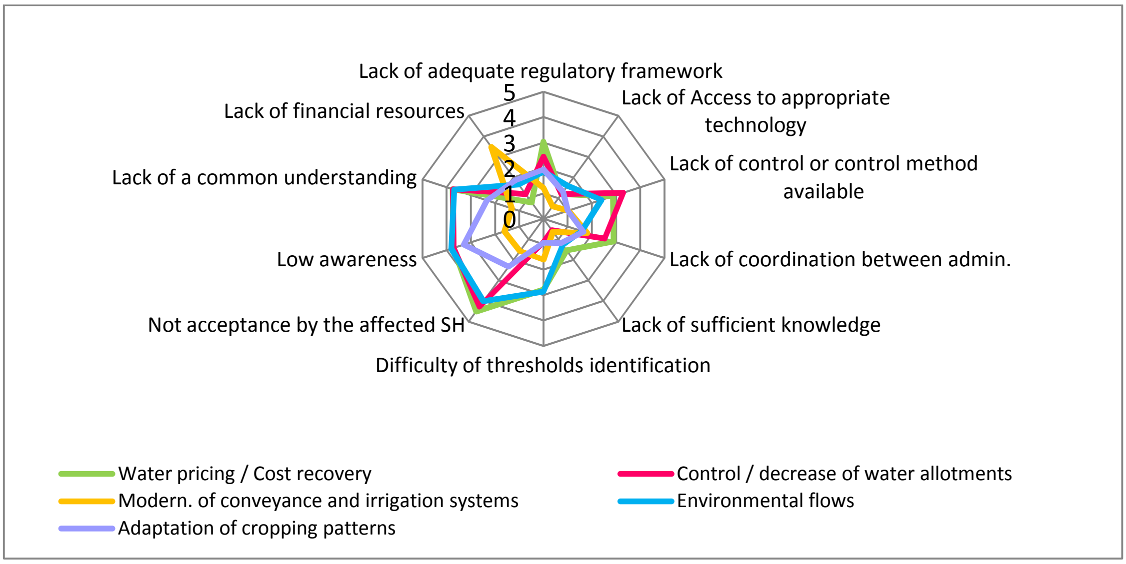
Table 17. Ranking and strengths of potential barriers to implementation of adaptation

1	Lack of acceptance by the affected SH	63/100
2	Lack of a common understanding	62/100
3	Low awareness	55/100
4	Lack of financial resources	47/100
5	Lack of coordination between administrations	42/100
6	Lack of adequate regulatory framework or conflict with the existing regulatory framework	41/100
7	Difficulty of thresholds identification	40/100
8	Lack of control or no control method available	38/100
9	Lack of sufficient knowledge	22/100
10	Lack of access to appropriate technology	15/100

Krysanova et al. (2010), in their study on adaptation in river basins around the world, evaluated current knowledge and awareness about climate change in the different basins considered. They also looked at the drivers behind adaptation and the strengths of a set of barriers for the implementation of adaptation strategies in general. If we compare our results for the Guadiana basin to the ones obtained by Krysanova et al. (2010) for the same basin we find many similarities, even if the list of potential barriers is not the same. The study by Krysanova et al. (2010) identified the spatial and temporal uncertainties around climate change and the lack of horizontal cooperation as strong barriers. They specifically stressed the relevance of the good coordination between the Guadiana RBA and the regional government, a fact that the SNM analysis and the analysis of barriers have also indicated here. Other barriers considered in the study by Krysanova et al. (2010) as moderate, are low awareness, lack of financial resources, lack of adequate regulatory framework, lack of knowledge production, and different preferences and local/sub-regional interests that may lead to the lack of acceptance by affected SH and lack of a common understanding, which has also been highlighted in this research.

Results of the analysis of barriers to the implementation of specific adaptation measures are shown in Figure 26. The figure reveals the aggregated SH perceptions on the strengths of the effect of the different potential barriers identified for each adaptation measure tested in the previous chapter. Perceptions on barriers by SH group are shown in Annex E.

Figure 26. Comparison of adaptation measures with respect to the strength of barriers



According to SH views, the measures that may face the greatest obstacles to their implementation are water pricing/cost recovery and control and/or decrease of water quotas. The most relevant barriers for the implementation of those measures are the lack of a common understanding, awareness and acceptance by SH, followed by the lack of good control. This coincides with other studies based on hydrological and economic assessments that highlight some of these issues, including cooperation among actors (especially water users), acceptance, enhanced common understanding and good control and monitoring. These are identified as key elements, without which many water resource management instruments cannot be effective (Albiac et al., 2008; Blanco-Gutiérrez et al, 2011; among others).

Maintaining environmental flows also faces important barriers. This is attributable to the lack of awareness and common understanding and the non-acceptance by farmers who may not be willing to reduce their water consumption in favour of the water ecosystems. Finally, the modernisation of conveyance and irrigation systems and the adaptation of cropping patterns would not face strong barriers for their planning and implementation. This is relevant as irrigation modernisation is a necessary step for the successful implementation of water tariffs, as shown in the previous chapter. Therefore, the implementation of irrigation modernisation programmes could enhance farmers' acceptance of measures oriented to decrease water consumption through the reduction of water allotments or the implementation of water pricing schemes. However, the lack of financial resources could be an obstacle in making the necessary investments for modernisation. Changing cropping patterns is also an effective and easy adaptation option, which, however, would suffer from the lack of awareness about climate change issues by irrigation farmers. More information, knowledge, and appropriate incentives would therefore be needed.

4.5 Conclusions

In this research we used participatory social network mapping and SH consultation in order to assess the main barriers to adaptation and the feasibility of specific measures in terms of socio-institutional preparedness and capacity.

The analysis of barriers to adaptation shows that the success of the adaptation process requires other elements apart from the identification of appropriate adaptation measures. Identifying barriers to adaptation supports decision-makers in planning adaptation processes as it provides a more realistic picture of the effectiveness and feasibility of adaptation strategies and allows for the development of approaches to overcome obstacles to adaptation.

The key barriers identified relate to the lack of awareness, common understanding and acceptance by water users and, more specifically, farmers. To overcome this, strengthening formal and informal relations among water users and between users and the scientific community can be very important. These elements, together with improved coordination across different administrations are not only relevant for climate change adaptation but also for the development and implementation of most natural resource management policies, as highlighted in the report of the EU Commission on the status of implementation of the WFD.

Analysis of barriers to the implementation of specific measures has shown that common water demand management instruments, especially water tariffs, face strong barriers related to the lack of acceptance, and the lack of common understanding. This emphasises the need to increase public participation, information and knowledge sharing and interactions among water users and other actors in order to promote the creation of a shared vision in the basin. This would contribute to increasing awareness on the need to adapt to climate change and protect water resources. This is relevant not only for climate adaptation but for integrated water resources management. It also underscores the widely recognised need to mainstream climate change adaptation in resource management policies, and legitimises the key principles of the Water Framework Directive in relation to the need to establish appropriate channels for public participation.

5. A regional view on future water scarcity: water, agriculture and climate change in Mediterranean countries

This chapter constitutes the last stage of this research. The previous chapter showed that the feasibility of adaptation strategies is determined by actors and decisions that operate at multiple geographical and decision-making scales, and highlights the role of national and supra-national level actors in facilitating adaptation. In line with this, this chapter provides a regional and national level assessment of water scarcity and climate change and explores the relevance of national level socio-economic contexts and policies. In this chapter, climate change and socio-economic scenarios are combined to look at future pressures on water resources in the Mediterranean region. Country case studies illustrate these scenarios and are used to analyse the effect of specific policies on future water demands and their contribution to mitigate the effects of climate change.

5.1 Abstract

In the Mediterranean region, climate change is expected to decrease water availability through reduced precipitation and more frequent drought spells. At the same time, climate change, population growth, economic development and an agricultural sector highly dependent on irrigation, will raise water demand, posing a daunting challenge on water managers. This research aims to provide a regional vision on the future of water demand in Mediterranean countries and its implications for water supply and demand balances. For this purpose, first, we identify the main drivers of water consumption in Mediterranean countries and project future water use using explorative scenarios of socio-economic development and an econometric model for water withdrawals. Second, we zoom in on two case studies, in Spain and Jordan, to analyse the potential impacts of climate change and water policies on water use, through the combination of agro-economic and water management models. Results show that the different structures of water use across sectors in each country, socio-economic development, and the potential for irrigation expansion will decidedly determine future water withdrawals. The countries that experience the most important demand expansions include Egypt, Turkey and Syria, independent of the socio-economic scenario. In other countries, however, the socio-economic scenario becomes determinant in future projections of water use, leaving more room for policy action. Climate change may increase water withdrawals by an additional 4%, but this will have diverse implications in the different countries. Country case studies show that sustainability oriented water policies will be key for securing water demands and sustaining socio-economic growth. In Spain, while different socio-economic scenarios will not produce significant changes in water resources, climate change may lead to the water supply substantially failing to meet demands around by the 2040s. In this context the implementation of water conservation policies and farm-level adaptation greatly contribute to reduce the risk of unmet demands. In Jordan, Climate change will further endanger vulnerable groundwater resources. In order to avoid further exploitation, water policies will need to improve control and reduce water abstractions in the Uplands. Water pricing, however, is not likely to achieve significant water savings. Instead, restructuring water rights and removing market distorting elements will be the most effective measures. Overall, this research demonstrates that good governance and sustainability oriented policies can contribute to addressing the challenges of socio-economic development and climate change in areas where water resources are scarce.

Keywords: agro-economic modelling, Mediterranean region, socio-economic scenarios, water balance, water demand

5.2 Challenges for water and irrigation in the Mediterranean region

Water resources have steadily supported socio-economic development throughout history (Flörke et al., 2013). Cities have grown around rivers, industry has developed and, most importantly, water has supported food production to feed an increasing world population. Irrigation expansion has permitted the increase of crop production in the last century, with 40% of world food being produced on irrigated lands, which represent 17% of world cultivated land (Schoengold and Zilberman, 2007). However, limits to increasing irrigation land and rising competition for water use between agricultural and other sectors and users make improvements of water use efficiency and water productivity necessary. Addressing the challenge of reducing hunger and poverty requires a great effort and large investments in improving water resources management, especially in developing countries (Rockström et al., 2007).

In water scarce regions, water is already constraining development. Climate change projected impacts, which include increased rainfall variability and more frequent water related extreme events, such as floods and droughts, will further intensify water stress. Climate change exacerbates the existing conflicts between socio-economic development and environmental protection hindering both of them, especially in areas of high vulnerability such as the Mediterranean region (EEA, 2008; IPCC, 2007b).

The Mediterranean region is considered a hotspot for climate change (Giorgi and Lionello, 2008; Iglesias et al., 2011; Varela-Ortega et al., 2013). Historically characterised by water scarcity, agriculture in the Mediterranean has largely relied on irrigation and crop yields have been limited by low precipitation and constrained water availability. Climate change is expected to exacerbate water scarcity and may limit agricultural productivity, increase the risk of crop failure and threaten food production (Hanjra and Qureshi, 2010; Rosegrant et al. 2009; Rosenzweig and Tubiello, 1997). Growing population, irrigation expansion and urbanisation are increasing pressures on water resources quantity and quality (Milano, 2012). These pressures together with climate change will reduce available water resources per capita significantly and affect socio-economic and environmental conditions (Chenoweth et al., 2011). In light of this, there is a need to explore how these pressures will evolve and what their likely effects on water resources will be in order to inform policy-makers on adequate ways to tackle them.

However, within the Mediterranean region we find a diversity of environmental, socio-economic and institutional contexts. Water resources availability and water use across sectors, population trends and policy settings will most likely determine the adequacy of different methods to address water scarcity problems. While in some countries such as Lebanon, Syria or Morocco, available renewable water resources per capita are around 1000 m^3, other countries like Jordan or Libya have only 150 m^3 per capita. However, in Lebanon and Syria civil conflicts may threaten access to water resources in some areas. Water infrastructure development in Turkey has largely contributed to an increase in water supply and an expansion in the irrigated area. However in other countries with large problems of water scarcity, such as Jordan, land orography provides limited capacity to increase water storage.

Therefore a detailed analysis that takes into account these differences across countries is essential.

In this context, the chapter aims to provide an overview of the future challenges that water managers will face in the Mediterranean region, looking at how different socio-economic and institutional settings may determine future water use and scarcity in light of projected increased pressures driven by climate change. For this, we will, first, identify the main drivers of water consumption in the Mediterranean and explore future scenarios of water use across countries. Second, focusing on the main drives of water use, we will zoom in on two country case studies and analyse the potential effects of specific policies on water use and water scarcity.

The methodology used for this study includes, first, an econometric model that explains water withdrawals that is used to project future water demands. Second, an integrated modelling framework, which combines a regional farm-based agro-economic optimisation model and a water management model, is used to analyse water demands at country level with a special focus on irrigation water policies, farm level decision-making and crop production. These models are driven by the use of future socio-economic and climate change scenarios that allow us to address the complexity and uncertainty in a structured and systematic way.

This research has been developed in the framework of the MedPro project[11], in which qualitative and quantitative scenarios have been developed for the MED 11 countries[12]. Based on the MEDPRO scenarios, this research analyses potential futures for water demands in the Mediterranean region taking account prospective socio-economic developments and the effects of climate change. The socio-economic scenarios are also the base for the country level assessments, which separately consider urban, industrial and agricultural demands and explore different approaches for water management in irrigation including demand-side policy instruments, such as water pricing, quotas, and other policies affecting agricultural production.

The scale of analysis is regional (Mediterranean) and national (selected Mediterranean countries). Although water problems are most often local, global and national analyses are frequently more feasible in terms of data availability and are useful for identifying particular vulnerabilities and risks and raising awareness in international and national contexts (Gleick, 2002; Rijsberman, 2006).

[11] MEDPRO (Prospective Analysis for the Mediterranean Region). Project No. 244578. Collaborative Project (Small). 7th Framework Programme. EU Commission, DG Research. 2010 – 2013

[12] Algeria, Egypt, Israel, Jordan, Lebanon Libya, Morocco, Syria, Tunisia, Turkey and West Bank and Gaza.

Overall, this scenario-based assessment is intended to provide an integrated view of potential future risks associated to water management in water scarce countries and to inform water policy decision-making.

5.3 Socio-economic scenarios for the Mediterranean region: approach and scales

In the current globalised world, water use and agricultural production in a country are determined by many different drivers such as world trade, international agricultural and economic policies, oil prices, international agreements, international conflicts or climatic conditions. Uncertainty about the evolution of these drivers, the complexities inherent to resource management and use and climate change make the challenge of preparing for future developments and designing policies an even more difficult task. In this context, the use of scenarios allows us to look into an uncertain and complex future in a structured and systematic manner.

Looking into the future and using aggregated scales of analysis requires us to make assumptions about the different aspects that affect water resource use and development. In our case, exploring water demand at country level requires making assumptions on, for example, demographic development or irrigation expansion. There are many different elements that will influence those variables and the use of different scenarios will therefore assist us in tackling uncertainty caused by these elements.

Scenario use allows us to analyse a given subject taking into account those aspects that may be relevant when looking into the future while making it easier to deal with uncertainty. Scenario-based approaches have been extensively used for public policy analysis and decision-making since the 1960s, assisting decision-makers to look into the future in a flexible and innovative approach (Amer et al., 2013; Hiltunen, 2009).

One of the most common approaches in scenario-based studies is the 2x2 matrix approach (Amer et al., 2013), which considers that two elements of variation, on which there is uncertainty, are the most relevant drivers that will determine future developments. Usually, this approach is represented by two axes that determine four quadrants. The axes represent two opposite directions that a specific element may follow in the future. Scenarios are then represented in the four quadrants conformed by the axes. This approach has been used in many studies in the field of climate change and sustainable development including often-cited works at the global level such as the Special Report on Emissions Scenarios (SRES) families of scenarios (Nakicenovic and Swart, 2000), B1, B2, A1 and A2, in which the two main axes are globalisation (as opposed to regionalisation or local approaches) and sustainability, or the GEO-4 scenarios (*Market First*, *Policy First*, *Security First* and *Sustainability First*) (Global Environmental Outlook 4, UNEP, 2007) that follow a similar approach.

There have been also several notable works on scenarios specifically developed for the assessment of water resources, as reflected by Kok and Alcamo (2007). These are, for example, the SCENES[13] scenarios which are based on the Global Environmental Outlook GEO-4 scenarios and are developed specifically for water use in Europe and in neighbouring countries. In addition, the European Water Outlook scenarios (Flörke and Alcamo, 2004), which include a baseline scenario and a climate policy scenario, or the Global Water Outlook scenarios (Rosegrant et al., 2002) that consider three plausible futures for water resources, namely *Business As Usual*, *Sustainable World* and *Water Crisis,* are examples of other scenarios used in the assessment of water resources.

Focusing on the Mediterranean region we also find different sets of scenarios such as the World Economic Forum's "Scenarios for the Mediterranean Region" (World Economic Forum, 2011), which explore three future scenarios based on projections of economic development, resource management and labour markets, and the MedAction scenarios (Kok et al., 2006), that build on the VISIONS European scenarios (Rotmans et al., 2000) and specify them for the northern Mediterranean regions. We also find the MEDPRO scenarios (Ayadi and Sessa, 2011), which are developed for the southern and eastern MED11 countries and which are constructed around to main axes: sustainability and integration and cooperation between the EU and the MED11 countries.

In the field of climate change impacts assessment, socio-economic scenarios are as important as climate scenarios are (Van Drunen et al., 2011), because climate change impacts and people's exposure, vulnerability and adaptive capacity will be determined by their socio-economic and institutional contexts (IPCC, 2007b). Therefore, climate change assessments must make assumptions about future socio-economic pathways, institutional and technical change (Berkhout et al., 2002).

[13] SCENES Project (Water Scenarios for Europe and for Neighbouring States). Project No. 036822-2. Integrated Project, 6th Framework Programme. EU Commission, DG Research. 2007 – 2010.

Because of this and considering that the scale of analysis is appropriate for the analysis of socio-economic scenarios, in this study we combine socio-economic scenarios with climate change scenario assessment in the context of water resources management and use. Other studies combining socio-economic and climate scenarios for the assessment of water management include Haasnoot et al. (2009) and Strzepek et al. (2001).

This study builds on the MEDPRO scenarios qualitative storylines (Ayadi and Sessa, 2011) and socio-economic quantitative projections, and combines them with a set of European scenarios, the Global Europe 2050 scenarios (EC, 2012d), which represent the conception of EU integration and sustainable development from the MEDPRO scenarios. The main assumptions behind these scenarios are shown in Figure 27.

These scenarios are combined with a severe climate change scenario (A2) and are used at the regional scale for projecting water consumption into the future, based on an econometric model. Downscaled to the national level, they are used in country case studies that apply an agro-economic and water management modelling framework. The scenario assessment approach for the different scales of analysis is summarised in Figure 28.

The main drivers of MedPro scenarios are sustainability and integration and cooperation with the EU. According to the plausible evolution of these drivers, four different scenarios are defined. The *Reference scenario* (SI) presents a "business as usual" situation, in which integration or cooperation with the EU exists to some extent but relations are stagnant. Sustainability is not a relevant goal and therefore degradation of resources persists and socio-economic development is unsustainable. The *Euro-MED area under threat scenario* (SIV) represents a degradation of current relations between the EU and the MED countries, together with economic crisis, mismanagement of natural resources and population growth stagnation. On the contrary, scenarios of *Sustainable development of an enlarged EU-MED union* (SII) and *Sustainable co-development of EU&MED regions* (SIII) present a renewed vision of policy decision-making that favours sustainable development. Within these scenarios, SII envisages a new alliance between the EU and MED countries in which EU policies, values and goals are shared across the southern and eastern Mediterranean region. SIII considers an effective cooperation between the EU and the MED countries that is based more on bilateral agreements and without a real sharing of values, policies and goals.

Figure 27. Socio-economic scenarios for the European Union and the MED 11 countries

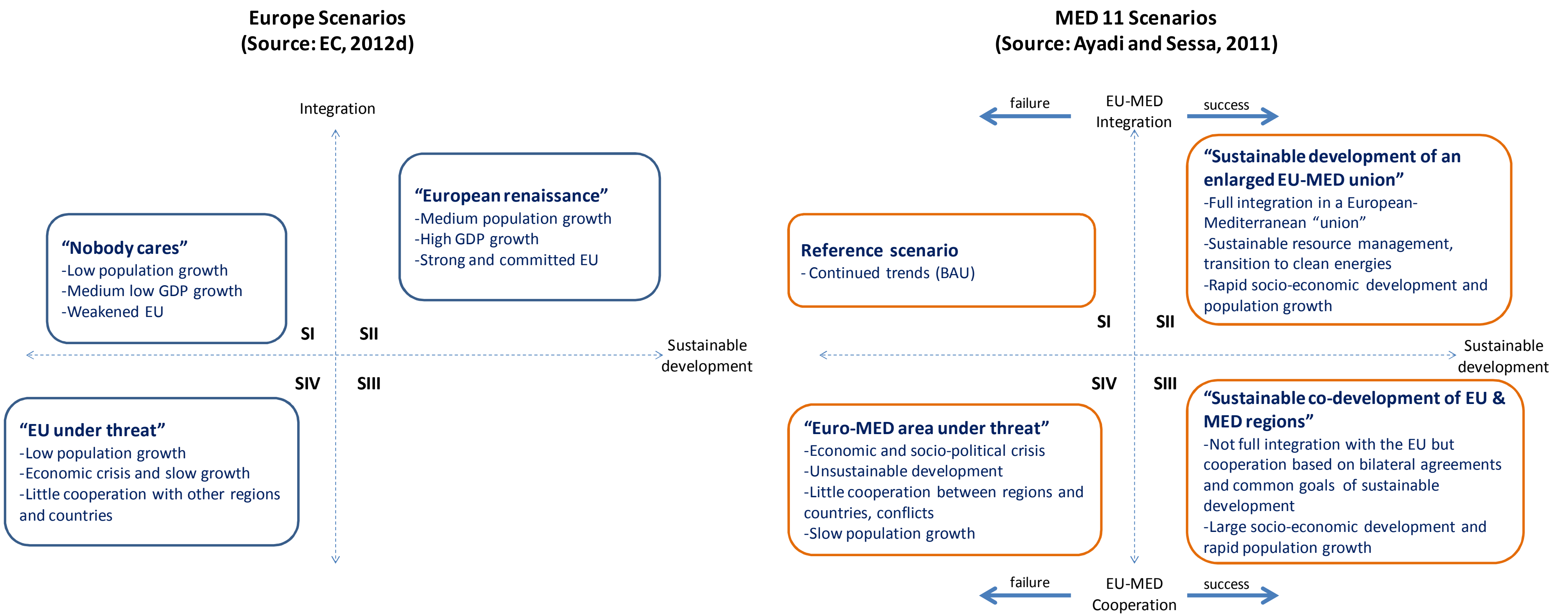
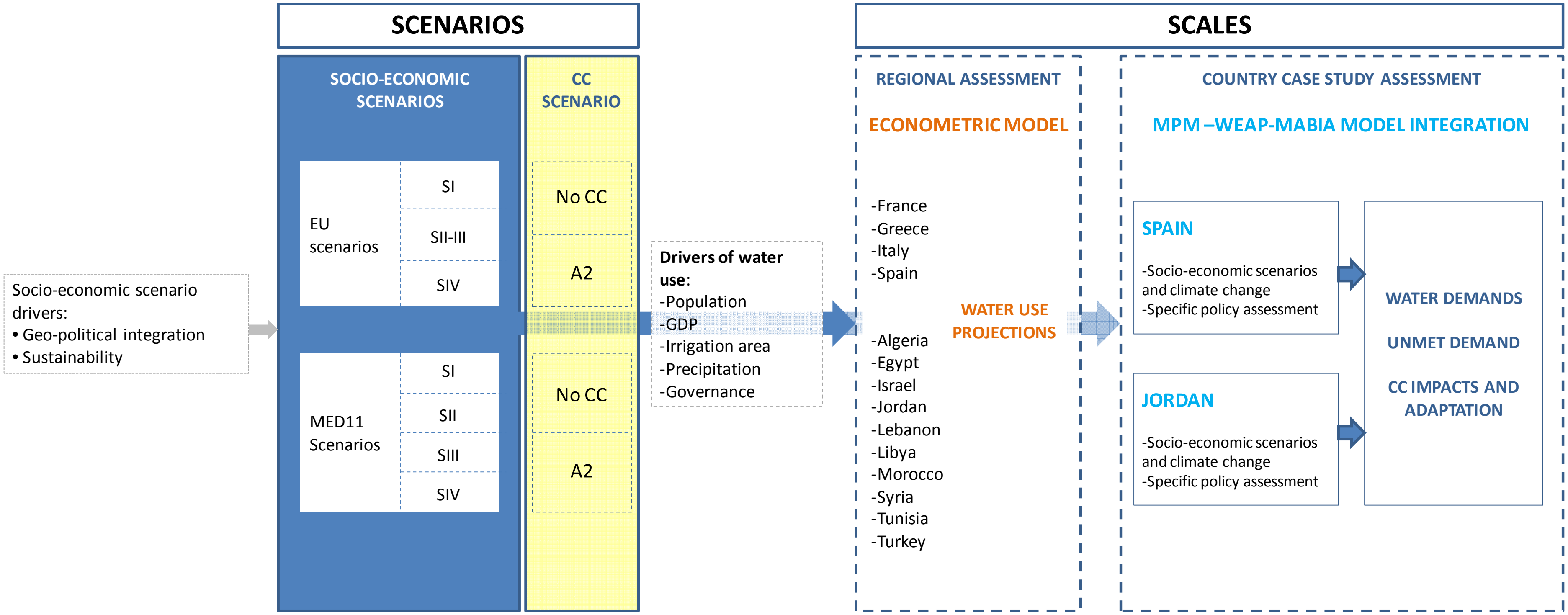


Figure 28. Methodological approach: scenarios and scales of analysis



The Global Europe 2050 scenarios are very similar to the MedPro scenarios with regard to their main drivers. The *Nobody cares scenario* (SI), is a continuation of current trends in Europe where, the lack of a shared vision across member states and the lack of a real European identity weaken the role of EU policies and the relevance of the EU in the World's economic context. The *EU under threat scenario* (SIV) shows a weakened EU in which relations with other regions and third countries are poor. In this scenario the EU is only worried by internal economic crisis and sustainable resource management and technology development are not relevant goals. Finally, the *European Renaissance scenario* (SII-III) shows a re-founded EU, in which union and commitment across countries is strong. Economic and technology development is fast and the EU recovers a prominent role within World regions. This scenario is named as SII-III because it is comparable to Mediterranean scenarios SII and SIII in that they include sustainability and economic growth as main elements in the scenario.

5.4 What can we expect from the future of water in the Mediterranean?

As the Mediterranean region is one of the most water scarce regions in the World, assessment of future pathways for water use is a relevant assignment that contributes to the sustainable development and informs water policy decisions at the country level. The use of scenarios allows for the exploration of the possible evolution of water demand in order to identify the main elements that should be targeted by water policy. These scenarios are meaningful at the country or regional levels as they address different types of drivers that have implications beyond the local scale.

In line with this, this section tries to take advantage of the use of scenarios for analysing water withdrawals at the regional and country levels using an econometric model for water withdrawals. This model will permit us to assess the significance of different types of drivers and to evaluate future water demand in light of different socio-economic pathways and climate change scenarios.

5.4.1 Econometric model for water use in the Mediterranean

To explain the evolution of water consumption over time and across countries we need to identify the main variables that affect water consumption. There are many different types of studies that focus on water use, water resources development and future projections on water demands. These studies aim to analyse the risk of water scarcity and future water stress either to draw attention to the importance of water resources management or to specifically identify the most appropriate management measures according to different criteria. Margat and Vallée (2000) studied current trends in water management in the Mediterranean region and explored future scenarios according to different perspectives on population, economic growth, tourism and technology. Flörke et al. (2011) highlights the Gross Domestic Product (GDP), GDP per capita, climate variables, irrigation area and population as key drivers of water scarcity. However, population growth and rising incomes are not the only relevant drivers for water use (Rijsberman, 2006).

Econometric models have been used before in the analysis of water demands, but those previous studies have usually focused on urban demands (Babel et al., 2007; Mazzanti and Montini, 2006; Renwick and Green, 2000) and industrial demands (Reynaud, 2003) and have had a restricted spatial coverage. The lack of sufficient data, both in terms of quality and in terms of quantity, across countries and time, and especially with respect to irrigation water use, precluded more ample analysis with a wider spatial coverage.

While it seems reasonable to assume that domestic and industrial demands will increase with economic development, it is not easy to determine how agricultural demands will evolve and how elements apart from population and GDP will affect water use (Rijsberman, 2006). Among the different drivers, institutions, policy or natural environment may determine not only water use but also the risks faced and vulnerability of population exposed to water scarcity problems.

In this study, an econometric model of water withdrawals (WW_{it}) is specified and estimated to identify the main drivers of total water use at country level. This is a panel data model in which the variable to explain is total water withdrawals per country (i) and year (t). The model is specified and estimated for a group of 14 countries that include the MED11 countries except the Palestinian Territories, i.e., Turkey, Syria, Lebanon, Israel, Jordan, Egypt, Libya, Algeria, Tunis and Morocco, and four representative countries from the EU northern Mediterranean countries, namely France, Greece, Italy and Spain. Time coverage is from 1996 to 2011, but there is an uneven distribution across countries because of the lack of data for some countries and variables. This may limit the models' potential for robust projections of water withdrawal. The model is corrected for heteroskedasticity and autocorrelation, and its general form is:

$$LWW_{it} = \propto +\beta_1 LPop_{i,t} + \beta_2 LGDP_{i,t} + \beta_3 LIrr\_area_{i,t} + \beta_4 PPT_{i,t} + \beta_g WGI_{1-4} + \beta_r Reg_{1-3} + u_{it}$$

, where LWW_{it} is the natural logarithm of total water withdrawals (measured in million cubic meters). The model explanatory variables include:

- $LPop_{i,t}$, the natural logarithm of country population (thousand inhabitants), which is assumed to determine urban demand and, to less extent irrigation demand, considering the need for food production to feed population.
- $LGDP_{i,t}$, the natural logarithm of gross domestic product (in 2000 constant Million US Dollars), as a measure of economic growth.
- $LIrr\_area_{i,t}$, the natural logarithm of the area equipped for irrigation (thousand hectares), which is used as a proxy variable for irrigation area.
- $PPT_{i,t}$, annual precipitation (million cubic meter), which is assumed to determine irrigation needs.
- WGI_{1-4}, the Worldwide Governance Indicators (The Worldbank, 2012 update). This is a set of six indicators that reflect different aspects of governance, policy and institutions performance. From these we included 4 in the model: *political stability and absence of violence*, *government effectiveness*, *regulatory quality* and *rule of law*. The value of these indicators range from -2.5 to +2.5, being -2.5 the worst and + 2.5 the best level of governance. They are based on information from different data sources and surveys of perceptions about governance to experts, organisations and private sector firms worldwide, as described by Kaufmann et al. (2010).
- Reg_{1-3}, dummy variables that capture the effect of regional characteristics on water use. The model distinguishes between three different regions: region 1-North (France, Greece, Italy and Spain), region 2-East (Israel, Jordan, Lebanon, Syria and Turkey) and region 3-South (Algeria, Egypt, Libya, Morocco and Tunisia).

Data for water withdrawals were compiled from different sources including AQUASTAT (2013), and a compilation carried out by the Plan Bleu (2011). Data for population, GDP, and area equipped from irrigation were obtained from the World Development Indicators database of the World Bank (World Bank, 2011). Data for annual precipitation were obtained from the Environment Statistics Database of the United Nations Statistics Division (UN, 2013).

5.4.2 Key drivers of water use and future projections for the Mediterranean region

The effect of the selected drivers on water withdrawal was assessed using the econometric model shown in section 5.4.1. The results of the model estimation are shown in Table 18. The model estimated is a generalised least squares model, correcting for heteroskedasticity and taking into account fixed effects of region.

As show in Table 18, all the variables are significant and most of them strongly significant with a confidence level of 99%. These include population (positive effect), irrigation area (positive effect), precipitation (negative effect) and the two governance indicators that represent regulation quality (negative) and rule of law (positive). The regional effect is also strongly significant. This indicates that water withdrawals in the northern countries are highest, followed by the eastern countries, with the southern countries showing the lowest water withdrawal.

Table 18. Results of the econometric model estimation for water withdrawals

L_WW	Coef.	Std. Err.	[95% Conf.	Interval]
L_population	0.568***	0.074	[0.422	0.713]
L_GDP	-0.052*	0.028	[-0.107	0.003]
L_irrig_area	0.783***	0.028	[0.728	0.837]
Precipitation	$-9.19 \cdot 10^{-7}$***	$1.59 \cdot 10^{-7}$	[$-1.23 \cdot 10^{-7}$	$-6.07 \cdot 10^{-7}$]
WGI_gov_effectiv	-0.109*	0.064	[-0.235	0.016]
WGI_regul_qual	-0.363***	0.047	[-0.454	-0.271]
WGI_stability	-0.075**	0.032	[-0.137	-0.012]
WGI_rule_law	0.498***	0.066	[0.370	0.627]
_Iregion_2	-0.291***	0.090	[-0.468	-0.114]
_Iregion_3	-0.579***	0.088	[-0.751	-0.407]
Constant	-0.917*	0.494	[-1.885	0.051]
R2=0.994 N=68				

** p<0.10; ** p<0.05; *** p<0.01*

Political stability is significant at 95% level and government effectiveness and GDP appears as significant with a 90% confidence. The effect of GDP on water consumption is negative, indicating that higher GDP implies lower water consumption. Many authors that studied water demand trends and future scenarios considered GDP (a proxy for socio-economic development) as a driver for water consumption (Flörke et al., 2011, 2013; Margat and Vallée, 2000; Varela-Ortega et al., 2013), however there are not many published works that carefully examine this relationship (Katz, 2008). Gleick (2003) did not find a significant relationship between per capita water withdrawals and income. Other authors argue the existence of Environmental Kuznets Curves[14] for water (Goklany, 2002; Katz, 2008; Rock, 2001), but different studies have criticized these conclusions and argue errors in the estimation of the underlying econometric models.

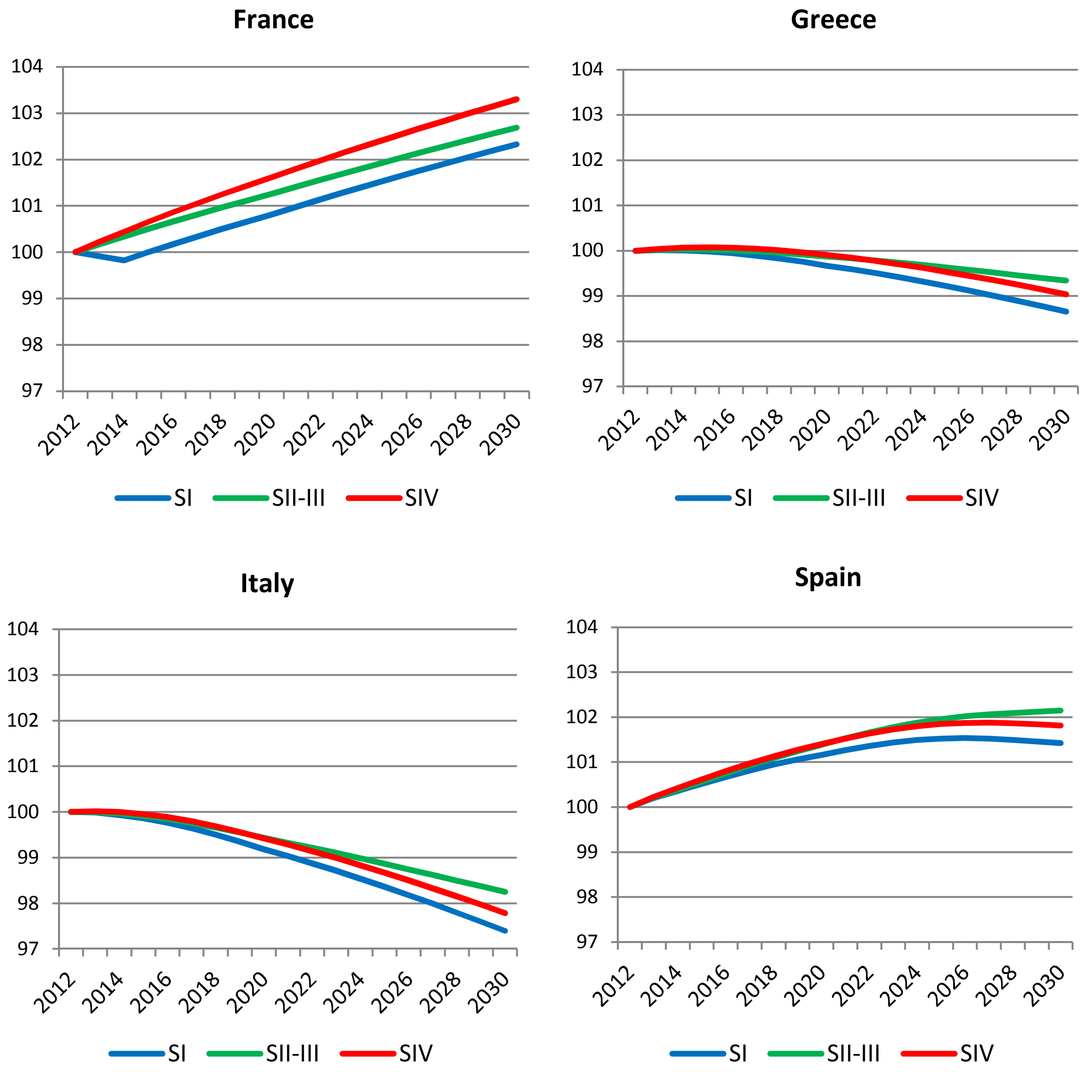
Some authors (Babel et al., 2007; Droogers et al., 2012; Renwick and Green, 2000; among others) consider income as a trigger for domestic and industrial water demand. However, when irrigation is included in the analysis we cannot conclude that GDP has a positive effect on water withdrawals. This may be conditioned by the countries that are included in the assessment. In every country considered, irrigation accounts for a large share of water withdrawals because of the relative aridity of climate. As GDP grows, technology improvement may increase efficiency of water use and thus reduce water withdrawals. Also, as GDP increases, agricultural activities become less relevant for the overall economy and potentially also for total water consumption.

Using the model estimated for water withdrawals, future scenarios for water use have been projected using the socio-economic scenarios explained above, which provide information on GDP and population growth. Irrigation area growth rates are obtained from Bruinsma (2009) with an upper limit set at current irrigation potential. Irrigation expansion is similar across scenarios, and governance quality is assumed constant across scenarios and over time.

Results of the projections show different trends across countries. Northern Mediterranean countries (Figure 29), i.e. France, Greece, Italy and Spain, show stable water withdrawals that are similar across scenarios: This corresponds to steady population trends and moderated changes of GDP. In these countries, water withdrawals will oscillate within the range of ±3% from 2012 up to 2030.

[14] An Environmental Kuznets Curve (EKC) represents the relationship between different indicators of environmental degradation and per capita income (Stern, 2004). It presents an inverted U shaped-curve, showing that environmental degradation increases as income per capita increases until it reaches a certain turning point at which increased economic development leads to decreased environmental impacts.

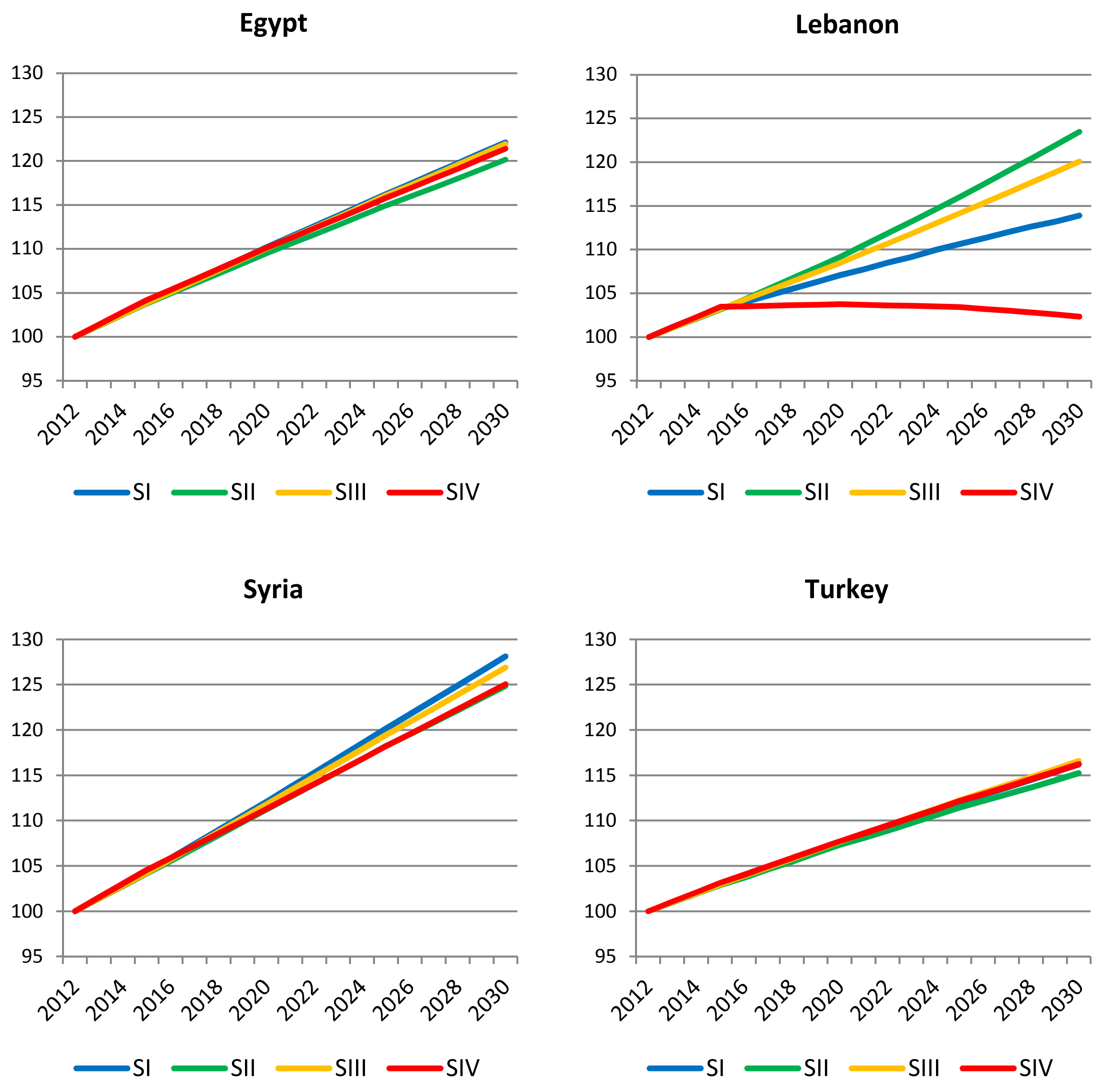
Figure 29. Projected water withdrawals in the four selected EU Mediterranean countries



However, countries in the eastern and southern Mediterranean rim show more varied trends. Within the countries that may experience more severe increases in water withdrawals (Figure 30) we find Syria (+25/28%), Egypt (+20/22%) and Turkey (+15/17%), coinciding with previous studies in the region (Margat, 2004; Benoit and Comeau, 2005). In addition, these countries show small differences across socio-economic scenarios. This is attributable to the prevailing role of irrigation in total water withdrawals and the large potential for expansion of irrigated land. In the case of Turkey, the large storage capacity can sustain irrigation expansion. However, Syria and Egypt may experience increased water stress.

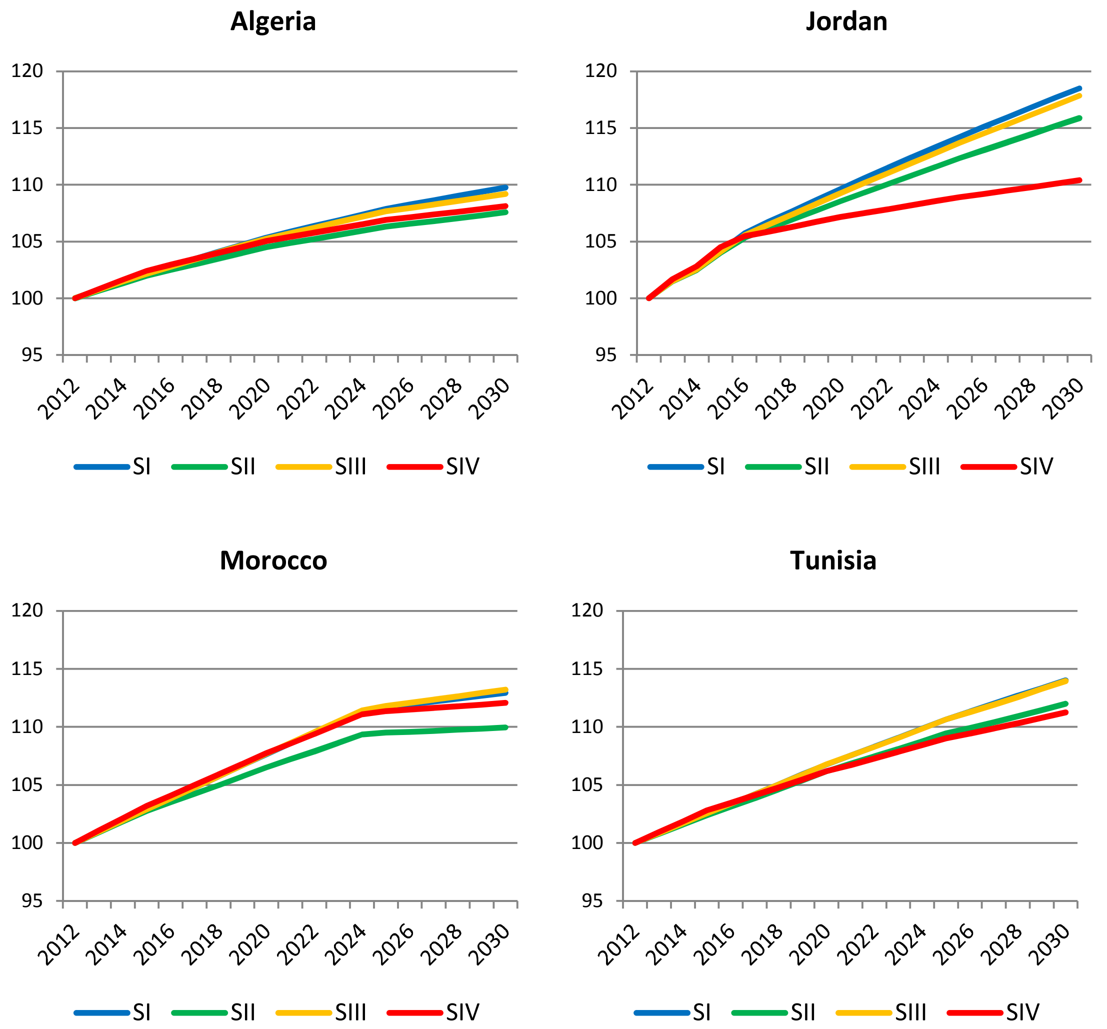
As in Turkey, Syria and Egypt, water withdrawals in Lebanon may increase significantly. However, projections show ample differences across scenarios, ranging from +2% in QIV scenario to +23% in QII. In this country, the scenario QIV, the most negative in terms of socio-economic development, shows a relatively constant evolution of withdrawals mainly driven by the stability of population and GDP growth. However, scenarios QII and QIII that consider larger economic and population growth show large increases in water withdrawals in 2030.

Figure 30. Projected water withdrawals in Egypt, Lebanon, Syria and Turkey



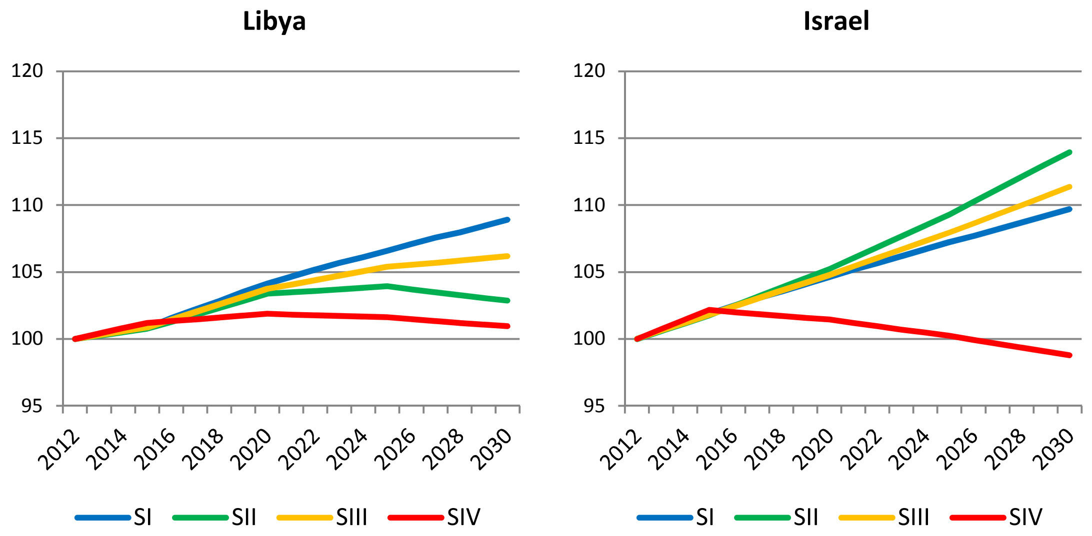
There is a third group of countries, shown in Figure 31, for which water withdrawals will evolve at an intermediate range. This group includes Algeria (+8/10%), Jordan (+10/18%), Morocco (+10/13%) and Tunisia (+11/14%). From this group, Algeria, Morocco and Tunisia present more moderate increases in water withdrawals and small differences across scenarios. However, Jordan shows important differences among scenarios. In Jordan, potential expansion of irrigation is very limited because of the current level of water scarcity and extremely arid conditions in a great part of the country. Socio-economic development in Jordan is already increasing pressure on water resources, and the envisaged evolution of population and industrial development will likely determine further water stress and competition among sectors. In this case, socio-economic scenarios are highly relevant and policy makers will need to develop ambitious water and sectoral policies that limit exploitation of the already scarce resources and ensure sustainable growth of the country's economy.

Figure 31. Projected water withdrawals in Algeria, Jordan, Morocco and Tunisia



Finally, Libya and Israel (Figure 32) behave similarly, with water withdrawal changes between +1/9% and -1/+14% respectively. Both countries show large variations across scenarios. Scenario QIV shows a negative trend in water withdrawal because of reduced population growth. In these two countries, potential for irrigation expansion is very reduced, especially if we consider that Israel uses 80% of its available renewable freshwater resources and Libya more than 600%.Socio-economic conditions will therefore be the main drivers for water use.

Figure 32. Projected water withdrawals in Algeria, Jordan, Morocco and Tunisia



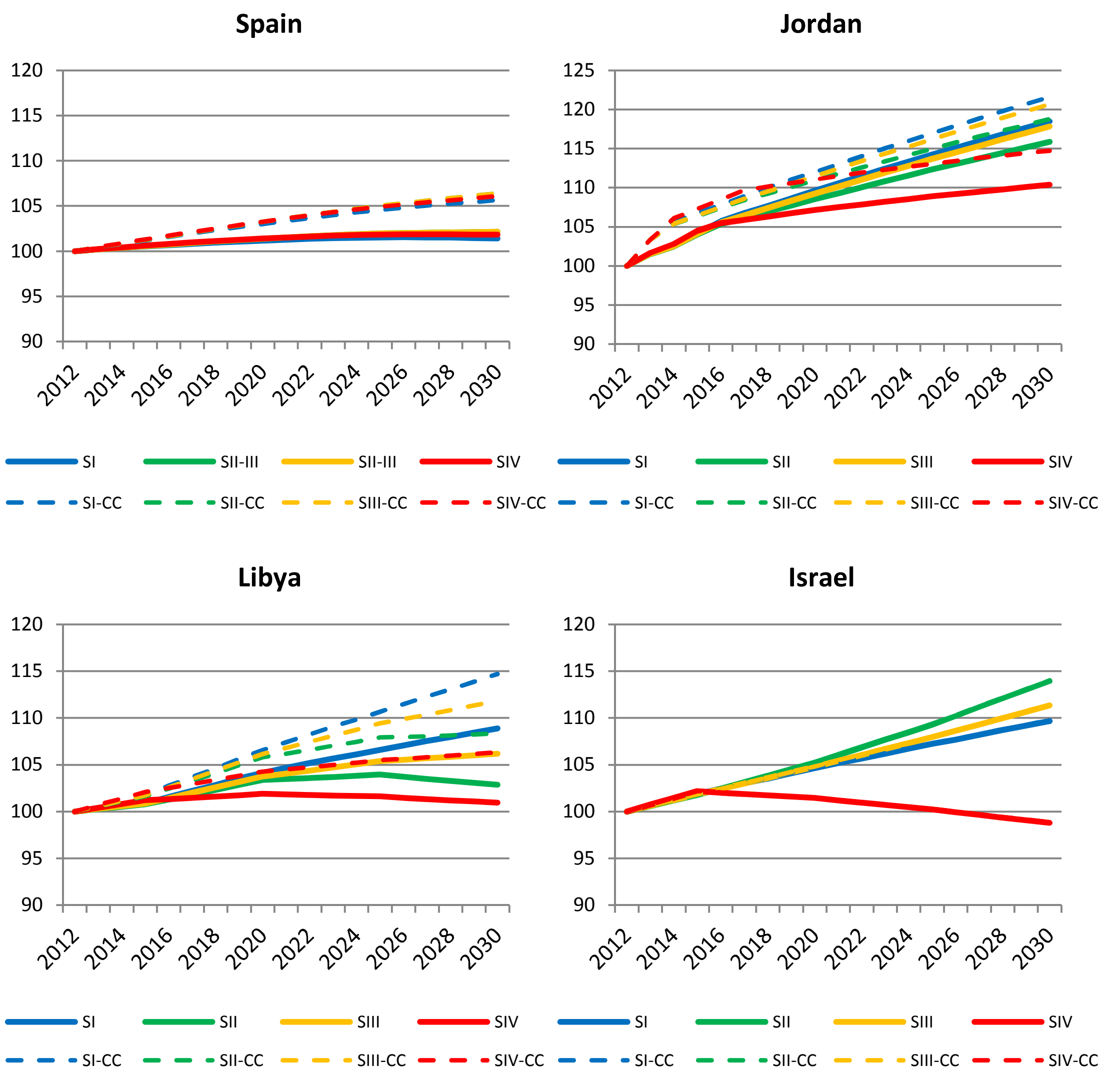
The projected changes in water withdrawals will exacerbate water scarcity already present in most of these countries and amplify the magnitude of the challenge faced by water authorities in countries like Egypt, Israel, Jordan, Libya or Syria. In these countries, water resources exploitation accounts for more than 85% of total renewable water resources, and thus, further exploitation of resources will significantly compromise sustainable development.

Climate change will add an additional burden to the challenge of sustainable water resource management and use. Based on Giorgi and Lionello (2008), we simulated the effect of a progressive decrease of annual precipitation of 15% by 2050, driven by severe climate change, on water withdrawal projections. Results for a selection of countries are shown in Figure 33.

The simulated impact of climate change differs across countries. The change in precipitation is simulated as a percentage reduction. However, absolute values are relevant. In a country like Israel in which precipitation is low, the effect of precipitation as compared to population and GDP trends is very limited. Because of this, projected trends in water withdrawals are not altered by changes in precipitation. In Spain, where population and GDP trends are relatively stable, and where irrigation is a relevant sector in terms of area and water use, differences across scenarios are negligible. However, changes in precipitation produce a 4% increase of water withdrawals in every socio-economic scenario.

In Jordan and Libya, reduction in precipitation produces a 4-5% increase in water withdrawals in the four scenarios. According to the projections for these two countries, the effect of climate change may offset the outcomes of the sustainability driven scenarios. As seen in Figure 33, in the socio-economic scenario SII with climate change (green dashed lines) water withdrawals would equal those of the SI-no climate change scenario (solid blue line), which is not sustainability-driven.

Figure 33. Projected water withdrawals for selected countries with and without climate change



Overall, results indicate that there are different effects that will determine the magnitude of the impacts of climate change across countries, including the average precipitation, the importance of irrigation agriculture for the country's economy and its weight in terms of total water use as well as the level of socio-economic development. This exemplifies the need to carry out specific country level assessments in order to identify what the main challenges are in each case and what the most adequate policy actions will be.

5.5 Macro-level study of water and irrigation in selected Mediterranean countries

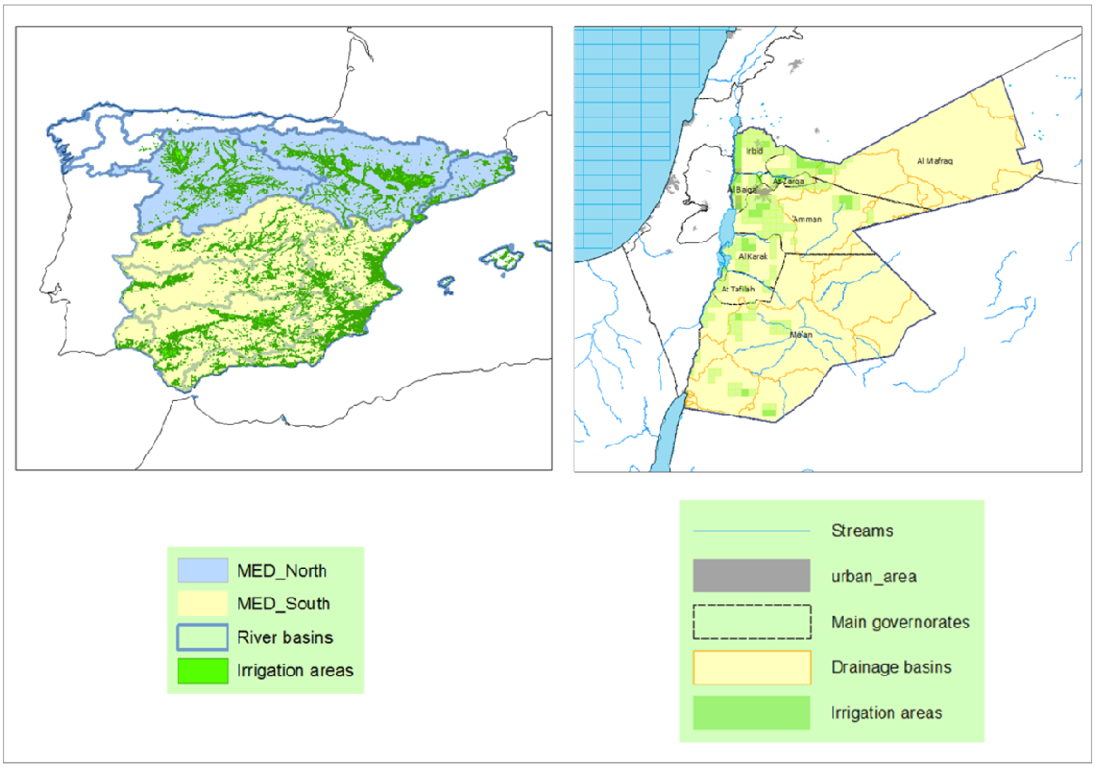
The results of the econometric model assessment and projections have indicated the relevance of socio-economic contexts and natural conditions at country level for the future of water resources use and management. Understanding future pathways for water management and illustrating potential actions and policies requires the assessment of selected case studies in the region.

This section analyses national level water demand and supply balances, looking specifically at the different water uses and at how each of them may evolve under different socio-economic and climate change scenarios. For this, we focus on two country case studies: Spain and Jordan.

5.5.1 Country case studies

The two country case studies selected illustrate water management under different scarcity and policy frame conditions. These two countries, Spain and Jordan, are shown in Figure 34.

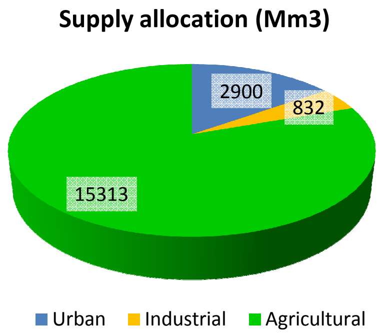
Figure 34. Case studies: Spain and Jordan irrigation areas



Source: Own elaboration based on data from MAGRAMA (2013), ESRI (2009), HydroSHEDS (Lehner et al., 2008) and Siebert et al. (2007)

Spain is one of the most water scarce countries in the European Union especially considering the water resources that are available and the water demands placed on these resources, particularly from agriculture. With a water availability of 2500 cubic meters per capita and an agricultural sector that accounts for more than 60% of total water consumption (AQUASTAT, 2013), Spain has a long history of dealing with water scarcity and conflicts over water use. This has led to intense social confrontation between different water users, different regions and between policy makers, farmers and environmental groups, as described in literature (Garrido et al., 2006; Martínez-Santos et al., 2010; Saurí and Del Moral, 2001, Varela-Ortega et al., 2011). Total exploitable renewable surface and groundwater resources are estimated at around 40000 Mm^3 and 4500 Mm^3 respectively, with a storage capacity of approximately 53000 Mm^3, according to AQUASTAT data (2013). Water supply allocation structure is summarised in Figure 35.

Figure 35. Spain water supply structure (data for 2008)



Source: Own elaboration based on INE (2011)

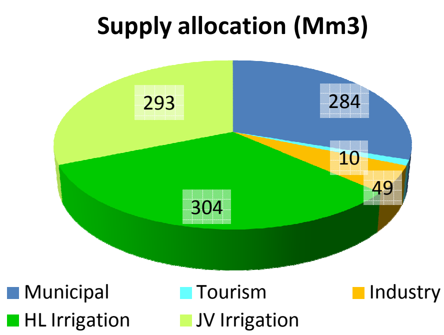
Irrigation agriculture covers an area of 3.4 million hectares and is mainly located in the central plateau and in the southern and eastern Mediterranean regions. Most relevant irrigated productions include olives and vineyards, that together account for 29.4% of irrigated area, cereals (26%), with maize, barley, wheat and rice accounting for 93.4% of total irrigated cereals, and fruit trees (16.6%), of which citrus represent 56% (MAGRAMA, 2012). According to agro-climatic conditions (Iglesias et al., 2009), we can consider two differentiated areas with respect to irrigation agriculture. On the one hand, the Northern Mediterranean area, with a Mediterranean-continental climate, holds a more extensive agricultural production in which cereal production predominates. On the other hand, in the Southern Mediterranean area, cereal production coexists with intensive fruit and horticultural production and irrigated olive groves. In this southern area, irrigation agriculture shows significantly higher productivity in terms of net margin per hectare (MMA, 2005a).

There is a long tradition in Spain's water management, with the prominent role of River Basin Authorities, a body under the Ministry of Environment, in regulating, controlling and providing water services. Also, in the agricultural sector, water user associations, so-called irrigation communities, have greatly contributed to irrigation water management and use, and have provided a voice to farmers in water management decision-making. Currently, water management policy is being revised in order to comply with the Water Framework Directive (WFD) (EC, 2000) mandate which imposes the attainment of good ecological status of all water bodies. In order to achieve this objective, the directive indicates different principles that must govern water management from which the recovery of water costs is one of the most challenging ones. To ensure compliance with the WFD mandate, Spanish river basin authorities are in the process of adopting new River Basin Management Plans that attempt to improve environmental protection and introduce economic principles in water management. Climate change is likely to make the achievement of the WFD goals more difficult, and, in this sense, it is relevant to analyse the potential effect of climate change on future water supplies and demands and define ways in which it can be tackled.

Jordan is one of the most water scarce countries in the world (Humpal et al., 2012), with per capita renewable water resources availability of 165 m^3 and a long term average annual precipitation of 111mm (AQUASTAT, 2013). Total renewable water resources in Jordan are estimated at around 1200 Mm^3, of which 650 Mm^3 correspond to surface waters and 550 Mm^3 to groundwater, and total dam capacity is around 280 Mm^3. Water supply allocation structure is summarised in Figure 36.

Over the last decades, Jordan has been immersed in intense transboundary conflicts over Jordan River water allocations (Gleick and Heberger, 2011), as a result of greatly reduced surface water supplies to Jordan from the Jordan river and the Yarmouk river, its main tributary. This has significantly limited irrigation expansion and productivity in the country.

Figure 36. Jordan water supply structure



Source: THKJ (2008)

There are two different types of irrigation systems which are clearly differentiated. On the one hand, irrigation in the Jordan Valley is based on surface water that is taken from the King Abdullah Canal. This system comprises an area of around 34000 hectares, in which the most relevant cultivations are vegetables (59%), with tomato and potato as the most prominent crops, followed by tree crops (32%), with citrus and bananas making of the largest proportion (DOS, 2008).

On the other hand, groundwater based irrigation covers an area of around 59000 hectares of land located in the Uplands, in the groundwater basins of Aman-Zarqa, Upper Yarmouk, Azraq and Dead Sea basins. These irrigation lands are mostly dedicated to tree crops (59%), from which olives represent 84%, and vegetables 33%, again with tomato and potato as the most relevant crops (DOS, 2008). Irrigation expansion in the Uplands, driven by public and private initiatives, has led to the overexploitation of groundwater resources with about 25% of consumption exceeding available renewable resources (THKJ, 2008).

Jordan's Water Strategy 2008-2022 (THKJ, 2008) defines the main goals for water resources in Jordan and establishes a set of priority actions for achieving them. The National Water Master Plan is currently evaluating the water system in the country's 15 river basins, and exploring future scenarios and potential measures. The various measures that are considered a priority for the management of water resources in Jordan include the introduction of water tariffs sufficient to recover the costs of water supply and improve efficiency in water use, the control and limitation of groundwater withdrawals in irrigation farms in the Uplands, and the enhancement of water supply mainly through infrastructure development. In this chapter we will focus on measures related to water demand management.

While there are clearly defined water management goals in order to deal with the limited available resources, there are also specific policies that incentivise the intensive use of water resources in agriculture. These include, for instance, a tariff to banana imports that protects banana production in the Jordan Valley, which is a water inefficient crop that would not be competitive when compared to imported bananas if the tariff did not exist (Norton and Jaberin, 2006). Also, the current system of water allotments to farmers is determined by the crops grown, granting higher allotments to citrus and bananas (7650 and 12550 m^3/ha respectively, compared to 3600 for vegetables) (Venot et al., 2007).

In this context, there is a need to evaluate how the current unsustainable use of water resources in Jordan may evolve under future socio-economic development and climate change, and to assess potential policies capable to reverse this situation.

5.5.2 The integrated modelling framework

For the analysis of future water demands and irrigation agriculture in the country case studies, we developed an integrated water-agro-economic model that combines an agro-economic Mathematical Programming Model (MPM) and a country level water balance model. The agro-economic model represents an aggregation of the irrigation agriculture sector that includes a representation of most relevant irrigation crops in the country. The study develops a MPM for regionalised farm-level resource use and irrigation agriculture production. This model optimises farmer's utility by modifying crops and technologies, subject to technical, structural and policy constraints. On the other hand, the water balance model consists of a WEAP model (Water Evaluation And Planning system) (Yates, 2005a, 2005b) application that allow us to upscale the farm-based analysis to the country level. This, together with urban and industrial water demands, provides a stylised representation of the water demand and supply balance at country level.

MPMs have been extensively applied in agricultural water management literature. They have been demonstrated to be adequate tools for investigating the effects of potential water and agricultural policies in resources use, crop production and socio-economic welfare. They have been used in the analysis of specific water management tools in a context of scarce water resources (Bazzani, 2005; Blanco-Gutiérrez et al. 2011; Garrido, 2000; Iglesias and Blanco, 2008; among many others). However, this type of local or regional farm-based agricultural MPMs do not fully take into account the bio-physical dimension of irrigation agriculture (Berger, 2001). They therefore do not consider the entire climate and water system characteristics that shape agricultural activity or the effect of competition with other water users in situations of scarcity. Responding to the need for considering an ample scope of external conditions, such as climate or water systems conditions, agro-economic MPMs have also been used in conjunction with other types of models, such as crop models, water management models and hydrology models. There are many examples in the literature of coupled economic-hydrologic models, as reviewed by Brouwer and Hofkes (2008) and Harou et al. (2009), most frequently used at the basin or catchment scales. These models are capable of including bio-physical conditions in economic modelling, providing more realistic boundaries to the model by taking into consideration elements such as water availability driven by climate or by the implementation of management measures. At the same time, these models allow for the possibility to simulate and optimise water management, thereby capturing the dynamic nature of water users' behaviour, such as changes in water demands due to economic stimuli.

There are not many studies that combine agro-economic and water management modelling at the country level. Country level studies provide an appropriate scale of analysis from the policy-making point of view. Although water resources processes take place at the basin scale, there are many elements, mostly related to policy-making, that contribute to water demand and supply that are determined at the national level. Using the country level as the scale of analysis allows for the analysis of socio-economic scenarios with sufficient detail as to specify types of policy measures that are meaningful for the different sectors and specific national contexts. Some past attempts to analyse the water and agricultural sectors at the national or regional scale of analysis include the works by Droogers et al. (2012), Rosenzweig et al. (2004) or Yates and Strzepek (1998).

5.5.2.1 The agro-economic model

This study develops a MPM of constrained optimisation that represents regionalised farm-level decision-making on crop production and resource use. It is an annual-based non-linear optimisation model that maximises farmer's utility under a set of policy, technology and structure-driven constraints. The model constitutes a simple stylised representation of farm resource use and land allocation that is easily adapted to different case studies. This type of farm based regional model is appropriate for the representation of the characteristics of different groups of farms (Osterburg et al., 2001). It can be used for aggregated quantitative policy assessment that differentiates different types of farms and productive orientations (Letcher et al., 2004; Olubode-Awosola et al., 2008).

The model represents the behaviour of a decision-maker at the farm level who tries to maximise a farm's gross margin. However, the decision-maker will not be neutral to risk (Hazell and Norton, 1986), and will adjust farm cropping patterns and resource allocation within a range of risk tolerance. Accordingly, the model's objective function will be the maximisation of farmer's utility, which will consider the utility losses driven by the risk inherent to crop production as a consequence of market and natural variability that will affect crop prices and yields. In this study we use the "mean-standard deviation" approach (as explained in Hazell and Norton, 1986) using the Baumol's decision rule (1963), where utility losses are represented by the standard deviation of the farm's gross margin multiplied by a risk aversion coefficient that represents farmers' behaviour towards risk and that is used as calibration parameter in the model.

The model is specified by the equations explained below.

Farmer's utility: $Max\ U = Z - \varphi \cdot \sigma(Z)$,

where U is farmer's utility, Z represents farm gross margin, φ is the risk aversion coefficient and $\sigma(Z)$ is the standard deviation of farm gross margin according to market and natural risks.

Farm gross margin:

$$Z = \sum_{c,r} gm_{c,r} \cdot X_{c,r} + sb - fco \cdot flab - hlw \cdot hlab - wpm^3 \cdot WC - wpha \cdot sirrg \ ,$$

Where $gm_{c,r}$ is the gross margin per hectare per crop (*c*) and technique (*r*), including any area-based subsidy linked to crops; $X_{c,r}$ is the surface devoted to each crop and technique and the decision variable in the model; *sb* represents any subsidy not linked to cropping area; *fco* and *flab* stand for family labour opportunity cost per hour and family labour used in the farm respectively; *hlw* and *hlab* are the wage of hired labour per hour and the hired labour employed on the farm; wpm^3 is the tariff paid per cubic meter of water and *WC* is the total water consumption of the farm; *wpha* is the tariff paid per hectare of irrigated land (when applicable) and *sirrg* represents the total irrigated land of the farm.

The most relevant constraints considered by the model are those relative to the maximum land available, labour use and water use limitations. These are illustrated by the following equations:

Land constraint: $\sum_{c,r,} X_{c,r} \leq surf$,

Labour constraint: $\sum_{c,r} labreq_{c,r} \cdot X_{c,r} \leq flab + hlab$,

Water constraint: $\sum_{c,ri} X_{c,ri} \cdot wreq_c / h_{ri} = WC$,

$WC \ \leq sirrg \cdot wavail$,

where *surf* is the farm size area; $labreq_{c,r}$ represents labour requirements per crop and technique; $wreq_c$ is the crop net water requirement and h_{ri} the technical efficiency of the irrigation technique (*ri*); *wavail* is the farm water endowment per hectare.

Spanish irrigation agriculture is represented by two different types of production systems that correspond to two agro-climatic areas as defined in the PESETA-Agriculture project (Iglesias et al., 2009): Southern-Mediterranean agriculture of the Mediterranean rim of Spain in South-eastern Spain, and the more continental North-Mediterranean irrigated production, mainly based on cereals, of the Central and Northern parts of Spain's central plateau. Northern river basins that account for half of Spain's natural water resources (more than 15000 Million cubic meters) are not included in the scope of the model, as there is little irrigated land within the limits of those basins, and because their inclusion would lead to an overestimation of resources availability (i.e. the resources exists but are available for a reduced number of uses).

In the case of Jordan, irrigation agriculture is normally differentiated in two areas (DOS, 2008; Venot et al., 2007), the Jordan Valley which relies mainly on surface water from the King Abdullah Canal, and the Uplands, which correspond to more elevated areas close to the desert regions and in which irrigation is based on groundwater pumped from irrigation wells.

Therefore, for each country analysed, irrigation agriculture is depicted by two types of farming systems represented by two farm types whose main characteristics are show in Table 19.

Table 19. Regional farm types for the two country case studies

Country	Farm type	Size (ha)	Cropping pattern	Water consumption (m3/ha)
Spain	North	50	Barley (49.6%), maize (41%), potato (9.4%)	5400
	South	7	Barley (10.6%), maize (13.5%), tomato (11.2%), oranges (15.6%), olives (49.1%)	4850
Jordan	Jordan Valley	3.5	Banana (6%), citrus (24%), tomato (43%), potato (18%), wheat (9%)	6700
	Uplands	12	Olives (57%), tomato (21%), potato (12%), wheat (10%)	6100

Farm type characterisation is based on data from MAGRAMA (2012) and INE (2009), in the case of Spain, and on data from DOS (2008) and Venot et al., (2007) in the case of Jordan. Model parameters and crop coefficients are based on data compiled from literature and public statistics review (MAPA, 2007; MARM, 2008, 2009b, 2010a, 2010b, for Spain; Ariza-Nino, 2004; DOS, 2008; IFAD, 2012; Rawabdeh et al. 2010, Venot et al., 2007 for Jordan), and from fieldwork carried out in the Jordan Valley in June 2012 in the context of the MEDPRO Project.

5.5.2.2 The WEAP Model

WEAP is a hydrology and water resources model developed by the Stockholm Environment Institute that has been widely applied for integrated water resources management and in the context of water management and climate change research (Groves et al., 2008; Lempert and

Groves 2010; Purkey et al., 2007, 2008; Rochdane et al., 2012; Vicuña et al., 2011, among many others). It considers the hydrological processes determining water supply, infrastructures, water demands per sector and water supply and demand management at the river basin or catchment level. It allocates water to different uses according to supply and demand priorities using a linear programming algorithm (Yates et al., 2005a, 2005b). This water modelling platform includes different modules and calculation methods making it a versatile tool that allows for the detailed representation of different elements in the water system. It provides built-in interfaces to link WEAP with other models such as MODFLOW and MODPATH (United States Geological Survey) for groundwater modelling, or LEAP (Long-range Energy Alternatives Planning System, Stockholm Environment Institute) for energy system modelling and planning. It also provides different calculation methods that allow for the representation of water and soil processes with different levels of detail. Of these, the MABIA calculation method is especially suited for modelling irrigation catchments. MABIA simulates daily transpiration, evaporation, irrigation and crop growth, based on the dual Kc method (Allen et al., 1998). Although previous works have used WEAP in combination with economic optimisation models (Varela-Ortega et al., 2011; Blanco-Gutiérrez et al., 2013) they did not take advantage of the potential benefits of using the MABIA module for simulating the effects of water scarcity and climate change at the crop level. Using the WEAP-MABIA-economic model integration allows us to analyse climate change and water management options in a comprehensive way, taking into consideration crop, farm and water system processes and the interactions among them.

Although WEAP is mostly used for its hydrological feature, WEAP can be also used as a water planning and management model based on computation of water balances. In this research, we combine a country level agro-economic model of farm decision-making with a country level water balance application of the WEAP-MABIA platform. In this way, we represent different dimensions relevant to water resource management and climate change at country level, including crop growth processes, regional farm decision-making and country level supply and demands.

Comparable studies include Droogers et al. (2012), for example, which combined the PCR-GLOBWB hydrological model (Van Beek et al., 2011) with the WEAP model to estimate future water supply and demand in 22 countries in the MENA region. In this study, hydrological processes for the estimation of water availability under climate change are calculated for major river basins with the PCR-GLOBWB model and in a second stage WEAP computes water balances at country level.

Rosenzweig at el. (2004) used WEAP to link water supply from the WATBAL model (Yates, 1996) with agricultural demands computed by three different crop models, using scenarios for population growth and technology development. They applied this modelling platform to five agricultural areas that corresponded to one or more different sub-basins.

Varela-Ortega et al. (2011), using a distinct approach, used WEAP for computing the water balance in a Spanish aquifer in combination with an optimisation agro-economic model. Using this model integration, the study analysed water demand management policies in a small area of groundwater irrigation in an overexploited aquifer.

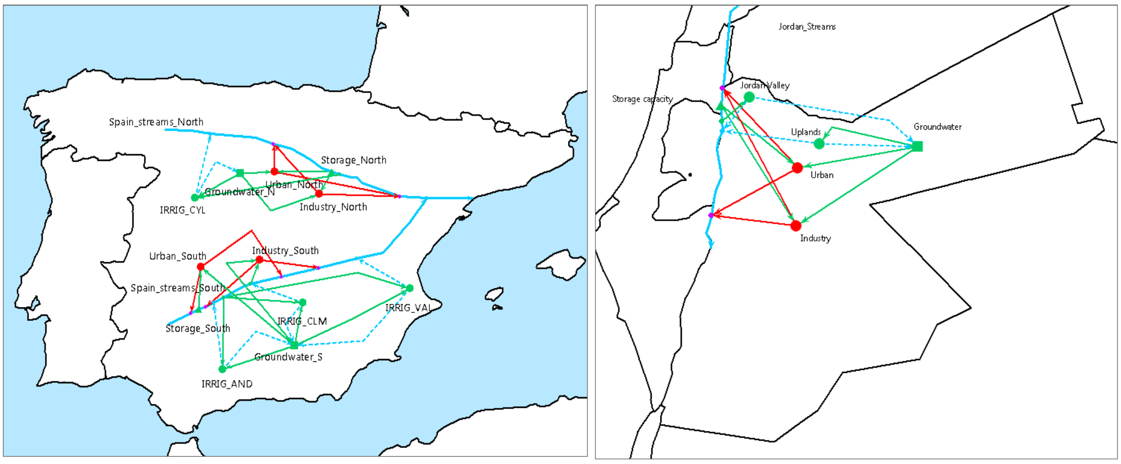
In the present study, stylised country level WEAP applications are based on the representation of surface water resources (including all sources different from groundwater) and groundwater resources, as a single stream and a single groundwater node respectively. Monthly distribution of available resources is also specified. All urban and industrial demands are represented as two aggregated demand nodes that take water from one or the two different available sources. Urban demands are computed using population projections and a fixed water consumption per capita that represents domestic and municipal water demand. Industrial water demand is estimated using the formula by Droogers et al. (2012)[15], in which industrial demand is calculated as a function of GDP and population projections.

Agricultural demands are represented by two catchments for which total irrigation area and cropping patterns are specified according to the regional farm types summarised in Table 19, and taken from the agro-economic farm model simulations for the different socio-economic and climate scenarios. Each irrigation catchment includes information on climate variables, crop growing cycles, irrigation applications, as well as water conveyance and irrigation systems efficiency. Schematic views of the model applications to Spain and Jordan are shown in Figure 37.

[15] Droogers et al. (2012) estimation of industrial water withdrawals (IWW):

$IWW_t = IWW_{t-1} \cdot GDP_t / GDP_{t-1} \cdot GDPcap_{t-1} / GDPcap_t$

Figure 37. Schematic views of the Spain and Jordan WEAP model applications.



Data on water resources supply and demand structure for Spain come from INE (2011), MAGRAMA (2013) and MMA (2005b). Data on water resources supply and demand for Jordan come from Courcier et al. (2005) and Raddad (2005). Monthly climate data for both models were obtained from the CRU-TS 3.10 Climate Database (Jones and Harris, 2011).

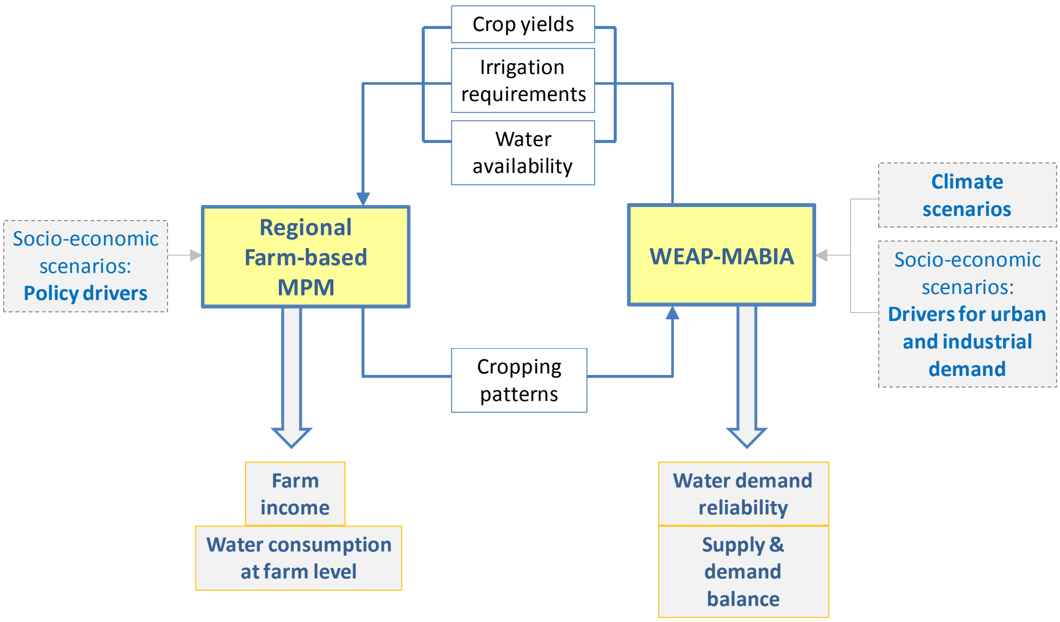
Soil characteristics for Jordan are obtained from IALC (2006) Soil Survey, and for Spain are obtained from MAPA (2002, 2004a, 2004b, 2004c, 2005). These data are used to calculate soil water capacity. Crop and irrigation parameters are based on Allen et al. (1998), on Doorenbos et al. (1979), and adjusted with data from the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 2002, 2004a, 2004b, 2004c, 2005) and from Rawabdeh et al. (2010).

5.5.2.3 Model integration

Figure 38 shows the scheme of the agro-economic and water management model integration.

Scenario simulation is driven by the economic model. Water use at farm level is determined by water policy and management decisions rather than physical water availability. Cropping patterns in an irrigation region are determined by water availability at farm level as well as by economic, technical and policy constraints. Simulations start with the economic model run, in which the MPM optimises cropping patterns under the corresponding scenario. The optimal cropping pattern obtained is the one that maximises farmers' utility according to policy constraints and expected crop water requirements, crop yields and water availability. Then, cropping patterns are used to specify the irrigation catchments in WEAP. Using cropping patterns as an input, and considering urban and industrial demands, WEAP calculates monthly demands and water diversions from the different sources to satisfy the irrigation demands and the urban and industrial demands. Using the MABIA method, WEAP calculates irrigation water requirements and allocates water to crops depending on water availability and established priorities, and then calculates crop yields. In a second iteration, the economic model uses WEAP results under the A2 climate change scenario to calculate farm level adaptation to changes in water availability, crop yields and irrigation needs. Then, changes in cropping patterns are used by WEAP to calculate new water demands and crop production after farm level adaptation as well as the water balance at country level.

Figure 38. Schematic overview of model integration



5.5.2.4 The modelling scenarios

The scenarios simulated correspond to the socio-economic and climate scenarios explained in section 5.3. These are specified for the two countries selected. From the socio-economic scenarios, data and descriptions of future population and GDP growth were used to estimate urban and industrial water consumption respectively. Irrigation water demand is based on the results from the MPM on cropping patterns and WEAP-MABIA calculations of crop evapotranspiration and irrigation needs. Policies simulated in the MPM and in the WEAP-

MABIA model are specified according to the storylines defined in the scenarios (Ayadi and Sessa, 2011; EC, 2012d) and explained in section 5.3. These policies include, for Spain:

- SI: no policy change. Due to low willingness and capacity to fully implement WDF, cost recovery is not applied.
- SII-III: the strengthened role of the EU and the policy focus on sustainability lead to the effective implementation the WFD. For this, a 10 % reduction of water allotments is simulated for southern irrigation farms to guarantee a sustainable use of water resources and the protection of water ecosystems. Also, as mandated by the WFD, a cost recovery volumetric tariff is implemented. According to MMA (2007), current costs of water paid by farmers are 5 cent€/m^3, while the full cost of water services amount to 8 cent€/m^3 (weighted average of costs of irrigation water services)
- SIV: no policy change. Due to low willingness and capacity to fully implement WDF, cost recovery is not implemented.

Policies simulated for Jordan include:

- SI: no changes in agricultural or irrigation policies because of a stronger focus on economic development and low relevance of sustainability values.
- SII: The integration on a new union with the EU produces the sharing of values and policy goals and contributes to advances on trade liberalisation. This leads to a removal of trade barriers that significantly lowers banana prices. At the same time, policy focus on sustainability leads to the reform of the water allotments system. Irrigation water allotments are decoupled from crops, and instead, similar allotments are granted to all farmers according to farm area. Operation and maintenance cost recovery is applied in the Jordan Valley surface water-based farms, estimated at 2 cent€/m3 according to Venot et al. (2007). In the Uplands, water abstraction is controlled and water quotas are applied to reduce water consumption by 25% to stop overexploitation.
- SIII: without strong integration with the EU, trade barriers are kept. However, in the Jordan Valley the sustainability focus of policies still favours the decoupling of water allotments from specific crops, which are linked to land area instead, operation and maintenance cost recovery is applied as well. In the Uplands, as in the SII scenario, water abstraction is controlled and water quotas are applied to reduce water consumption by 25% to stop overexploitation.

- SIV: as in SI, there are no changes in agricultural or irrigation policies as the main concerns for policy-making are economic crisis and conflicts in the region.

Both in Spain and in Jordan simulations, SI and SIV are similar with respect to water policy. However, these scenarios will significantly differ in demographic and economic trends.

Socio-economic scenarios are combined with a climate change scenario. We use projections of changes in temperature and precipitation from the CGCM3-A2[16] climate change scenario (CCAFS, 2012), which represent severe climate change conditions, and compare it with a "No climate change" scenario to look at the combined effects of socio-economic and climate scenarios on water supply and demand balances.

5.5.2.5 Model limitations

Models are simplified and stylised representations of reality, and, as such, they present limitations with respect to the level of detail of such representations. The integrated modelling exercise presented in this research shows limitations similar to those presented in chapter 3 regarding spatial and temporal scales of analysis, frequently referred to in hydro-economic modelling based research (Blanco-Gutiérrez et al., 2013; Brouwer and Hofkes, 2008; Harou et al., 2009; McKinney et al., 1999).

Nonetheless, in this case, the water balance model does not represent river basin hydrological processes, which on the one hand simplifies model specification and integration but on the other implies a less accurate representation of water supply and specifically of climate change impacts on water resources. The model uses average data for changes in water inflows based on the hydrological assessments reported in literature. However, it does not account for inter-annual variability and therefore it is not able to characterise variability or extreme events such as droughts.

Water problems are most often local, and as such, aggregated national level assessments as the one presented here fail to reflect specific concerns such as aquifer overexploitation, which is a relevant issue in Mediterranean countries and tend to mask the intensity of local problems. However, national level assessments are frequently more feasible with respect to data availability and are meaningful for the assessment of socio-economic regional or global scenarios.

[16] CGCM3-A2 from the Canadian Center for Climate Modelling and Analysis.

Overall, in spite of the limitations inherent to a very much stylised representation of the agricultural and water systems at country level, the model integration used in this research can still provide relevant information for identifying particular risks, raising awareness and contributing to water policy decision-making at national and supra-national levels.

5.5.3 Future scenarios for water use and irrigation water management in Spain and Jordan

This section presents the results of the country level case studies, focusing on the balance between demand and supply, sustainability of resources use and the effect of the policies analysed. This is a more detailed analysis (as compared to section 5.4) of water supply and demand under climate change scenarios, looking at crop processes, farmers' decision-making under different climatic and policy constraints, and water balances at country level.

Scenario simulation results are shown for the different socio-economic scenarios (SI to SIV) and for the combination of socio-economic scenarios with climate change scenario A2 and farm autonomous adaptation to climate change conditions (SI-A2 to SIV-A2). This implies that results on the total potential impacts of climate change without adaptation are not shown. In this way, this assessment tried to emphasise the relevance of socio-economic scenarios in future water balances at country level rather trying to quantify the negative impacts of climate change.

5.5.3.1 Future scenarios for water use in Spain

This section presents the results of the scenario simulation for Spain. Results refer to the socio-economic scenarios SI, SII-III and SIV and to the "no climate change" and A2 climate change scenario. According to CEDEX (2011), under the A2 scenario, surface water runoff decreases by 8.3% and 10% in the North and in the South respectively in the 2011-2040 period and by 16.7% and 21.6% in the 2041-2070 period. These reductions are introduced in WEAP for the simulation of climate change effects of water availability, as in this case the hydrological processes are not specified into the model.

The results of the WEAP model simulation show however, that supply delivered to irrigation does not diminish under the climate change scenario. In spite of a reduction of natural water resources availability, there are still sufficient water resources to meet demands. Therefore, the effects of climate change at farm level are only simulated through its impacts on crop yields and water requirements. Table 20 shows the simulated impacts of climate change on crops.

Table 20. Climate change impacts on crops in Spain

	Crop yields (% change)	Crop irrigation needs (% change)
Barley	0.0	18.6
Maize	0.0	10.4
Potato	0.0	0.7
Tomato	0.0	7.0
Olives	0.0	13.7
Citrus	-18.7	19.3

As Table 20 indicates, crop yields do not experience significant changes because of climate change. As long as there is enough water, all crops analysed showed similar yields on average, with the only exception of citrus, which experiences an 18.7% yields reduction with a 19.3% increase in irrigation requirements. For the rest of the crops, while yields remain constant, irrigation requirements increase, especially for barley (18.6%) and olives (13.7%). Other studies show uneven results for specific crops. Iglesias et al. (2000), for example, showed that climate change impact on yields of irrigated wheat is limited when water is not constrained. They show how in northern regions yields may increase while decreasing in the southern region. Rodríguez-Díaz et al. (2007) analysed a set of irrigation areas in the Guadalquivir river basin (southern Spain), focusing on olives and maize, and calculated changes in irrigation requirements of between 16% and 20% on average for the B2 and A2 scenarios. Olesen and Bindi (2002) looked at the impact of climate change on crop growth in different European regions and showed uneven results for Southern Europe. They indicate that vegetables and olive production may experience benefits from climate change as far as their water and nutrient requirements are fulfilled. Müller et al. (2010) computed crop yields for 3 emission scenarios and 5 General Circulation Models (GCMs) for major crops globally and estimated average yield changes of around 0% for Spain. In addition, they point to a general agreement across scenarios on yield increase in the 2050s. This is attributed to the impact of climate change in Spain when fertilisation driven by increased concentrations of CO_2 in the atmosphere is considered. There is however no agreement on the direction of the change when the effect of CO_2 is not considered, as in this study.

Table 21 summarise the main results of the economic model scenario simulation. Results indicate that farms in the southern region achieve higher income per hectare, with 1741 €/ha in the SI scenario. Farms in the northern region obtain 618€/ha.

Table 21. Economic results of the policy and climate change scenario simulation in Spain

		SI	SI-A2	SII-III	SII-III-A2	SIV	SIV-A2
North	Income (€/ha)	618	675	459	401	618	675
	Water consumption (m3/ha)	5400	5400	2755	3883	5400	5400
	Water marginal value (€/m3)	0.005	0.007	0	0	0.005	0.007
	Total labour (thousand h)	47770	84618	35884	42631	47770	84618
	Water productivity (€/m3)	0.114	0.125	0.167	0.103	0.114	0.125
South	Income (€/ha)	1741	1677	1592	1546	1741	1677
	Water consumption (m3/ha)	4850	4850	3213	1946	4850	4850
	Water marginal value (€/m3)	0.013	0.011	0	0	0.013	0.011
	Total labour (thousand h)	415709	318030	369902	214049	415709	318030
	Water productivity (€/m3)	0.359	0.346	0.496	0.794	0.359	0.346

Water policy (scenario SII-III) drives lower income for both farming systems when compared to scenarios SI and SIV in which the WFD goals are not pursued. This is mainly due to increase in water tariffs in the two regions and the reduction of water allotments in the South. In this scenario both farming systems experience similar income losses in absolute terms (comparing SI and SII-III). The impact of the water tariff amounts to 159 €/ha in the north and 149€/ha in the south, but it represents a larger share (24%) and leads to a sharper reduction in water consumption (49%) in the north. These results indicate that water productivity in the northern region decreases to levels that make not profitable to use similar amounts of water as in scenarios SI and SIV. Farmers in the northern region would therefore, adapt to new pricing conditions by choosing crops that consume less water. Farms in the southern region also reduce water use but to a lesser extent. Water productivity in southern irrigation is higher and this will determine a more inelastic water demand, as shown in Figure 39.

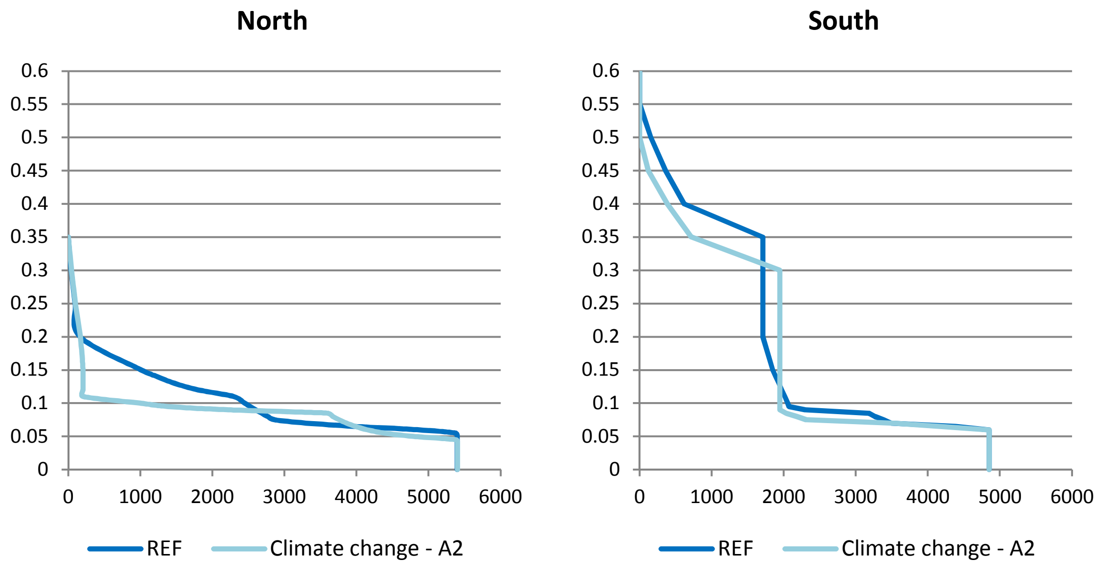
With respect to water productivity, the constraints to water use produced through the price increase in all areas and the reduction of water allotments in the south under the SII-III scenario, produce an increase of economic efficiency of water use in the northern and southern irrigation farms. This occurs because there is a shift in crop production that leads to higher water productivity. However, this shift is accompanied by a decrease in labour use, both in northern and southern farms.

When climate change occurs and farm systems adapt to new cropping conditions, farms in the northern region achieve a higher farm gross margin (+9%) in the SI and SIV scenarios. The reason for this is the large increase of barley water requirements (+18%) that produces a shift towards potato and maize, crops that face smaller increases in water requirements (Figure 40 shows changes in cropping patterns across scenarios). These two crops are more profitable than barley, but without climate change, farmers choose barley because of risk-averse behaviour. However, under the SII-III scenario climate change produces a negative impact on farm income. In this scenario, the effect of increased water tariffs forces farmers to reduce water consumption considerably (by almost 50%). This fact, together with higher irrigation requirements, driven by climate change, limits the possibility to switch to more profitable crops.

In the south, adaptation to new crop conditions produces income losses of 3-4% in the three socio-economic scenarios. In the most restrictive one SII-III, climate change produces an important increase in water productivity because of the crop substitution in favour of irrigated olives which consume lower amounts of water and have good margins.

Water demand curves (Figure 39) illustrate how farms in the different regions adapt their water consumption through their choices on crops and techniques when water prices increase. As shown by many authors (Berbel et al., 2007; Blanco-Gutiérrez et al., 2011; De Fraiture and Perry, 2007; Gómez-Limón and Riesgo, 2004), water demand curves are usually inelastic at low price ranges., There is therefore a threshold price under which water consumption remains constant. Inelastic sections reflect that water productivity in terms of €/m^3 is sufficient to maintain similar levels of water consumption up to higher water prices.

Figure 39. Irrigation water demand curves in the Northern and Southern regions in Spain



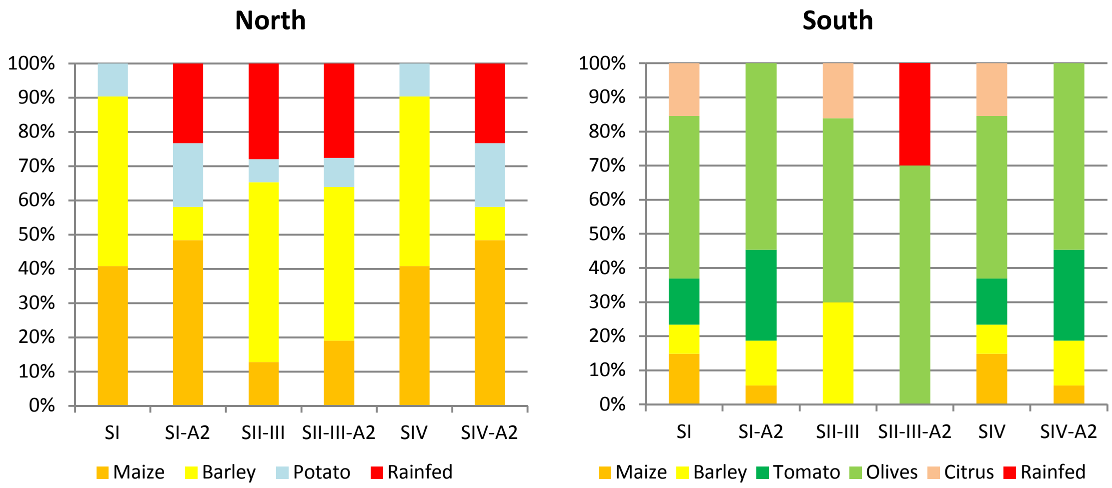
Water demand curves show a similar behaviour at low price ranges in the two regions considered. Water demand is inelastic in both regions for prices below 5 cents of euro. In the northern region, water consumption starts to decrease for prices above 5 cents/m^3, while in the south demand remains constant up to prices of around 7 cents/m^3. For cost recovery at a price of 8 cents/m^3, both regions reduce water consumption. At higher price ranges, water demand in the north becomes very elastic. For prices above 20 cents/m^3 water demand becomes almost zero. However, demand in the southern region is more inelastic showing that there are profitable and low-water-demanding cropping alternatives, which in this case correspond to olive production. In the southern region, water consumption is null for prices above 50 cents/m^3.

Water demand curves also show how water demand becomes more elastic under climate change. The increased irrigation requirements reduce water productivity and this produces a more elastic response to the increase in water prices. This effect is most noticeable in the case of farms in the north.

Figure 40 shows the changes in cropping patterns that take place in each region under the different scenarios considered. As explained above, results show that climate change produces a shift in crop production. Barley is replaced by potato and maize in the north in all three socio-economic scenarios, when there is climate change. Looking at the socio-economic scenarios without climate change, the figure shows that in scenario SII-III, the cost recovery tariff produces an increase in the rainfed area and a shift towards barley, which has lower water requirements.

In the south, climate change drives the substitution of citrus area and maize in favour of tomatoes and olives. In the SII-III scenario, however, when the cost recovery tariff applies and water allotments in the south are diminished by 10%, horticulture and maize disappear and irrigation production switches to irrigated olive production and rain fed production.

Figure 40. Crop changes in the Northern and Southern regions across scenarios



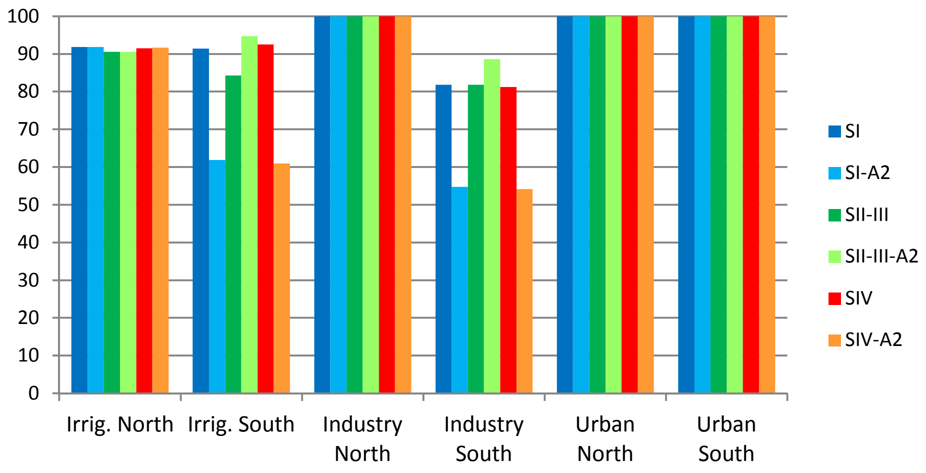
These results are supported by the trends observed in Spain in the last decade. The CAP reforms that took place in the first decade of the 21st century together with the expansion of modern irrigation techniques have driven the spread of irrigated permanent crops, especially olives. This has been accompanied by a reduction of irrigated cereal land, as shown by public statistics (MAGRAMA, 2012) and by Garrido and Varela-Ortega (2007) and Varela-Ortega (2011).

The WEAP model simulations upscale the results from the economic model to the country level. This shows how changes in the irrigation regions together with the different socio-economic pathways provided by the socio-economic scenarios affect the country's water demand and supply balance.

Figure 41 shows water demand reliability for the different demand sectors and irrigation regions. It is calculated by WEAP as the percentage time that water demand is fully met.

Results indicate that urban demands are not at risk of being not met in any future socio-economic or climate development. However, the industrial sector in the south is competing for water use with the agricultural sector, and demands are not fully satisfied in any scenario. Irrigation demands show uneven results. On average, demand reliability is higher in the northern irrigation region than in the southern region.

Figure 41. Demand reliability in Spain

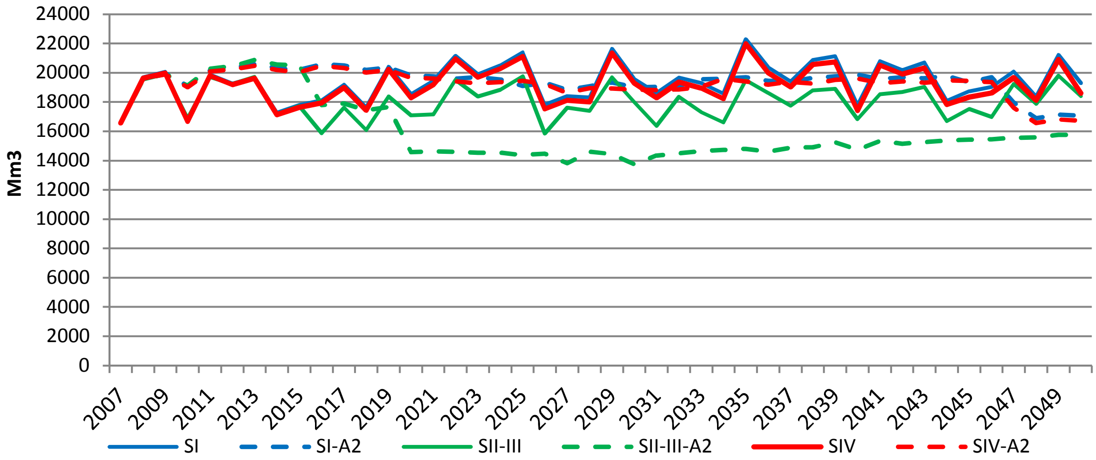


The analysis of socio-economic scenarios shows that in the sustainability scenario SII-SIII, demand reliability for the irrigation sectors decreases as compared to SI, especially in the south. In this scenario and in the southern region, policies aiming at achieving the good ecological status of water bodies reduce irrigation water demand through the use of tariffs and reduction of water endowments. However, the rapid socio-economic development in this scenario produces an increase in industrial and urban demands. Results for the SI and SIV scenarios are very similar, with demand reliability slightly higher in the SI scenario.

However, under climate change scenario the results are very different. In the southern region demand reliability decreases considerably under the climate change scenarios for SI and SIV scenarios and both in the irrigation sector and in the industrial sector. This means that adaptation of cropping patterns is not sufficient to overcome the negative effects of climate change on water availability and on irrigation requirements. In the SII-III socio-economic scenario, however, farm level adaptation of cropping patterns together with the implementation of water demand management policies that promote efficiency are sufficient to offset the negative effects of climate change and improve the reliability of the demands.

Figure 42 and Figure 43 show aggregated water supply delivered and water unmet demand in Spain across scenarios.

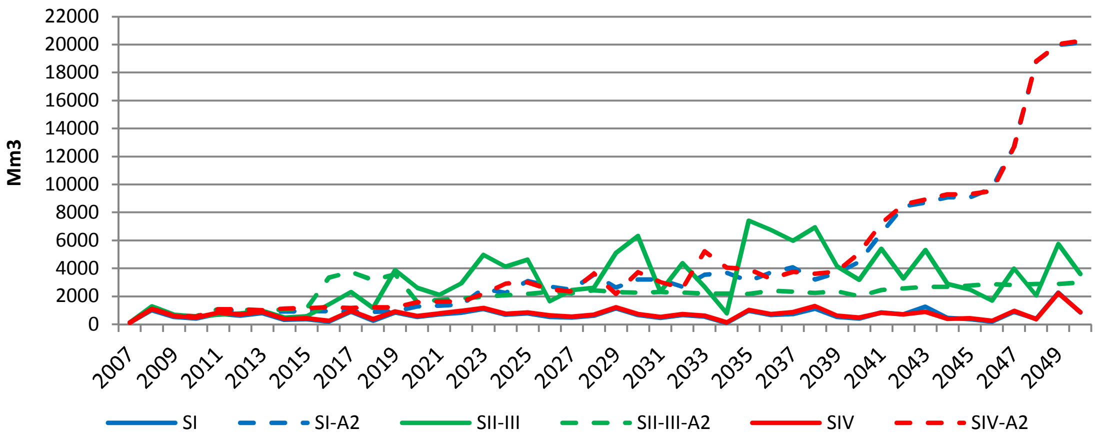
Figure 42. Supply delivered in Spain under the three socio-economic scenarios without and with A2 climate change scenario



Supply delivered in scenarios SI and SIV is very similar, while in scenario SII-III it decreases as a consequence of the reduction of water use from agriculture when cost recovery tariffs are applied. In the SII scenario, with higher urban and industrial demands, supply delivered and unmet demands are substantially lower. This is especially the case under the A2 climate change scenario, where farmers adapt cropping patterns to new crop water requirements driven by climate change. This illustrates that water policy is the key determinant and prominent driver for projecting water use and water scarcity. Adaptation to climate change (dashed lines) stabilises water supply delivered in all three scenarios and in SII-III it further reduces the supplies delivered.

Unmet demand (Figure 43) follows a similar trend in SI and SIV scenarios. Under severe climate change, these unmet demands increase with respect to the “no climate change” along the whole period with a dramatic increase in unfulfilled demands from 2040 onwards. This sharp increase of unmet demands is a consequence of the exhaustion of water storage capacity when water inflows decrease and crop water requirements increase. In the SII-III scenario, water conservation policy includes water tariffs for cost recovery and lower water endowments in the south as well as adaptation of cropping patterns to climate change. However, unmet water demand is stabilised for the whole period at lower levels than in the no climate change scenario. Therefore, sustainability oriented water policy contributes to adaptation to climate change and farm level autonomous adaptation offers a great potential for reducing unmet water demands.

Figure 43. Spain unmet water demand under the four scenarios selected



5.5.3.2 Future scenarios for water use in Jordan

This section presents and discusses the results obtained in the case study of Jordan. Similarly to the case of Spain, results presented correspond to the simulation of four socio-economic scenarios and two climate scenarios: the “no climate change” scenario and the A2 climate change scenario. In this case, climate change impact on surface water availability has been simulated as a 17% decrease in surface water runoff, based on Samuels et al. (2010). As in the case of Spain, climate change impacts in Jordan do not translate into lower water supply for farms. Instead, it intensifies the pressure on groundwater resources, both from urban and industrial demands and from irrigation water demand from the Uplands. To attend to increasing irrigation demands in the Jordan Valley, water supply for the urban and industrial demands would have to further rely on groundwater use. Therefore, in order to limit the impacts on groundwater the Water Authority would need to control water use and, when appropriate, reduce water allotments to farmers.

Table 22 illustrates the impact of climate change on crop yields and irrigation in the two regions analysed in Jordan. Results correspond to the comparison of average values along the 2011-2050 period of the “No CC” and A2 scenarios. For the assessment of climate change impacts on crops, we simulated temperature and precipitation changes using the WEAP-MABIA platform. This simulation calculates crop production and irrigation with the available water resources. This means that the resulting impacts on yields are subject to the simulated constraints in water use. Although results show that irrigation needs increase, additional irrigation could cushion climate impacts on yields.

Results of crop growth simulation in WEAP-MABIA show that climate change produces severe yield losses in the Jordan Valley. The most affected crops are citrus (-39%) followed by tomato and bananas (≈17-18%). However, crop yields in the Uplands are not significantly affected, as access to groundwater resources allows for a substantial increase in water applications. In fact, tomato in the Uplands experience substantial yield increases (30%). Irrigation needs increase in most cases, especially for potato (≈35%). Other studies that have analysed the effects of climate change on crop yields in this region include the study by Müller et al. (2010), which conclude that without considering CO2 fertilisation, crop yields in Jordan may be reduced by 10-20%. Again, they note that there is not agreement on the direction of the changes across models and scenarios. Giannakopoulos et al. (2005) analyse a selection of crops and conclude that potato and cereal yields may increase by 15 and 10% respectively when sufficient water is available.

Table 22. Climate change impacts on crops in Jordan (average of simulated values for the period 2011-2050)

		Crop yields (% change)	Crop irrigation needs (% change)
JORDAN VALLEY	Banana	-17	9.3
	Citrus	-39	11.7
	Potato	-0.2	35
	Tomato	-18.8	5.5
	Wheat	-5	10.4
UPLANDS	Olives	1.5	11.8
	Potato	-2.6	34.7
	Tomato	30	8.6
	Wheat	0.3	22.2

Table 23 summarises the main results of the economic model simulation for Jordan. These results show a high water productivity in both irrigation systems, especially in the Jordan Valley, where gross margin in the SI scenario amounts to 4078 €/ha compared to 2843 €/ha in the Uplands. However, it must be noted that farms in the Uplands are, on average, 4 times larger than farms in the Jordan Valley. In the Jordan Valley, a much smaller area is frequently the only source of income for rural families.

Table 23. Economic results of the scenario simulation in Jordan

		SI	SI-A2	SII	SII-A2	SIII	SIII-A2	SIV	SIV-A2
Jordan Valley	Income (€/ha)	4078	2337	4521	3524	4038	2296	4078	2337
	Water consumption (m3/ha)	6700	6700	6700	6700	6700	6700	6700	6700
	Water marginal value (€/m3)	0.400	0.234	0.086	0.129	0.394	0.228	0.400	0.234
	Total labour (thousand h)	4048	3003	4555	4367	4048	3003	4048	3003
	Water productivity (€/m3)	0.609	0.349	0.675	0.526	0.603	0.343	0.609	0.349
Uplands	Income (€/ha)	2843	3038	2405	2407	2405	2407	2843	3038
	Water consumption (m3/ha)	6100	6100	4575	4575	4575	4575	6100	6100
	Water marginal value (€/m3)	0.124	0.319	0.310	0.317	0.310	0.317	0.124	0.319
	Total labour (thousand h)	9020	9963	4543	8605	4543	8605	9020	9963
	Water productivity (€/m3)	0.466	0.498	0.526	0.526	0.526	0.526	0.466	0.498

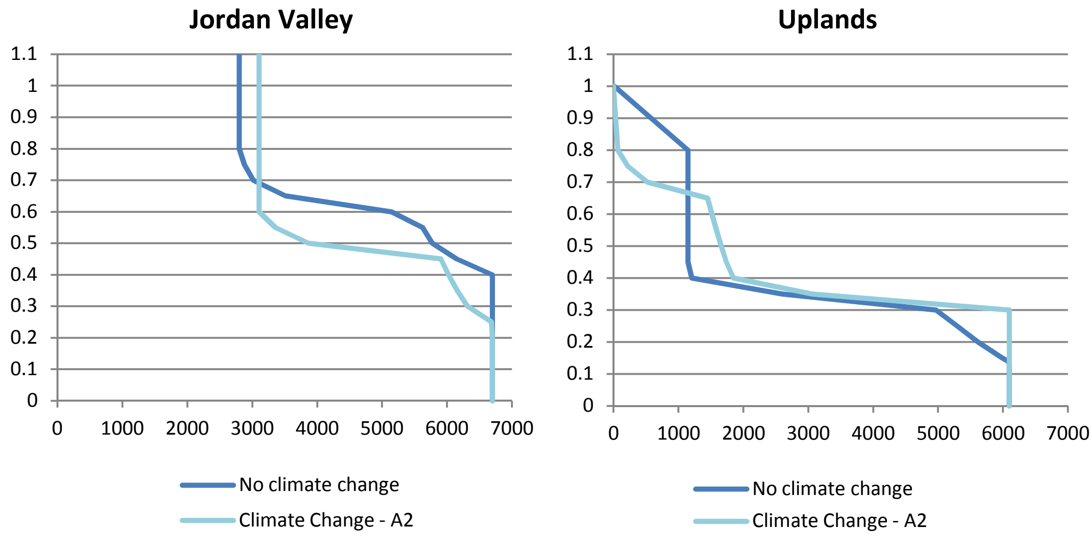
Comparison of socio-economic scenarios SI and SIV with scenario SIII shows that the application of the tariff for cost recovery (SIII) does not affect water consumption in any case. It slightly reduces farm income but there are no changes in cropping patterns. The reason for this is that water productivity and marginal value is far above its price and therefore farmers in Jordan still have incentives to continue using the same amount of water. Scenario SII shows that when the protection to banana production through trade barriers is removed and water allotments are decoupled from crops, farm income increases as farmers switch to more profitable crops (Figure 45), thereby increasing water productivity. This would also produce a substantial decrease in the water marginal value because banana production, which is the most water demanding activity, would not be such a profitable cropping alternative. This policy decision would also be accompanied by an increase in total labour used which would be beneficial for an area in which protecting agricultural labour is a priority.

In the Uplands, the effect of reducing water consumption by 25% to achieve the sustainability of groundwater use (SII and SIII) produces a 15% reduction of farm income and substantially reduces total labour use. Also, the increase of the marginal value and productivity of water suggests the ineffectiveness of the potential use of water tariffs to control and reduce water abstractions.

With respect to climate change, results show that the impact would be noticeable in the Jordan Valley, with 43% income losses in the SI, SIII and SIV scenarios and 22% losses in the SII scenario. These results show the need to implement planned adaptation strategies that minimise the impacts of climate change in the Jordan Valley. In addition it is important that these demonstrate the adequacy of policy measures that remove perverse incentives to water use and promote a higher economic efficiency of water use. However, in the Uplands, climate change would only produce a cropping pattern adjustment and, in scenarios SI and SIV, slight increases on farm income (7%).

Figure 44 illustrate water demand curves in the Jordan Valley and in the Uplands, which further explain the effect of water pricing.

Figure 44. Water demand curves in the Jordan Valley and in the Uplands

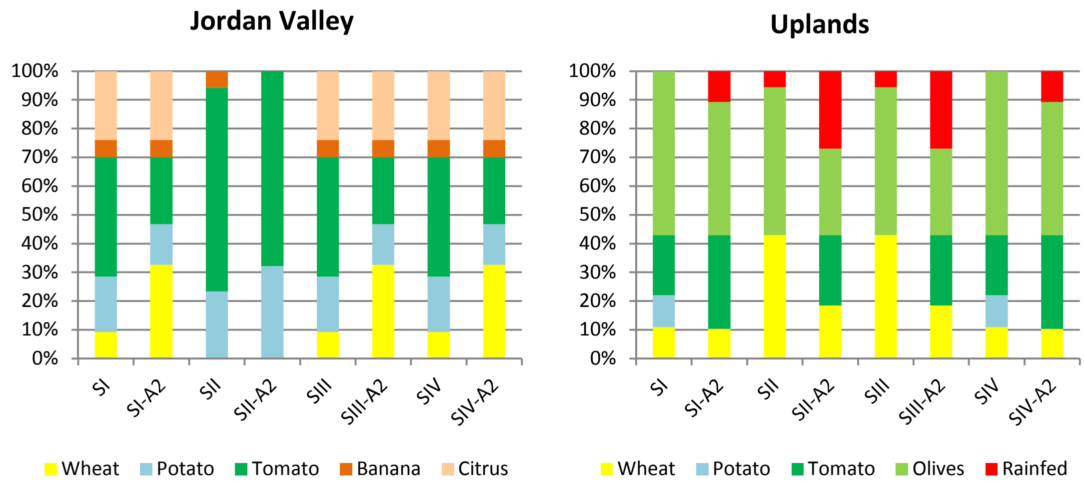


Water demand in Jordan is very inelastic, i.e. it shows low responsiveness to increasing water prices. In the Jordan Valley, farmers would not reduce water consumption until water price surpasses 0.4 €/m^3. In the Uplands water demand is inelastic below a price of 0.15 €/m^3. The effect of climate change, however, is different in the two areas. Climate change increases inelasticity in the Uplands as a consequence of the increase in tomato yields. However, in the Jordan Valley, reduced yields together with increased water requirements lead to lower water productivity and therefore a lower willingness to pay for water.

The results obtained in this study coincide with the results presented by Doppler et al. (2002). They used a linear programming model with and without considering risk and concluded that farmers' response is more determined by risk aversion than by profit maximisation. This is coherent with the high risk aversion determined by the Jordan economic model (the models calibrate for a phi of 1.55 and 0.9 in the Jordan Valley and in the Uplands respectively). Also, Doppler et al. showed a very inelastic water demand. In their study, farmers do not change their water consumption until water price reaches 0.175 $/m3. A water price above 0.325 $/m3 makes most agricultural alternatives unprofitable. However, when risk is considered, water demand appears to be more elastic. Venot et al. (2007) estimated the effects of different water prices aimed at reducing water consumption and recovering costs of water supply, both in the Jordan Valley and in the Uplands. However, they concluded that water demand would not decrease when cost recovery water tariffs are implemented. Instead, farmers would try to expand their farms in order to achieve higher total income.

Figure 45 shows the changes produced in cropping patterns in each simulated scenario. This figure shows, as explained above, that in the Jordan Valley, water tariffs in SIII do not produce any change in cropping patterns and water use as compared to SI and SIV. When trade barriers are removed and water allotments are decoupled from crops (SII), citrus and wheat production disappears in favour of vegetable crops. Climate change, however, also results in the phasing out of banana growing in scenario SII. In the Uplands, the reduction of water abstractions produces the substitution of vegetable production with wheat and a reduction of the irrigated surface. Climate change, however, drives the expansion of tomato area in all socio-economic scenarios and a greater expansion of rain fed area with a reduction of olive area.

Figure 45. Crop changes in the Jordan Valley and in the Uplands across scenarios

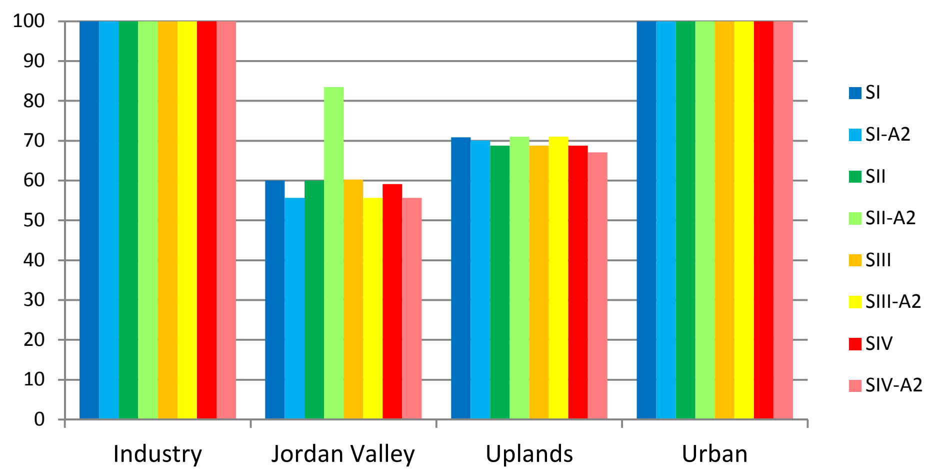


The results obtained in this study are coherent with those presented by other authors. Using scenarios, they have found that climate change impact on water resources together with the implementation of sustainability-oriented water and agricultural policies produces a shift towards more water efficient crops that increase water productivity. In line with this, Norton and Jaberin (2006), compare water productivity among different crops in the Jordan Valley and indicate the need to shift irrigation production. The suggested shift is towards those crops for which water productivity overcomes the unitary costs paid by urban users in Amman (≈1 JD/m^3), or at least its opportunity costs (≈0.0424 JD/m^3). According to these authors, the only crops able to achieve water productivities values above the cost of urban water are vegetables, especially tomatoes and potatoes.

These authors make a number of recommendations, including an increase in water tariffs for cost recovery to cover operation and maintenance. They also suggest a change in the water rights system to decouple water allotments from crops, as simulated here, as well as the improvement of on-farm water efficiency and the promotion of irrigation water user associations that enhance water management and control.

Figure 46 shows demand reliability for the different uses of water in Jordan. Irrigation water demand is not covered in any scenario, while industrial and urban demands are 100% fulfilled. This graph however, must be carefully studied. Actual urban and industrial demands are already constrained, and currently in Jordan there is no reliable and constant daily supply to cities. However, in this model, the demands set for cities and for the industry correspond to actual consumption, which is lower than real demand, and this consumption is secured.

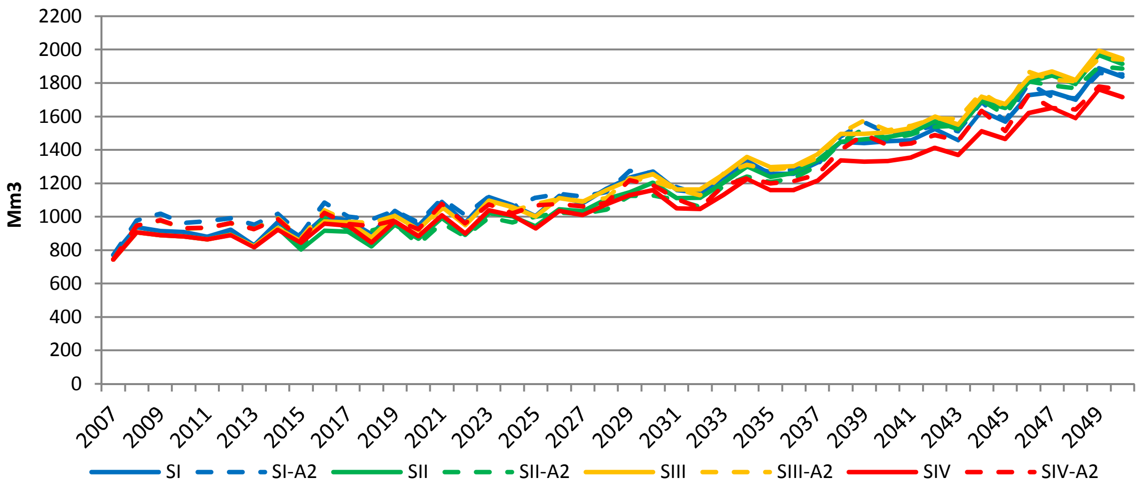
Figure 46. Demand reliability in Jordan under the four scenarios considered



Irrigation demand is not fully covered at the present. Currently, water scarcity leads farmers engage in deficit irrigation and they are forced to sacrifice part of their production potential. This situation is likely to worsen in the future. Even in scenario SII, in which high water demanding crops such as citrus are not grown in the Jordan Valley and water abstractions are reduced in the Uplands, demand reliability does not improve. This is because of the fact that although water demand is lower, it is still above the level of available resources. In order to improve reliability water demands need to decrease further or water supply must be improved through the use of alternative water sources.

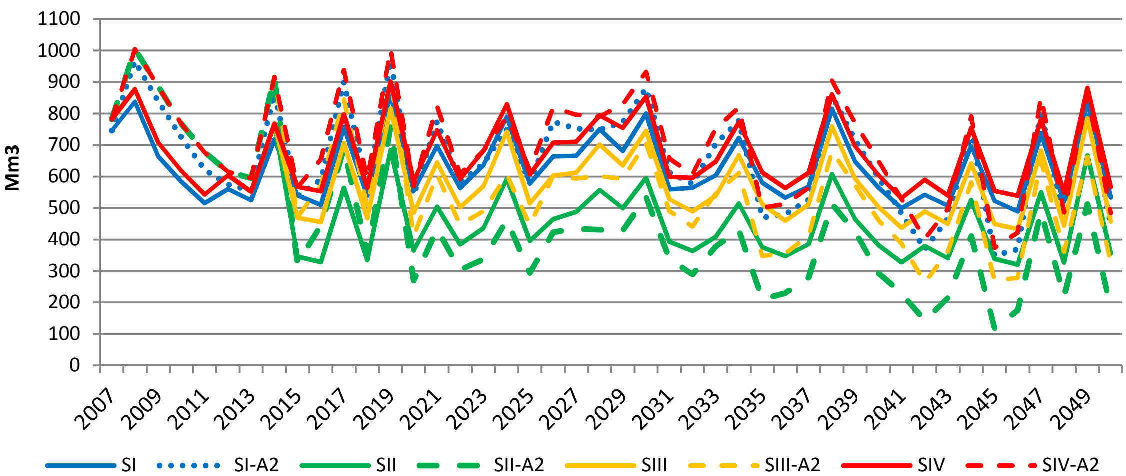
Figure 47 and Figure 48 show supply delivered and unmet demand, respectively. Supply delivered is higher for the sustainability scenarios (SII and SIII) as they show greater urban and industrial demands triggered by population and GDP growth. However, in those scenarios, unmet demand is lower, especially in the SII scenario. As explained above, urban and industrial supply is secured in this model. Therefore, when irrigation demands in the Jordan Valley increase, urban and industrial demands are satisfied by groundwater supplies. With respect to irrigation, in the SII and SIII scenarios, water policy limits groundwater withdrawals for irrigation in the Uplands reducing water demand by 25% and contributing to diminishing unmet demand. However, as Figure 47 shows, water supplies will continue rising in the future driven by socio-economic development which depends on the exploitation of groundwater resources. For sustainability to be achieved, more drastic measures are required to contain demand for the growing cities and industries, improve efficiency and increase supply in a sustainable manner as projected in current Jordanian water plans.

Figure 47. Projected supply delivered in Jordan under the four scenarios selected



The decreasing unmet demands shown in Figure 48 for scenarios SII and SIII are driven by reduced irrigation water demands but do not reflect the effect of increasing urban and industrial demands which are depleting the already overexploited groundwater resources.

Figure 48. Jordan unmet water demand under the four scenarios selected



Overall, results for the Jordanian case study show that, when compared to Spain, socio-economic scenarios have a strong relevance in the projection of water use as urban and industrial demands are likely to grow significantly in the future. This increases agricultural exposure to water scarcity. Increasing future water demands either because of economic development or because of climate change place pressure on groundwater resources. Maintaining irrigation in the Jordan Valley implies using more groundwater for satisfying urban and industrial demands. Adaptation of cropping patterns to climate change produces positive effects by substantially reducing water demand. The joint application of water conservation policies and adaptation to climate change may significantly reduce water consumption for irrigation and contribute to reduce the gap between demand and supply. However, socio-economic development will require stronger efforts to control and stabilise urban and industrial demands while at the same time, increasing water supply from new sources in the future.

5.6 Summary and conclusions

Water management and adaptation to climate change are multi-faceted and multi-level problems that require coordinated cross-sectoral actions involving multiple levels of decision-making. In this sense, this research provides a useful framework for drawing attention to potential future scenarios and to key aspects of water, agriculture and climate change policy that need to be addressed at the national level. As is the case with most country level assessments, aggregated results may underestimate vulnerability of minorities or communities particularly vulnerable or exposed to extreme conditions. However, this research highlights the relevance of the nation-wide socio-economic conditions and institutional and policy settings.

The econometric model used in the first section of this chapter demonstrates that good governance and policy development and its effective implementation are significant variables that determine trends in water consumption. This is especially relevant for the Mediterranean context, where water resources exploitation and water stress are high, population and economic development growth is high and current aridity is likely to intensify in light of projected climate scenarios.

Projections of water withdrawals show how different patterns of water resources availability and development across countries and different socio-economic contexts highly determine future water demands. This implies that while some countries may witness water demand increases of up to 30%, in other countries the structure of water demand across sectors or the socio-economic conditions will be much more decisive in determining more stable pathways with respect to water demand. Also, the effect of climate change will be experienced differently. On average, econometric projections show water demand increases of around 4% in 2030 as a consequence of climate change-driven lower precipitations, as compared to water withdrawal in the same year without climate change. While for some countries this amount may not be significant, for others, such as Jordan, climate change may offset the effect of different socio-economic and policy developments. This is illustrative of the need to look closer at country specificities.

Results of the country level assessments shed light on the potential of different types of irrigation policies to manage scarce water resources in countries with different institutional and socio-economic contexts and different natural conditions.

The country level assessments show that even if climate change exacerbates water stress in the two countries analysed, socio-economic and policy development is the element that determines to a greater extent imbalance between supply and demand of water. Spain, with fewer problems of water scarcity, and more stable water demand and population growth, faces a less uncertain future, with higher demand reliability and lower risks for irrigation agriculture. However, under severe climate change projections (A2 scenario), there is a high risk in southern agriculture of demands not being satisfied around the 2040s. Therefore, the need to advance in adaptation at farm level and the value of implementing water policies that protect ecosystems and increase water use efficiency become evident.

The case of Jordan differs from the Spanish one. In spite of increased aridity, climate change is not the main driver for water scarcity problems. It only aggravates, to a limited extent, the already existing water supply and demand imbalances and exacerbates groundwater exploitation. In this case, limiting groundwater abstraction for irrigation in the Uplands, and removing perverse incentives that constrain water use economic efficiency are key actions that policy-makers must address. However, the economic impact of climate change on farms in the Jordan Valley is not negligible and therefore, policy measures that support these vulnerable farms are required.

Altogether, the results of the analysis at country level show that the mounting challenges of water management in a context of scarcity and climate change will require the specialization of agricultural production towards crops which have a comparative advantage in each region. This implies a shift to vegetable production in the Jordan Valley, where tree crops are not sufficiently profitable to compensate for their large water consumption. In the case of Spain, in the more water scarce southern region, vegetables and tree crops will progressively substitute cereal production.

Both the regional econometric approach and the integrated modelling case studies at country level confirm that good governance and sustainability oriented policies can contribute to respond to the challenges of socio-economic development and climate change in areas were resources are scarce. However, in countries of absolute water scarcity such as Jordan, agricultural and irrigation policies alone are not sufficient as to overcome such unfavourable natural conditions and build sustainable development for future generations.

6. Final conclusions

This research presents an integrated view of water scarcity and climate change impacts, vulnerability and adaptation. Based on the combination of mathematical programming, hydrological and econometric modelling, and a participatory socio-institutional platform, this research addressed different aspects of vulnerability and adaptation. It combines outcome-oriented assessments, such as the quantification of vulnerability and adaptation through impacts on economic and hydrologic variables, with socially-oriented analysis that takes into account farm decision-making. It also includes the study of the main drivers for vulnerability and the socio-institutional aspects involved in climate change adaptation. Through the application of the selected tools to the specific case study of the Middle Guadiana basin in Spain, to the country level studies of Spain and Jordan and to the Mediterranean region, this research has yielded results relevant for decision-making in the Mediterranean water scarce territory. The study evolves within the context of global and European policies for climate change, water resources management and agriculture. The most relevant contributions and findings are summarised in the following sections.

6.1 Main general findings and research contributions

This research tries to respond to the need expressed by the IPCC, the EU Commission and the scientific community, of carrying out climate change impact, vulnerability and adaptation assessments at the local level that are able to show the relevance of local contexts for vulnerability, adaptation needs and the most appropriate adaptation strategies. In this sense, the assessment of climate change impacts, vulnerability and adaptation in the Middle Guadiana provided relevant findings that underline the vulnerability of different farms and irrigation districts driven by particular technical, socio-economic and institutional contexts.

The integrated approach adopted for the analysis of water scarcity and climate change impacts, vulnerability and adaptation constitutes an important original contribution of this research. The methodological framework developed proven to be capable of addressing the most relevant dimensions and decision-making scales and to be applicable at different geographical scales.

Previous studies that approached farm level analysis using normative farm decision models considered only in a limited manner the structural, social and institutional variables that have important implications for how farms adapt to changes in water availability and access. On the other hand, studies based on statistical and econometric techniques that consider a wider set of variables very often fail to capture the decision-making of adaptation agents' and do not take into consideration structural changes that may affect the relation between farmers' characteristics and outcomes to water related shocks. The combination of both methods provided a more comprehensive view on water policy impacts and can be a valuable contribution to water policy-decision-making.

The effects of climate change and adaptation measures are analysed at different scales from the crop, farm and irrigation community to the basin level in a comprehensive way, considering not only geographical scales but also decision-making scales. The inclusion of a biophysical model that represents the water system and agronomic processes and an agro-economic model that addresses farmer's behaviour allows us to consider the different dimensions of water scarcity and climate change impacts on irrigation.

The analysis of socio-institutional contexts of adaptation complements impact-oriented modelling results by enhancing the understanding on adaptation processes and on the feasibility of the different adaptation measures considered. In this sense, the involvement of stakeholders through the use of participatory SNM contributed to this by providing local perceptions on the potential success of adaptation processes and on the feasibility of proposed adaptation measures.

The approach adopted in this research contributed to closing the gap between outcome-oriented impact and vulnerability assessments and socially-based vulnerability and adaptation studies. It reflected the interactions across geographical and decision-making scales both from a bio-physical perspective and from a social perspective.

The models developed and the conclusions drawn from this research are easily transferrable to other basins, countries or semi-arid regions of the world and are therefore a useful framework for climate change impacts, vulnerability and adaptation research and policy-making.

6.1.1 Conclusions on the methodological approach

This research explored the potential of a set of modelling techniques for the analysis of different aspects of water scarcity and climate change impacts, bio-physical and socio-economic, at different scales. It presented an evolving process in which the scope of the analysis is progressively enlarged introducing new dimensions of water resources and climate change at every step of the analysis.

Starting from the farm level assessment, an economic optimisation model provided relevant insights on the role of farm level adaptations when constraints to water use are applied. This analysis highlights the differential impacts of water policy across different types of farms and reflects their capacity to respond to changes in access to water resources, by representing farmers' behaviour. The joint application of MPM and econometric modelling allowed for the analysis of the main drivers of income loss for real farms and helped to identify the most vulnerable farms and establish vulnerability profiles in the Middle Guadiana. In this sense, this study provides policy-relevant insights that improve understanding of the farm level responses and adaptation under the implementation of the quality-oriented EU WFD, in an area in which the application of such a policy may have undesired socio-economic effects due to water scarcity conditions. Moreover, it provided relevant conclusions that may assist policy-makers in the elaboration of water management strategies that take into account the different structural characteristics of affected rural areas.

Farmers' adaptation behaviour determines the impact of constraints to water use. However, economic modelling does not account for the physical dimension of water resources. The hydrology system as well as basin level management of water resources determine adaptation needs. But beyond the specific water availability at each demand point, the hydrology system connects all water users and different scales.

The integrated modelling approach developed in this research, based on a hydrology model, an agronomic module and an economic optimisation model, is shown to be a useful tool for Integrated Water Resources Management and climate change adaptation policy support. It addresses the three most relevant levels in agricultural water management and climate change impacts on irrigation: the crop system, the farm system and the water system.

In this way, this integrated modelling framework contributes to adaptation decision-making by improving understanding on the likely impacts of climate change, multi-scale vulnerability and the effect of different adaptation options. Economic models are crucial for understanding water demand and the behaviour of economic agents and water users, and provide meaningful results using economic indicators. Hydrologic modelling provides a representation of the physical dimension of water resources, which is essential for the assessment of climate change and, specifically, for the representation of the supply side of water management. More importantly, it connects all different scales from the crop to the farm to the basin. This feature is crucial for climate change impacts, vulnerability and adaptation assessments as evidenced in the Middle Guadiana case study. In this basin, spatial location outweighs the technical characteristics and management of farms and irrigation communities as the most important determining impact factor. Zújar, a modern irrigation community located upstream in the Middle Guadiana, experiences a large reduction of water supply even if water storage capacity is greater in this area than it is downstream. The reason for this is the excessive water demand in the neighbouring rice growing irrigation districts. This is an issue that could not be understood without the support of a hydrology model that accounts for the spatial dimension of water and that reflects the interconnectedness of different water users. In addition, the water supply problems in Zújar IC and its causes illustrate the need to look at the socio-institutional networks linking different water users, irrigation communities and water management institutions.

In line with this, the identification of effective measures that facilitate adaptation to climate change is a necessary condition but it is not sufficient to guarantee the success of adaptation processes. The study demonstrated the need to combine quantitative impact assessment methods with more social-oriented methods that are able to consider socio-institutional elements and the human dimension of natural resource use. Identifying barriers to adaptation supports decision-makers in planning adaptation processes as it provides a more realistic picture of the effectiveness and feasibility of adaptation strategies. In fact, the assessment of barriers to adaptation based on the analysis of social networks helped to identify social and institutional barriers that technical studies frequently overlook. Although adaptation processes are most often local, the analysis of social networks in the Middle Guadiana highlighted the important role of national (Spain) and supra-national (EU) institutions in guiding water and adaptation policy and building adaptive capacity.

In addition, the methods applied in this research have proven to be useful tools for country level assessments of socio-economic and climate change scenarios. The combination of farm-based agro-economic modelling with a water balance model demonstrated the relevance of the country-specific socio-economic, natural and structural conditions. Even if country level assessments may underestimate climate change impacts and the vulnerabilities of specific regions, they can contribute to guide policies at national level and prioritise adaptation actions.

Overall, this study highlights the multi-scale and interrelated nature of vulnerability and adaptation, as vulnerability and adaptation in one irrigation community depends on farm cropping and technical characteristics, water management at the irrigation community level, decision-making in neighbouring irrigation districts and spatial location in the basin (which determines climate variables and water infrastructures). In this sense, the integrated modelling platform developed in this research provides an appropriate framework for analysing climate change impacts, vulnerability and adaptation taking into consideration the multi-scale nature and the complexity inherent in vulnerability and adaptation processes. Specifically, the methods applied have proven to be useful for the analysis of relevant aspects of water scarcity, water management and irrigation. These methods can be applied from the farm level (MPM) to the irrigation community and river basin (MPM+ WEAP-MABIA) and to the national level (MPM+WEAP-MABIA water balance), capturing the multifaceted nature of water scarcity and climate change impacts, vulnerability and adaptation and providing relevant information for all decision-making levels.

6.1.2 Conclusion on the empirical research: scales, case studies and policy recommendations

Farm level vulnerability

Agriculture is a sector that is accustomed to the concept of adaptation. It is the economic activity most exposed to climate variability, and as such, farm-level decisions play a major role in climate change adaptation.

This research showed that there are some types of farms better prepared to adapt to climate change than others. Technology adoption determines the outcome and success of water policies and the impacts and adaptation to climate change. Water policy implementation may have very different outcomes depending on the policy instrument utilised. In the case of the Middle Guadiana basin, the need to reduce water consumption to preserve ecosystems can be addressed by implementing different policy instruments. In this research we tested water tariffs and water quotas. Both achieve similar water savings, but research showed how the economic effects at farm level will vary according to variations in the flexibility and adaptive capacity of farms which is determined by irrigation technology, labour decisions and the type of farm management. This research shows that water tariffs may result in serious economic damage to most traditional farms. Nonetheless, when accompanied by appropriate public support for irrigation modernisation, water pricing can be a valuable water policy instrument that promotes farmers' adaptation to water scarcity and climate change by enhancing technical and economic efficiency. This underscores the role of water policy on climate change adaptation and the need to mainstream climate change adaptation into sectoral policies.

At the same time, water pricing cannot be the *panacea* of water management. The effect of water tariffs will depend in different underlying conditions. Their effect on efficiency and water consumption will depend on other factors such as farm profitability and farm level technology adoption. In some cases farms cannot improve efficiency because they already use the most efficient irrigation techniques or because modern technologies are not available or are too costly. In other cases, as shown in the case study of Jordan, if farm profitability is high and the cost of water represents a small portion of the total costs, water tariffs would have to reach very high levels in order achieve the intended outcomes and would be accompanied by large economic losses.

This research showed that cropping pattern trends already observed in Spain that show a shift to more water efficient and typical Mediterranean crops will be further promoted by water scarcity and climate change. Both in Jordan and in Spain, the re-orientation of irrigation cropping activities may contribute significantly to alleviate water scarcity and enhance climate change adaptation. In order to further promote this, the removal of distorting trade policies and subsidies, as accomplished in the past by the EU, will be crucial. At the same time, changes in cropping activities towards mono-crop production may have relevant implications for risk management and for local markets which should be further analysed.

River basin implications of climate change

Previous studies in Spain and, in particular, in the Guadiana basin have demonstrated the high vulnerability of water resources to climate change. This research showed that vulnerability of water resources will translate into a high vulnerability of the dependent irrigation sector. The Middle Guadiana basin is not currently considered to be a water scarce basin, as the development of water storage infrastructures has allowed for the use of large volumes of water for irrigation and has mitigated the impacts of severe droughts over the past years.

However, this research shows that under scenarios of climate change the water storage system may fail to secure water demands in the basin around the middle of the 21st century. This may have severe consequences in the region, as current awareness and preparedness is low because of high confidence in the security of the water supply system.

The Middle Guadiana basin exhibits a remarkable dichotomy of irrigation farming systems. Currently, modern irrigation districts that use efficient pressurised irrigation techniques and that implement volumetric water pricing coexist with traditional ICs of lower water use efficiency. The results showed that technology adoption is a key element that determines vulnerability at farm and irrigation community level. However, spatial location is a more important determining factor. Contrary to what would be expected, upstream irrigation communities are more vulnerable than their downstream counterparts, even if water storage in the upper part is greater than in the lower part. The reason for this is the excessive water demand and use in some irrigation districts which do not respect the legally established allotments. This suggests the need to strengthen the role of institutions and improve water policy enforcement. Also, this reinforces the central role of socio-institutional networks in climate change adaptation and demonstrates the need to integrate biophysical and socio-institutional assessments in climate change research to provide a comprehensive view of water scarcity and the multiple facets of climate change and to support effective decision-making on adaptation.

Last but not least, the analysis in the Middle Guadiana proved the effectiveness and important contribution of the EU Water Framework Directive as a tool for climate change adaptation. It is generally accepted that climate change is a transversal concern affecting many different sectors and resources and as such, it must be addressed by different sectoral policies. This is underscored by this research, which shows that advancing in an ambitious implementation of the WFD can significantly contribute to climate change adaptation by setting an adequate regulatory and institutional environment that promotes water efficiency, the protection of ecosystems and the internalisation of the economic value of water as a scarce resource. Therefore, the implementation of this Directive must be a priority for the water administration.

Socio-institutional barriers to adaptation

The analysis of barriers to adaptation shows that the success of the adaptation process requires other elements apart from the identification of appropriate adaptation measures. Identifying barriers to adaptation supports decision-makers in planning adaptation processes as it provides them with a more realistic picture of the effectiveness and feasibility of adaptation strategies and helps them to initiate policies to overcome obstacles to adaptation.

The key barriers identified in the Middle Guadiana context relate to the lack of awareness, common understanding and acceptance of policy constraints by the water users. In order to combat this, it is necessary to strengthen one of the main elements advocated by IWRM: public participation and SH involvement in management decisions. Strengthening formal and informal relations among water users and between users and the scientific community can be very important and public participation processes can contribute to this. Also, enhancing participation can contribute to increase the legitimacy and acceptance of policy decisions. This coincides with the views of many of the stakeholders involved in this research who emphasised of the need to strengthen participation channels to build more formal and strong relations among different actors in the basin.

These elements, together with the coordination across different administrations are not only relevant for climate change adaptation but also for the development and implementation of most natural resource management policies, as highlighted in the recent review of the status of implementation of the WFD carried out by the EU Commission.

Socio-economic and climate change implications at regional and country level

Country level assessments of water withdrawals demonstrated the relevance of governance, policy developments and effective policy implementation, which may be crucial in determining future trends in water consumption and the future balance between demand and supply. This is especially relevant in the Mediterranean context, where water resources exploitation and water stress are high, population and economic development growth rates are high and current aridity is likely to intensify in light of projected climate scenarios.

Even if climate change is likely to exacerbate water stress in the countries analysed, socio-economic and policy developments are more important elements in determining the extent of the imbalance between supply and demand of water. Spain is not as water scarce as Jordan and water demand and socio-economic trends are more stable than in Jordan. However, preparing for climate change and implementing policies that contribute to sustainability will be required if the worst climate change projections are confirmed. Jordan may also experience relevant impacts from climate change, however, the current structure of water demands and supply and the projected pressures from population growth require more of a focus on sustainable socio-economic trends than specifically on climate change.

6.2 Limitations and future paths for research

In the last section of this doctoral thesis some of the limitations of this research are presented together with recommendations for future improvements.

The main limitations of this study relate to the design of the different models used. Although the models selected address the most relevant dimensions of water management and climate change, the models' intrinsic characteristics limit the realistic representation of specific elements of water scarcity and water management. This limitation is mainly driven by the different spatial and temporal scales of the models. The MPM is a farm-based annual model while the WEAP model represents the basin scale and long term scenarios. With respect to the spatial scale, WEAP can represent smaller portions of the basin such as small irrigation catchments. However, it is not able to include lower scale decision-making elements that can be very relevant especially when water shortages occur. This can include, for example farmers' decisions to prioritise the irrigation of some crops over others in severe drought events. In this sense, the models developed were useful for representing water scarcity conditions and farm decision-making in a continued situation of reduced availability of water resources, but the analysis does not properly address the implications of severe drought episodes.

In relation to the temporal scales, the farm model represents annual activity and decision-making, while WEAP, which runs on a monthly base, is a dynamic model. It uses the results of the simulation in one time step as the input for the simulation of the next time step, and is thereby able to simulate long time periods. In the present study, for long term WEAP model runs, the farm MPM simulates farmers' decisions in specific moments of time. This limits the extent to which dynamic nature of water management and climate change vulnerability and adaptation is represented.

Overcoming this limitation could imply different future developments. On the one hand, a monthly based specification of the farm-based economic model would be appropriate for a better representation of the crop growth cycle. On the other hand, it would be appropriate to develop a more dynamic application of the farm-based economic model that simulates scenarios of drought conditions, that comprises deficit irrigation cropping alternatives and that account for multi-annual processes such as permanent crop cycles.

Improving the linkage of the economic MPM and WEAP hydrology model would also allow for a more dynamic and realistic adjustment of cropping patterns in the basin. However, this is a difficult task in modular or compartmentalised hydro-economic models and could be more easily approached through the development of an application programming interface that is capable of linking the two models through a flexible and automated connection.

With respect to the crop growth cycle simulation through the use of the MABIA module in WEAP, an important limitation of this study is the lack of consideration for the climate change driven potential beneficial effects of increased CO2 concentration in the atmosphere. MABIA does not account for CO2 concentrations, and therefore crop yield losses may be overestimated. Overcoming this limitation would entail the use of a different crop model, such as AQUACROP or DSSAT, which can simulate different atmospheric CO2 concentrations and their impact on crop growth. However, this would need to be externally linked to WEAP leading to less efficient exchange of inputs and outputs and longer model runs.

The country level application of the integrated MPM-WEAP framework presents the evident limitations inherent to aggregated models with respect to lower level of detail. On the one hand, this reduces the model data requirements, but on the other hand, a less detailed model fails to represent elements that are relevant for water management, such as groundwater overexploitation in the case study of Jordan. Overcoming this limitation would only be possible by increasing the level of detail in the model by further specifying the groundwater bodies and the access of users to these resources. In the case of Jordan, this would not be a difficult task because of the country's size and the number of groundwater basins, but in most cases it would be contrary to the approach of this type of assessment and detrimental to the main advantage of this study, which lies in its simplicity.

Stakeholder involvement constituted a valuable contribution to this research, in which consideration of SH perceptions on the implementation of adaptation processes provided a more realistic view on the effectiveness and feasibility of adaptation measures. However, a common limitation of participation-based tools is the dependence of results on the selection and attendance of participants. In the SNM carried out in the Middle Guadiana case study, industrial and domestic water users are two main SH groups that were not represented. Even if the focus of this study is on agriculture, the participation of these groups could have enhanced the acceptability of the results.

Finally, validation and dissemination of results to key stakeholders would be crucial for contributing to water management and adaptation policy-making in the Guadiana basin. Some of the findings of this research have already been presented to selected stakeholders in the context of the MEDIATION and MedPro projects, but a more complete dissemination of the results of this thesis is required in order to increase its impact repercussion and contribute to the linking of science and policy.

While several limitations are recognised, this research presents a coherent integrated framework for the assessment of water management and climate change impacts, vulnerability and adaptation that, considering most relevant dimensions of water management and decision making-scales, can contribute to adaptation policy-making.

7. References

Adger, W.M, Kelly, P.M., 1999. Social Vulnerability to Climate Change and the Architecture of Entitlements. Mitigation and Adaptation Strategies for Global Change, 4, 253–266.

Adger, W.N., 1999. Social Vulnerability to climate change and extremes in coastal Vietnam. World Development, 27(2), 249-269.

Adger, W.N., 2006. Vulnerability. Global Environmental Change, 16, 268–281.

Adger, W.N., Agrawala, S., Mirza, M.M.Q., 2007. Assessment of adaptation practices, options, constraints and capacity. In Parry, M., Canziani, O., Palutikof, J., van der Linden, P., Hanson, C. (Eds.): Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. Pp 717–743.

Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Global Environmental Change, 15, 77–86.

Adger, W.N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D.R., Naess, L.O., Wolf, J., Wreford, A., 2009. Are there social limits to adaptation to climate change? Climatic Change, 93, 335–354.

Agrawal, A., 2010. Local institutions and adaptation to climate change. In Mearns R., Norton, A. (Eds.) Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World. The World Bank. Washington DC, US. Pp. 173–197.

Albiac, J., Tapia, J., Meyer, A., Hanemann, M., Mema, M., Calatrava, J., Uche, J., Calvo, E., 2008. Los problemas económicos de la planificación hidrológica. Revista de Economía Aplicada, 47, 25–50.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing CropWater Requirements. FAO Irrigation and Drainage Paper No. 56. FAO (Food and Agriculture Organization of the United Nations). Rome, Italy. 300 p.

Amer, M., Daim, T.U., Jetter, A., 2013. A review of scenario planning. Futures, 46, 23–40.

Antle, J.M., Stoorvogel, J.J., Valdivia, R.O., 2006. Multiple equilibria, soil conservation investments, and the resilience of agricultural systems. Environment and Development Economics. 11, 477-492.

Apata, T.G., Samuel K. D., Adeola, A. O., 2009. Analysis of Climate Change Perception and Adaptation among Arable Food Crop Farmers in South Western Nigeria. Paper presented at the XXVII Conference of the International Association of Agricultural Economists. 16 – 22 August 2009. Beijing, China.

AQUASTAT, 2008. Jordan Country Profile. Food and Agriculture Organization of the United Nations. Rome, Italy.

AQUASTAT, 2013. AQUASTAT Main Country Database. Food and Agriculture Organization of the United Nations. Rome, Italy. Available online at: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en (Last accessed July 2013).

Ariza-Nino, E., 2004. Crop Water Use Efficiency by Type of Crop and Farming System in the Jordan Valley. Knowledge and Action Fostering Advances in Agriculture. Development Alternatives, Inc. Report. November, 2004. 85 p.

Arnell, N., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change, 14, 31–52.

Ayadi, R., Sessa, C., 2011. What scenarios for the Euro-Mediterranean in 2030 in the wake of the post-Arab spring? MEDPRO Policy Paper No. 2. October 2011, CEPS.

Babel, M.S., Das Gupta, A., Pradhan, P., 2007. A multivariate econometric approach for domestic water demand modeling: An application to Kathmandu, Nepal. Water Resources Management, 21, 573–589.

Bartolini, F., Bazzani, G.M., Gallerani, V., Raggi, M., Viaggi, D., 2007. The impact of water and agriculture policy scenarios on irrigated farming systems in Italy: An analysis based on farm level multi-attribute linear programming models. Agricultural Systems, 93, 90–114.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 p.

Baumol, W.J., 1963. An expected gain-confidence limit criterion for portfolio selection. Management science, 10, 174–182.

Bazzani, G., Di Pasquale, S., Gallerani, V., Morganti, S., Viaggi, D., 2005. The sustainability of irrigated agricultural systems under the Water Framework Directive: first results. Environmental Modelling & Software, 20, 165–175.

Bazzani, G.M., 2005. An integrated decision support system for irrigation and water policy design: DSIRR. Environmental Modelling & Software, 20, 153–163.

Bear, J., Levin, O., Buras, N., 1964. Optimal utilization of aquifers as elements of water resources systems. Progress report No1: Basic concepts and program of research, Technion – Israel Institute of Technology, Hydraulic laboratory, Haifa, Israel.

Below, T.B., Mutabazi, K.D., Kirschke, D., Franke, C., Sieber, S., Siebert, R., Tscherning, K., 2012. Can farmers' adaptation to climate change be explained by socio-economic household-level variables? Global Environmental Change, 22, 223–235.

Benoit, G., Comeau, A., 2005. A Sustainable Future for the Mediterranean. The Blue Plan's Environment and Development Outlook. Plan Bleu. Earthscan, London. 432 p.

Berbel, J., Calatrava, J., Garrido, A., 2007. Water Pricing and Irrigation: A Review of the European Experience, in: Molle, F., Berkoff, J. (Eds), Irrigation Water Pricing Policy: the Gap between theory and practice. CABI, IWMI, pp. 295 – 327.

Berbel, J., Gómez-Limón, J. A., 2000. The impact of water-pricing policy in Spain: an analysis of three irrigated areas. Agricultural Water Management, 43(2), 219-238.

Berger, T., 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agricultural Economics, 25, 245–260.

Berkes, F., 2007. Understanding uncertainty and reducing vulnerability: lessons from resilience thinking. Natural Hazards, 41, 283–295.

Berkes, F., Jolly, D., 2001. Adapting to climate change: social-ecological resilience in a Canadian western Arctic community. Conservation Ecology, 5(2), 18.

Berkhout, F., Hertin, J., Gann, D.M., 2006. Learning to adapt: organisational adaptation to Climate change impacts. Climatic Change, 78, 135–156

Berkhout, F., Hertin, J., Jordan, A., 2002. Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines'. Global Environmental Change, 12, 83–95.

Bharwani, S., Ballard, D., Varela-Ortega, C., Carmona, G., Watkiss, P., Downing, T., Devisscher, T., Taylor, R., 2012. Visualization of institutional networks and the flows of information used for making adaptation decisions in a range of policy contexts. Mediation Delivery Report 1.4. MEDIATION Project (Methodology for Effective Decision.making for Impacts and AdaptaTION) – DG Research, European Commission.

Biesbroek, G.B., Swart, R.J., Carter, T.R., Cowan, C., Henrichs, T., Mela, H., Morecroft, M.D., Rey, D., 2010. Europe adapts to climate change: Comparing National Adaptation Strategies. Global Environmental Change, 20, 440–450.

Blanco-Gutiérrez, I., Varela-Ortega, C., Flichman, G., 2011 Cost-effectiveness of groundwater conservation measures: A multi-level analysis with policy implications. Agricultural Water Management, 98, 639–652.

Blanco-Gutiérrez, I., Varela-Ortega, C., Purkey, D., 2013. Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. Journal of Environmental Management, 128, 144-160.

Blinda, M., 2012. More efficient water use in the Mediterranean. Plan Bleu Papers n° 14. Plan Bleu, Valbonne.

Bodin, O., Crona, B.I., 2009. The role of social networks in natural resource governance: What relational patterns make a difference? Global Environmental Change, 19, 366–374.

Brooks, N., Adger, W.N., Kelly, P.M., 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change 15, 151-163.

Brouwer, R., Hofkes, M., 2008. Integrated hydro-economic modelling: Approaches, key issues and future research directions. Ecological Economics, 66, 16–22.

Bruinsma, J., 2009. The resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050? Paper presented at the FAO Expert Meeting "How to Feed the World in 2050", 24-26 June 2009. Rome, Italy.

Buongiorno, J., 1996. Forest sector modeling: a synthesis of econometrics, mathematical programming, and system dynamics methods. International Journal of Forecasting, 12, 329–343.

Butt, T.A., McCarl, B.A., Kergna, A.O., 2006. Policies for reducing agricultural sector vulnerability to climate change in Mali. Climate Policy, 5(6), 583-598.

Buysse, J., Van Huylenbroeck, G., Lauwers, L., 2007. Normative, positive and econometric mathematical programming as tools for incorporation of multifunctionality in agricultural policy modeling. Agriculture, Ecosystems & Environment, 120, 70-81.

Cai, X., McKinney, D., Lasdon, L., 2003. Integrated Hydrologic-Agronomic-Economic Model for River Basin Management. Journal of Water Resources Planning and Management, 129(1), 4–17.

Cai, X., Rosegrant, M.W., 2002. Global water demand and supply projections. Part 1: A modelling approach. Water International, 27 (3), 159–169.

Carmona, G., Varela-Ortega, C., Bromley, J., 2013. Supporting decision making under uncertainty: Development of a participatory integrated model for water management in the middle Guadiana river basin. Environmental Modelling & Software, 50, 144–157

Cash, D.W., Moser, S.C., 2000. Linking global and local scales: designing dynamic assessment and management processes. Global Environmental Change, 10, 109–120.

CCAFS (Climate Change, Agriculture and Food Security), 2012. Downscaled GCM Data Portal. CGIAR Research Program on Climate Change, Agriculture and Food Security. Available online at: http://www.ccafs-climate.org/. (Last accessed June 2012).

CEDEX (Centro de Estudios y Experimentación de Obras Públicas), 2011. Evaluación de los impactos del cambio climático en los recursos hídricos en régimen natural. Dirección General del Agua. Ministerio de Medio Ambiente y Medio Rural y Marino. 268 p.

Chenoweth, J., Hadjinicolaou, P., Bruggeman, A., Lelieveld, J., Levin, Z., Lange, M.A., Xoplaki, E., Hadjikakou, M., 2011. Impact of climate change on the water resources of the eastern Mediterranean and Middle East region: Modeled 21st century changes and implications. Water Resources Research, 47, W06506.

CHG (Confederación Hidrográfica del Guadiana), 2008. Estudio general de la demarcación hidrográfica del Guadiana. Parte I. Confederación Hidrográfica del Guadiana. Spanish Ministry of Environment, and Rural and Marine Affairs. Badajoz, Spain.

CHG (Confederación Hidrográfica del Guadiana), 2013a. Plan Hidrológico de la parte española de la Demarcación Hidrográfica del Guadiana. Spanish Ministry of Agriculture, Food and Environment. Badajoz, Spain.

CHG (Confederación Hidrográfica del Guadiana), 2013b. Plan Hidrológico de la parte española de la Demarcación Hidrográfica del Guadiana. Documento respuesta a las alegaciones presentadas. Spanish Ministry of Agriculture, Food and Environment. Badajoz, Spain.

Chohin-Kuper, A., Rieu, T., Montginoul, M., 2003. Water policy reforms: Pricing water, cost recovery, water demand and impact on agriculture. Lessons from the Mediterranean experience, paper presented at Water Pricing Seminar, Agencia Catalana del Agua and World Bank Institute, Barcelona, 30 June-2 July.

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P., Palmer, R.N., 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change, 62, 337–363.

Courcier, R., Venot, J.P., Molle, F., 2005. Historical transformations of the lower Jordan river basin (in Jordan): Changes in water use and projections (1950-2025). Comprehensive Assessment Research Report 9. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. 85 p.

Cutter, S.L., Boruff, B.J., Shirley,W.L., 2003. Social Vulnerability to Environmental Hazards. Social Science Quarterly, 84 (2), 242–261.

De Bruin, K., Dellink, R.B., Ruijs, A., Bolwidt, L., van Buuren, A., Graveland, J., de Groot, R.S., Kuikman, P.J., Reinhard, S., Roetter, R.P., Tassone, B.C., Verhagen, A., van Ierland, E.C., 2009. Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climatic Change, 95, 23–45.

De Fraiture, C., Perry, C.J., 2007. Why is Agricultural Water Demand Unresponsive at Low Price Ranges? In Molle, F., Berkoff, J. (Eds.) Irrigation Water Pricing: The Gap between Theory and Practice. Comprehensive Assessment of Water Management in Agriculture. CAB International, Wallingford, United Kingdom. pp. 94–107.

De Janvry, A., 1988. Propiedad de la tierra y desarrollo económico. In Varela Ortega C. (Ed.): El Mercado y los Precios de la Tierra: funcionamiento y mecanismos de intervención. Serie Estudios. Ministerio de Agricultura Pesca y Alimentación. Secretaría General Técnica. Madrid, Spain.

De Janvry, A., Sadoulet E., 2001. Income strategies among rural households in Mexico: the role of off-farm activities. World Development, 29 (3), 467-480.

Deininger, K., Byerlee, D., 2012. The Rise of Large Farms in Land Abundant Countries: Do They Have a Future? World Development, 40 (4), 701–714.

Dolan, A.H., Smit, B., Skinner, M.W., Bradshaw, B., Bryant, C.R., 2001. Adaptation to climate change in agriculture: evaluation of options. Occasional Papers in Geography No. 26. University of Guelph. 51 p.

Doorenbos, J., Kassam, A.H., Bentvelsen, C., 1979. Yield response to water. FAO Irrigation and Drainage Paper No. 33. FAO (Food and Agriculture Organization of the United Nations). Rome, Italy.

Doppler, W., Salman, A.Z., Al-Karablieh, E.K., Wolff, H.P., 2002. The Impact of water price on the allocation of irrigation water: the case of the Jordan Valley. Agricultural Water Management, 55, 171–182.

DOS (Jordan Department of Statistics), 2008. Agricultural Survey. Crop statistics.

Downing, T.E., 2012. Views of the frontiers in climate change adaptation economics. WIREs Climate Change, 3, 161–170.

Downing, T.E., Aerts, J., Soussan, J., Barthelemy, O., Bharwani, S., Ionescu, C., Hinkel, J., Klein, R.J.T., Mata, L., Moss, S., Purkey, D., Ziervogel, G., 2006. Integrating social vulnerability into water Management. SEI Working Paper and NeWater Working Paper No. 4. Stockholm Environment Institute. Oxford, United Kingdom. 32 p.

Downing, T.E., Bharwani, S., 2006. Baseline Vulnerability Assessment. Newater Report D2.1.1. Stockholm Environment Institute. Oxford, United Kingdom.

Downing, T.E., Lüdeke, M., 2002. International Desertification: Social Geographies of Vulnerability and Adaptation. In: Reynolds, J.F., Stafford Smith, D.M. (Eds.), Global Desertification: Do Humans Cause Deserts? Dahlem University Press, pp. 233-252.

Downing, T.E., Patwardhan, A., 2005. Assessing vulnerability for climate adaptation. In: Lim, B., Spanger-Siegfried, E., Burton, I., Malone E., Huq, S. (Eds.), Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures. Cambridge University Press, Cambridge and New York, pp. 67–90.

Droogers, P., Immerzeel, W.W., Terink, W., Hoogeveen, J., Bierkens, M.F.P., van Beek, L.P.H., Debele, B., 2012. Water resources trends in Middle East and North Africa towards 2050. Hydrology and Earth System Sciences, 16, 3101–3114.

Eakin, H., Luers, A.L., 2006. Assessing the vulnerability of social-environmental systems. Annual Review of Environment and Resources, 31, 365–394

Easterling, E.W., Chhetri, N., Niu, X., 2003. Improving the realism of modeling agronomic adaptation to climate change: simulating technological substitution. Climatic Change, 60, 149–173.

Easterling, W.E., Crosson, P. R., Rosenberg, N. J., McKenney, M. S., Katz, L. A., Lemon, K. M., 1993. Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region. Climatic Change, 24(1/2), 23–62.

Ebi, K.L., Hallegate, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J.A., Kriegler, E., Mathur, R., O'Neill, B.C., Riahi, K., Winkler, H., Van Vuuren, D.P., Zwickel, T., 2013. A new scenario framework for climate change research: background, process, and future directions. Climatic Change. DOI:10.1007/s10584-013-0912-3

EC (European Commission), 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Official Journal of the European Communities L327. Office for Official Publications of the European Union, Luxemburg.

EC (European Commission), 2001. Communication from the Commission. A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development. COM (2001) 264 final. Brussels, 15.5.2001.

EC (European Commission), 2006. Review of the EU Sustainable Development Strategy (EU SDS) − Renewed Strategy. DOC 10917/06. Brussels, Belgium.

EC (European Commission), 2009. Mainstreaming sustainable development into EU policies: 2009 Review of the European Union Strategy for Sustainable Development. Communication from the

Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, Belgium.

EC (European Commission), 2011a. Proposal for a regulation of the European Parliament and of the Council on support for rural development by the European Agricultural Fund for Rural Development (EAFRD). Brussels, 19.10.2011. COM(2011) 627 final/2.

EC (European Commission), 2011b. Proposal for a regulation of the European Parliament and of the Council establishing rules for direct payments to farmers under support schemes within the framework of the Common Agricultural Policy. Brussels, 19.10.2011. COM(2011) 625 final/2.

EC (European Commission), 2012a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Blueprint to Safeguard Europe's Water Resources. COM (2012) 673 final. Brussels, 14.11.2012.

EC (European Commission), 2012b. Report from the Commission to the European Parliament and the Council on the Implementation of the Water Framework Directive (2000/60/EC) River Basin Management Plans. COM(2012) 670 final. Brussels, 14.11.2012.

EC (European Commission), 2012c. Report on the Review of the European Water Scarcity and Droughts Policy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2012) 672 final. Brussels, Belgium.

EC (European Commission), 2012d. Global Europe 2050. Directorate-General for Research and Innovation 2012. Socio-economic Sciences and Humanities. European Union, Brussels. 158 p.

EC (European Commission), 2013a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. An EU Strategy on Adaptation to Climate Change. COM (2013) 216 final. Brussels, 16.4.2013.

EC (European Commission), 2013b. Political agreement on new direction for Common Agricultural Policy. European Commission Press Release. IP/13/613. Brussels, 26.6.2013.

Échevin, D., 2013. Characterising vulnerability to poverty in rural Haiti: A multilevel decomposition approach. Journal of Agricultural Economics. DOI: 10.1111/1477-9552.12017.

EEA, 2008. Impacts of Europe's changing climate - 2008 indicator-based assessment. Report No 4/2008. Brussels, Belgium. 19 p.

EEA, 2012. Climate change, impacts and vulnerability in Europe 2012. An indicator based report. European Environmental Agency. EEA, Copenhagen, 2012. 300 p.

Engle, N.L., 2011. Adaptive capacity and its assessment. Global Environmental Change, 21, 647–656.

Engle, N.L., Lemos, M.C., 2010. Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. Global Environmental Change, 20, 4–13.

Eriksen, S.H., Kelly, P.M., 2007. Developing credible vulnerability indicators for climate adaptation policy assessment. Mitigation and Adaptation Strategies for Global Change, 12, 495–524.

ESRI, 2009. ESRI Data & Maps 10. California, United States of America

Esteve, P., 2007. Análisis de la Gestión del Agua en el Alto Guadiana: vulnerabilidad económica, social y medioambiental. Dissertation. Escuela Técnica Superior de Ingenieros Agrónomos. Universidad Politécnica de Madrid. Madrid, Spain.

Estrela, T., Rodríguez, A., 2008. La gestión de la sequía de los años 2004 a 2007. Ministerio de Medio Ambiente. Madrid, Spain. 198 p.

Fankhauser, S., Smith, J.B., Tol, R.S.J., 1999. Weathering climate change: some simple rules to guide adaptation decisions. Ecological Economics, 30, 67–78.

FAOSTAT, 2012. Statistical database from the Food and Agriculture Organization from the United Nations. Available online at: http://faostat.fao.org/ (Last accessed December 2012).

Flörke M., Alcamo J., 2004. European Outlook on Water Use, Center for Environmental Systems Research - University of Kassel, Final Report, EEA/RNC/03/007. 86 p.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environmental Change, 23, 144–156.

Flörke, M., Wimmer, F., Laaser, C, Vidaurre, R., Tröltzsch, J., Dworak, T., Stein, U., Marinova, N., Jaspers, F., Ludwig, F., Swart, R., Giupponi, C., Bosello, F., Mysiak, J., 2011. Climate Adaptation – Modelling water scenarios and sectoral impacts. Final Report. European Commission. Directorate-General Environment. Contract N° DG ENV.D.2/SER/2009/0034. CESR – Center for Environmental Systems Research. 158 p.

Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. Annual Review of Environment and Resources, 30, 441–473.

Freeman, L.C., 1979. Centrality in social networks conceptual clarification. Social Networks, 1 (3), 215–239.

Füssel, H.M., 2007. Vulnerability: a generally applicable conceptual framework for climate change research. Global Environmental Change, 17, 155-167.

Füssel, H.M., Klein, R.T.J., 2006. Climate Change Vulnerability Assessments: an Evolution of Conceptual Thinking. Climatic Change, 75, 301–329.

Gallai, N., Salles, J.M., Settele, J., Vaissière, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecological Economics, 68, 810-821.

García-Ruiz, J.M., López-Moreno, J.I., Vicente-Serrano, S.M, Lasanta–Martínez, T., Beguería, S., 2011. Mediterranean water resources in a global change scenario. Earth-Science Reviews, 105, 121–139.

Garrido, A., 2000. A mathematical programming model applied to the study of water markets within the Spanish agricultural sector. Annals of Operations Research, 94, 105–123.

Garrido, A., Calatrava J., 2009. Trends in Water Pricing and Markets. In Garrido, A. and Llamas M.R. (eds.) Water Policy in Spain. Routledge Taylor & Francis Group. London, pp. 131-144.

Garrido, A., Martínez-Santos, P., Llamas, M.R., 2006. Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience. Hydrogeology Journal, 14 (3), 340–349.

Garrido, A., Varela-Ortega, C., 2007. Economía del agua en la agricultura e integración de políticas sectoriales. Panel Científico técnico de seguimiento de la política de aguas. University of Seville and Minsitry of the Environment. January 2008. Seville, Spain.

Giannakopoulos, C., Bindi, M., Moriondo, M., Tin, T., 2005. Climate change impacts in the Mediterranean resulting from a 2ºC global temperature rise. WWF Report. Gland, Switzerland.

Giorgi, F., 2006. Climate change hot-spots. Geophysics Research Letters, 33, L08707.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean región. Global and Planetary Change, 63, 90–104.

Gisser, M., Mercado, A., 1972. Integration of the agricultural demand function for water and hydrologic model of the Pecos basin. Water resources research, 8 (6), 1373–1384.

Gleick, P., 2002. The World's Water: The Biennial Report on Freshwater Resources 2002–2003. Island Press, Washington, DC.

Gleick, P., 2003. Water Use. Annual Review of Environment and Resources, 28,275–314.

Gleick, P., Heberger, M., 2011. Water conflict chronology. In Gleick, P., Allen, L., Cohen, M.J., Cooley, H., Christian-Smith, J., Heberger, M., Morrison, J., Palaniappan, M., Schulte, P., The World’s Water Volume 7: the biennial report on freshwater resources. Island Press, Washington D.C.

Glewwe, P., Hall, G., 1998. Are some groups more vulnerable to macroeconomic shocks than others? Hypothesis tests based on panel data from Peru. Journal of Development Economics, 56, 181-206.

Gobierno de Extremadura, 2013. Plan de adaptación al cambio climático de Extremadura. Recursos hídricos. Consejería de Agricultura, Desarrollo Rural, Medio Ambiente y Energía. Badajoz, Spain.

Goklany, I.M., 2002. Comparing 20th Century Trends in U.S. and Global Agricultural Water and Land Use. Water International, 27(3), 321–329.

Gómez-Limón, J.A., Riesgo, L., 2004. Irrigation water pricing: differential impacts on irrigated farms. Agricultural Economics, 31, 47–66.

Groves, D.G., Yates, D., Tebaldi, C., 2008. Developing and applying uncertain global climate change projections for regional water management planning. Water Resources Research, 44, W12413.

Guillaumont, P., 2009. An Economic Vulnerability Index: Its Design and Use for International Development Policy. Oxford Development Studies, 37 (3), 193–228.

GWP (Global Water Partnership), 2000. Integrated Water Resources Management. Global Water Partnership TAC Background Paper 4. Stockholm, Sweeden.

GWP (Global Water Partnership), 2012. Water Demand Management: the Mediterranean Experience. Global Water Partnership Technical Focus Paper.

Haasnoot, M., Middelkoop, H., van Beek, E., van Deursen, W.P.A., 2009. A method to develop sustainable water management strategies for an uncertain future, Sustainable Development, Wiley Interscience, doi:10.1002/sd.438.

Hahn, M.B., Riederer, A.M., Foster, S.O., 2009. The Livelihood Vulnerability Index: A pragmatic approach to assessing risks from climate variability and change — A case study in Mozambique. Global Environmental Change, 19, 74–88.

Hall, J., Murphy, C., 2010. Vulnerability analysis of future public water supply under changing climate conditions: a study of the Moy catchment, Western Ireland. Water Resources Management, 24, 3527–3545.

Hall, J., Murphy, C., 2011. Robust adaptation assessment – climate change and water supply. International Journal of Climate Change Strategies and Management, 3(3), 302–319.

Hamdy, A., 2007. Water use efficiency in irrigated agriculture: an analytical review. In: Lamaddalena, N., Shatanawi, M., Todorovic, M., Bogliotti, C., Albrizio, R. (Eds). Water use efficiency and water productivity: WASAMED project. Options Méditerranéennes: Série B. Etudes et Recherches, 57, 9–19. CIHEAM, Bari.

Hanjra, M.A., Qureshi, M.E., 2010. Global water crisis and future food security in an era of climate change. Food Policy, 35, 365–377.

Harou, J.J., Pulido-Velazquez, M., Rosernberg, D.E., Medellín-Azuara, J. Lund, J.R., Howit, R.E., 2009. Hydro-economic models: concepts, desing, applications and future prospects. Journal of Hydrology, 375, 627–643.

Hazell, P., Norton, R.D., 1986. Mathematical programming for economic analysis in agriculture. Macmillan, London, pp. 76–110.

He, L., Tyner, W.E., Doukkali, R., Siam, G., 2006. Policy Options to Improve Water Allocation Efficiency: Analysis on Egypt and Morocco. Water International, 31 (3), 320–337.

Heinz, I., Pulido-Velazquez, M., Lund, J.R., Andreu, J., 2007. Hydro-economic Modeling in River Basin Management: Implications and Applications for the European Water Framework Directive. Water Resources Management, 21, 1103–1125.

Hiltunen, E., 2009. Scenarios: process and outcome. Journal of Futures Studies, 13, 151–152.

Hinkel, J., 2010. Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface. Global Environmental Change, 21(1), 198–208.

Hoddinott, J., Quisumbing, A.R., 2008. Methods for microeconometric risk and vulnerability assessment. International Foof Policy Research Institute. Working Paper Series. Washington, D.C. 40 p.

Holman, I.P., Rounsevell, M.D.A., Shackley, S., Harrison, P.A., Nicholls, R.J., Berry, P.M., Audsley, E., 2005. A Regional, Multi-Sectoral and Integrated Assessment of the Impacts of Climate and Socio-Economic Change in the UK. Part I. Methodology. Climatic Change, 71, 9–41.

Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proceedings of the National Academy of Sciences of the United States of America, 104 (50), 19691–19696.

Howitt, R., 1995. Positive Mathematical Programming. American Journal of Agricultural Economics, 77(2), 329–342.

Humpal, D., El-Naser, H., Irani, K., Sitton, J., Renshaw, K., Gleitsmann, B., 2012. A review of water policies in Jordan and recommendations for strategic priorities. Jordan Water Assessment Program. USAID. 96 p.

Hurd, B.H., Coonrod, J., 2012. Hydro-economic consequences of climate change in the upper Rio Grande. Climate Research, 53, 103–118.

IALC, 2006. Jordan Soils and Land Management. Soil Survey. International Arid Lands Consortium (IALC). http://ag.arizona.edu/oals/IALC/jordansoils/index.html

IFAD, 2012. Hashemite Kingdom of Jordan Country Programme Evaluation. International Fund for Agricultural Development. United Nations. Rome, Italy. 109 p.

Iglesias, A., Garrote, L., Diz, A., Schlickenrieder, J., Martin-Carrasco, F., 2011. Re-thinking water policy priorities in the Mediterranean region in view of climate change. Environmental Science & Policy, 14, 744–757.

Iglesias, A., Garrote, L., Flores, F., Moneo, M., 2007. Challenges to Manage the Risk of Water Scarcity and Climate Change in the Mediterranean. Water Resources Management, 21, 775–788.

Iglesias, A., Garrote, L., Quiroga, S., Moneo, M., 2009, Impacts of climate change in agriculture in Europe. PESETA-Agriculture study. European Commission. Joint Research Centre. Institute for Prospective Technological Studies. 51 p.

Iglesias, A., Rosenzweig, C., Pereira, D., 2000. Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. Global Environmental Change, 10, 69–80.

Iglesias, E., Blanco, M., 2008. New directions in water resources management: The role of water pricing policies. Water Resources Research, 44 (6), W06417.

IGN (Instituto Geográfico Nacional), 2006. CORINE Land Cover 2006 (CLC2006). Ministerio de Fomento. Madrid, Spain.

INE, 2009. Censo Agrario. Instituto Nacional de Estadística. Madrid, Spain.

INE, 2011. España en cifras 2011. Instituto Nacional de Estadística. Madrid, Spain.

IPCC, 2001. Climate Change 2007 – Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.). Cambridge University Press, Cambridge, UK, 1032 p.

IPCC, 2007a. Climate Change 2007 – Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri, R.K., Reisinger, A. (Eds.). Geneva, Switzerland, 104 p.

IPCC, 2007b. Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.). Cambridge University Press, Cambridge, UK. 976 p.

Ivey, J.L., Smithers, J., De Loe, R.C., Kreutzwiser, R.D., 2004. Community capacity for adaptation to climate-induced water shortages: linking institutional complexity and local actors. Environmental Management, 33 (1), 36–47.

Jabloun, M., Sahli, A., 2012. WEAP-MABIA Tutorial. A collection of stand-alone chapters to aid in learning the WEAP-MABIA module. Available online at: http://www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Acsad_dss/tutorial_weap-mabia_pdf.pdf?__blob=publicationFile&v=2

Jalan,J., Ravallion, M., 1999. Are the poor less well insured? Evidence on vulnerability to income risk in rural China. Journal of Development Economics, 58, 61–81.

Jeuland, M., 2010, Economic implications of climate change for infrastructure planning in transboundary water systems: An example from the Blue Nile, Water Resources Research, 46, W11556.

Johansson, R.C., Tsur, Y., Roe, T.L., Doukkali, R., Dinar, A., 2002. Pricing irrigation water: a review of theory and practice. Water Policy, 4, 173–199.

Jones, L., Boyd, E., 2011. Exploring social barriers to adaptation: Insights from Western Nepal. Global Environmental Change, 21, 1262–1274.

Jones, P., Harris, I., 2011. CRU-TS 3.10 Climate Database. University of East Anglia Climatic Research Unit (CRU). NCAS British Atmospheric Data Centre, 2008, 2011.

Joyce, B.A., Mehta, V.K., Purkey, D.R., Dale, L.L., Hanemann M., 2011. Modifying agricultural water management to adapt to climate change in California's central valley. Climatic Change, 109 (Suppl 1), S299–S316.

Junta de Extremadura, 2008. Datos estadísticos sobre el sector agropecuario y forestal de Extremadura. Superficies de cultivos herbáceos y leñosos por municipio. Badajoz. Consejería de Agricultura, Desarrollo Rural, Medio Ambiente y Energía. Gobierno de Extremadura. Badajoz, Spain.

Junta de Extremadura, 2009. Determinación de la capacidad de pago adicional para el coste del agua de riego de las explotaciones de regadío de Extremadura en el ámbito de la Directiva Marco de Aguas. Consejería de Agricultura y Desarrollo rural. Dirección General de Estructuras Agrarias, Servicio de Ordenación de Regadíos. Badajoz, Spain.

Kahil, T., Albiac, J. 2012. Instrumentos de política de cambio climático en la agricultura de Aragón. Revista Española de Estudios Agrosociales y Pesqueros, 233(3), 13–42.

Katz, D.L., 2008. Water, economic growth, and conflict: three studies. PhD Dissertation. University of Michigan. UMI Dissertation Publishing. United States of America. 106 p.

Kaufmann, D., Kraay, A., Mastruzzi, M., 2010. The Worldwide Governance Indicators : A Summary of Methodology, Data and Analytical Issues. World Bank Policy Research Working Paper No. 5430.

Kemp-Benedict, E.J., Bharwani, S., Fischer, M.D., 2010. Using Matching Methods to Link Social and Physical Analyses for Sustainability Planning. Ecology and Society, 15(3), 4.

KfW, 2011. Adaptation to Climate Change. Cooperation with developing countries - Climate and Development. KfW Development Bank. Frankfurt, Germany. 32 p. Available online at: https://www.kfw-entwicklungsbank.de/International-financing/KfW-Entwicklungsbank/Environment-and-climate/Klima-Umwelt-und-Entwicklung/

Kok, K., Alcamo, J., 2007. Report reviewing existing large-scale scenarios and reasons for selection of the set most relevant to European water issues for the fast-track process. Deliverable 2.2. SCENES Project. 30 p.

Kok, K., Rothman, D.S., Patel, M., 2006. Multi-scale narratives from an IA perspective: Part I. European and Mediterranean scenario development. Futures, 38(3), 261–284.

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.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., Shiklomanov, I.A., 2007. Freshwater resources and their management. In Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 173-210.

Kuruppu, N., Gero, A., Mukheibir, P., Herriman, J., 2012. Cross-Scale Barriers to Climate Change Adaptation in Local Government, Australia – Workshop One Report. Prepared for NCCARF. Institute for Sustainable Futures, University of Technology, Sydney. 30 p.

Laux P., Jäckel, G., Tingem, R.M., Kunstmann, H., 2010. Impact of climate change on agricultural productivity under rainfed conditions in Cameroon—A method to improve attainable crop yields by planting date adaptations. Agricultural and Forest Meteorology, 150, 1258–1271.

Lehner, B., Verdin, K., Jarvis, A., 2008. New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, 89(10): 93-94. HydroSHEDS. http://www.worldwildlife.org/hydrosheds and http://hydrosheds.cr.usgs.gov.

Leichenko, R., O'Brien, K., 2002. The dynamics of rural vulnerability to global change: the case of Southern Africa. Mitigation and Adaptation Strategies for Global Change, 7, 1–18.

Lempert, R.J., Groves, D.G., 2010. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American West. Technological Forecasting and Social Change, 77(6), 960–974.

Letcher, R.A., Jakeman, A.J., Croke, B.F.W., 2004. Model development for integrated assessment of water allocation options. Water Resources Research., 40, W05502.

Liu, Y., Gupta, H., Springer, E., Wagener, T., 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environmental Modelling & Software, 23, 846 – 858.

Lorenzoni, I., Nicholson-Cole, S., Whitmarsh, L., 2007. Barriers perceived to engaging with climate change among the UK public and their policy implications. Global Environmental Change, 17 (3–4), 445–459.

Luers, A. L., Lobell, D.B., Sklar, L.S., Addams, C.L. Matson, P.A., 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environmental Change, 13 (4), 255–267.

MAGRAMA, 2012. Encuesta de Superficies y Rendimientos de Cultivos. Ministerio de Agricultura, Alimentación y Medio Ambiente. Madrid, Spain.

MAGRAMA, 2013. SIIA. Sistema Integrado de Información del Agua. Ministerio de Agricultura, Alimentación y Medio Ambiente. Madrid, Spain. Available online at: http://servicios2.magrama.es/sia/visualizacion/descargas/documentos.jsp (Last accessed June 2013).

Malone, E.L., Engle, N.L., 2011. Evaluating regional vulnerability to climate change: purposes and methods. WIREs Climate Change, 2, 462–474.

MAPA, 1990. Anuario Estadístico de Agricultura 1990. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2000. Anuario Estadístico de Agricultura 2000. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2002. Evaluación de la zona regable de Vallelado y análisis de la oscilación de niveles del acuífero de abastecimiento. Dirección General de Desarrollo Rural. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2004a. Evaluación de la zona regable del Valle del Guadalhorce (Málaga). Secretaría General de Agricultura y Alimentación, Dirección General de Desarrollo Rural. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2004b. Evaluación de la zona regable de Riegos de Levante margen izquierda del Segura (Alicante). Secretaría General de Agricultura y Alimentación, Dirección General de Desarrollo Rural. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2004c. Evaluación de la Zona Regable de Virgen del Aviso (Zamora). Secretaría General de Agricultura y Alimentación, Dirección General de Desarrollo Rural. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2005. Evaluación de la Zona Regable de Montijo. Secretaría General de Agricultura y Alimentación, Dirección General de Desarrollo Rural. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

MAPA, 2007. Resultados técnico-económicos de explotaciones agrícolas de Extremadura en 2006. Análisis de la economía de los sistemas de producción. Subsecretaría de Agricultura, Pesca y Alimentación. Ministerio de Agricultura, Pesca y Alimentación. Madrid, Spain.

Margat, J., 2004, L'eau des Méditerranéens: situation et perspectives, MAP Technical Report Series No. 158, UNEP/PAM, Athens, Greece. 366p.

Margat, J., Vallée, P., 2000. Mediterranean Vision on water, population and the environment for the 21st Century. Blue Plan for the Mediterranean. Sophia Antipolis, France. 62p.

MARM, 2008. Resultados técnico-económicos de explotaciones agrícolas de Castilla La Manch en 2007. Análisis de la economía de los sistemas de producción. Subsecretaría de Medio Ambiente y Medio Rural y Marino. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain.

MARM, 2009a. Mapa de Cultivos y Aprovechamientos de España 2000 – 2009. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain.

MARM, 2009b. Resultados técnico-económicos de explotaciones agrícolas de Aragón en 2008. Análisis de la economía de los sistemas de producción. Subdirección general de Análisis, Prospectiva y Coordinación. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain.

MARM, 2010a. Resultados técnico-económicos de explotaciones agrícolas de Andalucía en 2009. Análisis de la economía de los sistemas de producción. Subdirección general de Análisis, Prospectiva y Coordinación. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain.

MARM, 2010b. Resultados técnico-económicos de explotaciones hortofrutícolas de la Comunidad Valenciana en 2009. Análisis de la economía de los sistemas de producción. Subdirección general de Análisis, Prospectiva y Coordinación. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain.

Martínez-Santos, P., Henriksen, H.J., Zorrilla, P., Martínez-Alfaro, P.E., 2010. Comparative reflections on the use of modelling tolos in conflictive water management settings: The Mancha Occidental aquifer, Spain. Environmental Modelling & Software, 25, 1439–1449.

Massarutto, A., 2003. Water pricing and irrigation water demand: economic efficiency versus environmental sustainability. European Environment, 13, 100–119.

Mazzanti, M., Montini, A., 2006. The determinants of residential water demand: empirical evidence for a panel of Italian municipalities. Applied Economics Letters, 13(2), 107–111.

McKinney, D., Cai, X., Rosegrant, M.W., Ringler, C., Scott, C.A., 1999. Modeling Water Resources Management at the Basin Level: Review and Future Directions. SWIM Paper 6. International Water management Institute, Colombo. 71 p.

Medellín-Azuara, J., Harou, J.J., Olivares, M.A., Madani, K., Lund, J.R., Howitt, R.E., Tanaka, S.K., Jenkins, M.W., 2008. Adaptability and adaptations of California's water supply system to dry climate warming. Climatic Change 87 (Suppl. 1), S75–S90.

Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J., Taylor, K.E., 2007. The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. Bulletin of the American Meteorological Society, 88, 1383–1394.

Meinke, H., Howden, S.M., Struik, P.C., Nelson, R., Rodriguez, D., Chapman, S.C., 2009. Adaptation science for agriculture and natural resource management— urgency and theoretical basis. Current Opinion in Environmental Sustainability, 1, 69–76.

Mendelsohn, R., Dinar, A., 1999. Climate Change, Agriculture, and Developing Countries: Does Adaptation Matter? The World Bank Research Observer, 14 (2), 277-293.

Milano, M., 2012. Will water demands still be met in the Mediterranean basin by the 2050 horizon? Plan Bleu notes No. 25. Blue Plan for the Mediterranean. Sophia Antipolis, France.

MMA, 2000. Libro Blanco del Agua en España. Ministerio de Medio Ambiente. Madrid, Spain. 638 p.

MMA, 2005a. Memoria Económica del Proyecto de Reforma del Real Decreto del Reglamento del Dominio Público Hidráulico. Ministerio de Medio Ambiente. Madrid, Spain.

MMA, 2005b. Resumen Nacional de los Artículo 5 y 6 de la Directiva Marco de Agua. Ministerio de Medio Ambiente. Madrid, Spain.

MMA, 2007. Precios y costes de los Servicios del Agua en España. Informe integrado de recuperación de costes de los servicios de agua en España. Artículo 5 y anejo III de la Directiva Marco de Agua. 219 p.

Moneo, M., 2008. Drought and climate change impacts on water resources: management alternatives. PhD Thesis. Universidad Politécnica de Madrid. Madrid, Spain. 341 p. Available online at: http://oa.upm.es/1222/1/MARTA_MONEO_LAIN_A1b.pdf.

Moriondo, M., Bindi, M., Zbigniew W. Kundzewicz, Szwed, M., Chorynski, A., Matczak, P., Radziejewski, M., McEvoy, D., Wreford, A., 2010. Impact and adaptation opportunities for European agriculture in response to climatic change and variability. Mitigation and Adaptation Strategies for Global Change, 15 (7), 657–679.

Moser, S.C., Ekstrom, J., 2010. A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences of the United States of America, 107(51), 22026-22031.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.H., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature. 463 (7282), 747-756.

MPC (Migration Policy Center), 2013. Jordan MCP Migration Profile. Report. European University Institute. 13 p. Available online at: http://www.migrationpolicycentre.eu/docs/migration_profiles/Jordan.pdf

Müller, C., Bondeau, A., Popp, A., Waha, K., Fader, M., 2010. Climate change impacts on agricultural yields. Background note to the World Development Report 2010. Potsdam Institute for Climate Impact Research (PIK), Germany.

Nakicenovic, N., Swart, R. (Eds.), 2000. Special Report on Emissions Scenarios. Cambridge: Cambridge University Press.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I: A discussion of principles. Journal of Hydrology, 10, 282–290.

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R.,Ewing, M., Lee, D., 2009. Climate change: Impact on Agriculture and Costs of Adaptation. Food policy report. International Food Policy Research Institute (IFPRI), Washington, D.C., USA. 19 p.

Nicholas, K.A., Durham, W.H., 2012. Farm-scale adaptation and vulnerability to environmental stresses: Insights from winegrowing in Northern California. Global Environmental Change, 22, 483–494.

Nicholls, R.J., Tol, R.S.J., 2006. Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Philosophycal Transactions of the Royal Society A, 364, 1073–1095.

Nielsen, J.O., Reenberg, A., 2010. Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso. Global Environmental Change, 20, 142–152.

Norton, R., Jaberin, A., 2006. Toward more efficient agricultural production and marketing in Jordan. United States Agency for International Development. 38 p.

Notenbaert, A., Karanja, S.N., Herrero, M., Felisberto, M., Moyo, S., 2013. Derivation of a household-level vulnerability index for empirically testing measures of adaptive capacity and vulnerability. Regional Environmental Change, 13, 459–470.

O'Brien, K., Eriksen, S., Nygaard, L., Schjolden, A., 2007. Why different interpretations of vulnerability matter in climate change discourses. Climate Policy, 7, 73–88.

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., West, J., 2004. Mapping vulnerability to multiple stressors: climate change and globalization in India. Global Environmental Change, 14, 303–313.

OECC (Spanish Office for Climate Change), 2008. The Spanish National Climate Change Adaptation Plan. Oficina Española de Cambio Climático. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain.

Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. European Journal of Agronomy, 16, 239–262.

Olubode-Awosola, O.O., van Schalkwyk, H.D., Jooste, A., 2008. Mathematical modeling of the South African land redistribution for development policy. Journal of Policy Modeling, 30(5), 841–855.

Orr, P., Eales, R., White, O., Walljes, I., 2008. Annex 1: Overcoming Barriers to the Delivery of Climate Change Adaptation – ESPACE Summary Report. ESPACE Project (European Spatial Planning: Adapting to Climate Events). 67 p.

Osterburg B., Offermann, F., Kleinhanss, W., 2001. A Sector Consistent Farm Group Model for German Agriculture. In: Heckelei, T., Witzke, H.P. and Henrichsmeyer, W. (Eds.) Agricultural Sector Modelling and Policy Information Systems. Kiel, Wissenschaftsverlag, Vauk 2001. Pp. 152-159

Pahl-Wostl, C., Downing, T., Kabat, P., Magnuszewski, P., Meigh, J., Schlueter, M., Sendzimir, J., Werners, S., 2005. Transition to Adaptive Water Management; The NeWater project. Water Policy. NeWater Working Paper 1. Institute of Environmental Systems Research, University of Osnabrück, Germany. 19 p.

Peña-Haro, S., Pulido-Velazquez, M., Sahuquillo, A., 2009. A hydro-economic modelling framework for optimal management of groundwater nitrate pollution from agriculture. Journal of Hydrology, 373, 193–203.

Pfenninger S., Hanger S., Dreyfus M., Dubel A., Hernández-Mora N., Esteve P., Varela-Ortega C., Watkiss P., Patt A., 2010. Report on perceived policy needs and decision contexts. D1.1. Report. MEDIATION Project (nº 244012) - DG Research, European Commission. 108 p.

Plan Bleu (2011). SIMEDD (Mediterranean Information System on Environment and Sustainable Development). Available online at: http://www.planbleu.org/donnees/eau/simed/eau_simed_demandeUk.html (Last accessed October 2011).

Postel, S.L., 2000. Entering an Era of Water Scarcity: The Challenges Ahead. Ecological Applications, 10 (4), 941–948.

Purkey, D.R., Huber-Lee, A., Yates, D.N., Hanemann, M., Herrod-Julius, S., 2007. Integrating a climate change assessment tool into stakeholder-driven water management decision-making processes in California. Water Resources Management, 21, 315–329.

Purkey, D.R., Joyce, B., Vicuna, S., Hanemann, M.W., Dale, L.L., Yates, D., Dracup, J.A., 2008. Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley. Climatic Change, 87 (Suppl 1), S109–S122.

Qureshi, M.E., Whitten, S.T., Mainuddin, M., Marvanek, S., Elmahdi, A., 2013. A biophysical and economic model of agriculture and water in the Murray-Darling Basin, Australia. Environmental Modelling & Software, 41, 98–106.

Raddad, K., 2005. Water supply and water use statistics in Jordan. Presented at the IWG-Env, International Work Session on Water Statistics, Vienna, June 20-22. 2005.

Ragab, R., Prodhomme, C., 2002. Climate change and water resources management in arid and semi-arid regions: prospective and challenges for the 21st century. Biosystems Engyneering, 81(1), 3–34.

Rajaona, A.M., Sutterer, N., Asch, F., 2012. Potential of Waste Water Use for Jatropha Cultivation in Arid Environments. Agriculture, 2, 376–392.

Randall, D. A., Wood, R.A., 2007. Climate models and their evaluation. In Solomon, S., Qin, D. and Manning, M. (Eds.): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. Pp 589–662.

Rao, E.J.O., Qaim, M., 2011. Supermarkets, Farm Household Income, and Poverty: Insights from Kenya. World Development, 39 (5), 784–796.

Raskin, P., Hansen, E., Zhu, Z., Stavisky, D., 1992. Simulation of Water Supply and Demand in the Aral Sea Region. Water International, 17, 55-67.

Rawabdeh, H., Scardigno, A., Shatanawi, M., Todorovic, M., 2010. Optimization of the cropping pattern in Northern and Southern part of the Jordan Valley under drought conditions and limited water availability. In: López-Francos A. (comp.), López-Francos A. (collab.). Economics of drought and drought preparedness in a climate change context. Options Méditerranéennes: Série A. Séminaires Méditerranéens, 95. Zaragoza: CIHEAM / FAO / ICARDA / GDAR / CEIGRAM / MARM. Pp. 199–206.

Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2010. Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. European Journal of Agronomy, 32, 91–102.

Renwick, M.E., Green, R.D., 2000. Do Residential Water Demand Side Management Policies Measure Up? An Analysis of Eight California Water Agencies. Journal of Environmental Economics and Management, 40, 37–55.

Reynaud, A., 2003. An Econometric Estimation of Industrial Water Demand in France. Environmental and Resource Economics, 25, 213–232.

Rijsberman, F.R., 2006. Water scarcity: Fact or fiction? Agricultural Water Management, 80 (1–3), 5–22.

Risbey, J., Kandlikar, M., Dowlatabadi, H., 1999. Scale, context, and decision making in agricultural adaptation to climate variability and change. Mitigation and Adaptation Strategies for Global Change, 4, 137–165.

Rochdane, S., Reichert, B., Messouli, M., Babqiqi, A., Khebiza, M.Y., 2012. Climate Change Impacts on Water Supply and Demand in Rheraya Watershed (Morocco), with Potential Adaptation Strategies. Water, 4, 28-44.

Rock, M.T., 2001. The Dewatering of Economic Growth What Accounts for the Declining Water-Use Intensity of Income? Journal of Industrial Ecology, 4(1), 57–73.

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences of the United States of America - PNAS, 104(15), 6253–6260.

Rodríguez-Cabello, J.A., 2009. Personal communication.

Rodríguez-Díaz, J.A., Weatherhead, E.K., Knox, J.W., Camacho, E., 2007. Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. Regional Environmental Change, 7, 149–159.

Rosegrant, M.W. and the IMPACT Development Team, 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute (IFPRI), Washington, D.C. 50 p.

Rosegrant, M.W., Cai, X., Cline, S.A. 2002. World Water and Food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington D.C. 322 p.

Rosegrant, M.W., Ringler, C., McKinney, D.C., Cai, X., Keller, A., Donoso, G., 2000. Integrated economic–hydrologic water modelling at the basin scale: the Maipo river basin. Agricultural Economics, 24, 33–46.

Rosegrant, M.W., Ringler, C., Zhu, T., 2009. Water for Agriculture: Maintaining Food Security under Growing Scarcity. Annual Review of Environment and Resources, 34, 205–222.

Rosenzweig, C., Strzepek, K.M., Major, D.C., Iglesias, A., Yates, D.N., McCluskey, A., Hillel, D., 2004. Water resources for agriculture in a changing climate: international case studies. Global Environmental Change, 14, 345–360.

Rosenzweig, C., Tubiello, F.N., 1997. Impacts of global climate change on Mediterranean agriculture: current methodologies and future directions. An introductory essay. Mitigation and Adaptation Strategies for Global Change, 1, 219–232.

Rosenzweig, C., Wilbanks, T.J., 2010. The state of climate change vulnerability, impacts and adaptation research: strengthening knowledge base and community. Climatic Change, 100, 103–106.

Rothman, D.S., Romero-Lankao, P., Schweizer, V.J., Bee, B.A., 2013. Challenges to adaptation: a fundamental concept for the shared socio-economic pathways and beyond. Climatic Change, DOI 10.1007/s10584-013-0907-0.

Rotmans, J., van Asselt, M.B.A., Anastasi, C., Greeuw, S.C.H., Mellors, J., Peters, S., Rothman, D.S., Rijkens-Klomp, N., 2000. Visions for a sustainable Europe. Futures, 32, 809–831.

Rygel, L., O'Sullyvan, D., Yarnal, B., 2006. A method for constructing a social vulnerability index: an application to hurricane storm surges in a developed country. Mitigation and Adaptation Strategies for Global Change, 11, 741–764.

Sadoulet, E., De Janvry, A., 1995. Quantitative Development Policy Analysis. Chapter 9: Transaction Costs and Agrarian Institutions. The Johns Hopkins University Press. Baltimore, United States, and London, United Kingdom. 438 p.

Safa, M.S., 2005. Socio-Economic Factors Affecting the Income of Small-scale Agroforestry Farms in Hill Country Areas in Yemen: A comparison of OLS and WLS Determinants. Small-scale Forest Economics, Management and Policy, 4(1), 117-134.

Sahli, A., Jabloun, M., 2005. MABIA-ETc: a tool to improve water use in field scale according to the FAO guidelines for computing water crop requirements. The WUEMED Workshop (Improving Water Use Efficiency in MEDiterranean Agriculture: what limits the adoption of new technologies?), Rome, Italy, 29-30 September 2005.

Samuels, R., Rimmer, A., Hartmann, A., Krichak, S., Alpert, P., 2010. Climate Change Impacts on Jordan River Flow: Downscaling Application from a Regional Climate Model. Journal of Hydrometeorology, 11, 860–879.

Saurí, D., del Moral, L., 2001. Recent developments in Spanish water policy. Alternatives and conflicts at the end of the hydraulic age. Geoforum, 32(3), 351–362.

Scheffran, J., Marmer, E., Sow, P., 2012. Migration as a contribution to resilience and innovation in climate adaptation: Social networks and co-development in Northwest Africa. Applied Geography, 33, 119–127.

Schiffer, E., Hauck, J., 2010. Net-Map: Collecting Social Network Data and Facilitating Network Learning through Participatory Influence Network Mapping. Field Methods, 22(3), 231–249.

Schoengold, K., Zilberman, D., 2007. The Economics of Water, Irrigation, and Development. In: Evenson, R. and Pingali, P. (Eds), Handbook of Agricultural Economics, Vol. 3, Chapter 58, pp. 2939–2984.

Schreinemachers, P., Berger, T., 2011. An agent-based simulation model of human–environment interactions in agricultural systems. Environmental Modelling & Software, 26, 845–859.

Scott, J. 2000. Social network analysis: A handbook. Newbury Park, CA, USA: SAGE Publications. 208 p.

Seo, S.N., Mendelsohn, R., 2008. An analysis of crop choice: Adapting to climate change in South American farms. Ecological Economics, 67, 109–116.

Shatanawi, M., Fardous, A., Mazahrih, N., Duqqah, M., 2005. Irrigation systems performance in Jordan. In: Lamaddalena, N., Lebdi, F., Todorovic, M., Bogliotti, C. (Eds.) Irrigation systems performance, Options Méditerranéennes: Série B. Etudes et Recherches, 52, 126 – 135. CIHEAM-IAMB, Bari.

Sieber, J., Purkey, D.R., 2011. WEAP: Water Evaluation And Planning System – User guide. Stockholm Environment Institute, U.S. Center. January 2011. Available online at: http://www.weap21.org/downloads/WEAP_User_Guide.pdf.

Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K., 2007. Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany, and Food and Agriculture Organization of the United Nations, Rome, Italy.

Simonet, S., 2011. Adapting to climate change in the water sector in the Mediterranean: situation and prospects. Blue Plan Papers, 10. Plan Bleu, Valbonne 2011.

Smit, B., Pilifosova, O., 2001. Adaptation to climate change in the context of sustainable development and equity. In McCarthy, J.J., Canziani, O.F., Leary, N.A. Dokken, D.J. White, K.S. (Eds.), Climate Change 2001 - Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK, 1032 p.

Smit, B., Skinner, M., 2002. Adaptation options in agriculture to climate change: a typology. Mitigation and Adaptation Strategies for Global Change, 7, 85–114.

Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. Global Environmental Change, 16, 282–292.

Smith, M., 1992. CROPWAT. A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No. 46. FAO (Food and Agriculture Organization of the United Nations). Roma, Italy. 126 p.

Stern, D.I., 2004. The Rise and Fall of the Environmental Kuznets Curve. World Development, 32(8), 1419–1439.

Strzepek, K., Yates, D., Yohe, G., Tol, R., Mader, N., 2001. Constructing ‘‘not implausible’’ climate and economic scenarios for Egypt. Integrated Assessment, 2, 139–157.

Tanaka, S.K., Zhu, T., Lund, J.R., Howitt, R.E., Jenkins, M.W., Pulido, M.A., Tauber, M., Ritzema, R.S., Ferreira, I.C., 2006. Climate warming and water management adaptation for California. Climatic Change, 76, 361–387.

THKJ (The Hashemite Kingdom of Jordan), 2008. Water for life. Jordan’s Strategy for Water 2008 – 2022.

Tingem, M., Rivington, M., 2009. Adaptation for crop agriculture to climate change in Cameroon: Turning on the heat. Mitigation and Adaptation Strategies for Global Change, 14, 153–168.

Tompkins, E.L., Adger, W.N., 2004. Does Adaptive Management of Natural Resources Enhance Resilience to Climate Change? Ecology and Society, 9(2), 10.

Tsur, Y., Dinar, A., Doukkali, R.M., Roe, T., 2004. Irrigation water pricing: policy implications based on international comparison. Environment and Development Economics, 9, 735–755.

Tubiello, F.N., Donatelli, M., Rosenzweig, C., Stockle, C., 2000. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. European Journal of Agronomy, 13, 179–189.

Tubiello, F.N., Rosenzweig, C., 2008. Developing climate change impact metrics for agriculture. The Integrated Assessment Journal, 8 (1), 165–184.

Tubiello, F.N., Rosenzweig, C., Goldberg, R.-A., Jagtap, S., Jones, J.W., 2002. Effects of climate change on US crop production: simulation results using two different GCM scenarios. Part I: Wheat, potato, maize, and citrus. Climate Research, 20, 259–270.

UN, 2013. Environment Statistics Database. United Nations, Statistics Division. Available online at: http://data.un.org/ (Last accessed April 2013)

UNEP, 2002. Mediterranean Strategy for Sustainable development. UNEP. Mediterranean Action Plan. United Nations Environment Program. Rome, Italy.

UNEP, 2012. The UN-Water Status Report on the Application of Integrated Approaches to Water Resources Management. United Nations Environment Programme. 106 p.

UNEP. 2007. Global Environment Outlook 4. Environment for development. UNEP, Nairobi. Available online at: http://www.unep.org/geo/geo4/.

UNEX, 2000. Catálogo de Suelos de Extremadura. Universidad de Extremadura. Available online at: www.unex.es/edafo/IndComarcas.html.

Van Beek, L. P. H.,Wada, Y., Bierkens, M. F. P., 2011. Global monthly water stress: 1. Water balance and water availability. Water Resources Research, 47, W07517.

Van Delden, H., Luja, P., Engelen, G., 2007. Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management. Environmental Modelling & Software, 22, 223–238.

Van Drunen, M.A., van't Klooster, S.A., Berkhout, F., 2011. Bounding the future: The use of scenarios in assessing climate change impacts. Futures, 43, 488–496.

Van Vuuren, D.P., Edmonds, J., Thomson, A., Riahi, K., Kainuma, M., Matsui, T., Hurtt, G.C., Lamarque, J.F., Meinshausen, M., Smith, S., Granier, C., Rose, S.K., Hibbard, K.A., 2011a. Representative concentration pathways: an overview. Climatic Change, 109, 5–31.

Van Vuuren, D.P., Isaac, M., Kundzewicz, Z.W., Arnell, N., Barker, T., Criqui, P., Berkhout, F., Hilderink, H., Hinkel, J., Hof, A., Kitous, A., Kram, T., Mechler, R., Scrieciu, S., 2011b. The use of scenarios as the basis for combined assessment of climate change mitigation and adaptation. Global Environmental Change, 21, 575–591.

Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2013. A new scenario framework for Climate Change Research: scenario matrix architecture. Climatic Change. DOI 10.1007/s10584-013-0906-1.

Van Vuuren, D.P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S.K., Arnell, N., 2012. A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change, 22, 21–35.

Van Wijk, M.T., Rufino, M.C., Enahoro, D., Parsons, D., Silvestri, S., Valdivia, R.O., Herrero, M., 2012. A review on farm household modelling with a focus on climate change adaptation and mitigation. Working Paper No. 20. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. 116 p. Available online at: www.ccafs.cgiar.org

Vano, J.A., Scott, M.J., Voisin, N., Stöckle, C.O., Hamlet, A.F., Mickelson, K.E.B., McGuire Elsner, M., Lettenmaier, D.P., 2010. Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. Climatic Change, 102, 287–317.

Varela-Ortega C., Esteve, P., 2012. Environmental standards in the fruits and vegetables sector of Spain. In: Brouwer, F., Fox, G., Jongeneel R. (Eds.) The Economics of Regulation in Agriculture. Compliance with Public and Private Standards. CABI Press, Wallingford, UK, 181-195pp.

Varela-Ortega, C. 2011. Water Policies in Spain: Balancing water for food and water for nature, in: Garrido, A., Ingram, H. (Eds.), Water for Food in a Changing World. Series: Contributions from the Rosenberg International Forum on Water Policy Rosenberg International Forum on Water Policy. Routledge Publishing, Taylor and Francis Group; London and New York, pp. 262–308.

Varela-Ortega, C., Blanco, I., Bharwani, S., Esteve, P., Downing, T.E., Fronzek, S. (*submitted*). How can irrigation agriculture adapt to climate change? Insights from the Guadiana basin in Spain. Regional Environmental Change, submitted (REC-D-13-00254).

Varela-Ortega, C., Blanco-Gutiérrez, I., Swartz, H.S., Downing, T.E., 2011. Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: A hydro-economic modeling framework. Global Environmental Change, 21, 604–619.

Varela-Ortega, C., Carmona, G., Esteve, P., 2009. Second drafts of storylines and conceptual models at the Regional and Pilot Area levels. Annex D1: Guadiana Pilot Area, SCENES Deliverable IA2.3. SCENES Project. (nº 036822) - DG Research, European Commission. 32 p.

Varela-Ortega, C., Esteve, P., Blanco, I., Carmona, G., Ruiz, J., Rabah, T., 2013. Assessment of Socio-Economic and Climate Change Effects on Water Resources and Agriculture in Southern and Eastern Mediterranean countries. MEDPRO Technical Report No. 28/March 2013. 118p. Available online at: www.MEDPRO-foresight.eu.

Varela-Ortega, C., Sumpsi, J., Garrido, A., Blanco, M., Iglesias, E., 1998. Water pricing policies, public decision making and farmers' response: implications for water policy. Agricultural Economics, 19(2), 193–202. Special issue of the XXIII Conference of the IAAE, Sacramento, USA, August 10-16 1998.

Vatn, A., Bakken, L., Bleken, M.A., Baadshaug, O.H., Fykse, H., Haugen, L.E., Lundekvam, H., Morken, J., Romstad, E., Rørstad, P.K., Skjelvåg, A.O., Sogn, T., 2006. A methodology for integrated economic and environmental analysis of pollution from agriculture. Agricultural Systems, 88 (2–3), 270–293.

Venot, J.P., Molle, F., Hassan, Y., 2007. Irrigated agriculture, water pricing and water savings in the Lower Jordan River Basin (in Jordan). Comprehensive Assessment of Water Management in Agriculture, Research Report 18.Colombo, Sri Lanka: International Water Management Institute. 61p.

Ventrella, D., Charfeddine, M., Moriondo, M., Rinaldi, M., Bindi, M., 2012. Agronomic adaptation strategies under climate change for winter durum wheat and tomato in southern Italy: irrigation and nitrogen fertilization. Regional Environmental Change, 12, 407–419.

Vicuña, S., Garreaud, R.D., McPhee, J., 2011. Climate change impacts on the hydrology of a snowmelt driven basin in semiarid Chile. Climatic Change, 105, 469–488.

Volk, M., Hirschfeld, J., Dehnardt, A., Schmidt, G., Bohn, C., Liersch, S., Gassman, P.W., 2008. Integrated ecological-economic modelling of water pollution abatement management options in the Upper Ems river basin. Ecological Economics, 66 (1), 66–76. Special Section: Integrated Hydro-Economic Modelling for Effective and Sustainable Water Management.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Reidy Liermann, C., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561.

Wang, J., Wang, E., Yang, X., Zhang, F., Yin, H., 2012. Increased yield potential of wheat-maize cropping system in the North China Plain by climate change adaptation. Climatic Change, 113(3-4), 825–840.

Weglarczyk, S., 1998. The interdependence and applicability of some statistical quality measures for hydrological models. Journal of Hydrology, 206, 98–103.

Weichselgartner, J., Kasperson, R., 2010. Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. Global Environmental Change, 20 (2), 266‑277.

Westerhoff, L., Smit, B., 2008. The rains are disappointing us: dynamic vulnerability and adaptation to multiple stressors in the Afram Plains, Ghana. Mitigation and Adaptation Strategies for Global Change, 14, 317–337.

Wheeler, S., Zuo, A., Bjornlund, H., 2012. Farmers' climate change beliefs and adaptation strategies for a water scarce future in Australia. Global Environmental Change, 23 (2), 537–547.

Wilbanks, T.J., Kates, R.W., 1999. Global change in local places: How scale matters. Climatic Change, 43, 601–628.

Wood, N.J., Burton, C.G., Cutter S.L., 2010. Community variations in social vulnerability to Cascadia-related tsunamis in the U.S. Pacific Northwest. Natural Hazards, 52, 369–389.

World Bank, 2011. World Development Indicators. Online database. Available online at: http://data.worldbank.org/data-catalog/world-development-indicators (Last accessed October 2011).

World Economic Forum, 2011.Scenarios for the Mediterranean Region. World Economic Forum, Geneva, Switzerland. 40p.

Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., 2005a. WEAP21 – A Demand-, Priority-, and Preference-Driven Water Planning Model. Part 1: Model Characteristics. Water International, 30 (4), 487–500.

Yates, D., Sieber, J., Purkey, D., Huber-Lee. A., Galbraith, H., 2005b. WEAP21 – A Demand-, Priority-, and Preference-Driven Water Planning Model. Part 2: Aiding Freshwater Ecosystem Service Evaluation. Water International, 30 (4), 501–5012.

Yates, D.N., 1996. WatBal: an integrated water balance model for climate impact assessment of river basin runoff. Water Resources Development, 12 (2), 121–139.

Yates, D.N., Strzepek, K.M., 1998. An assessment of integrated climate change impacts on the agricultural economy of Egypt. Climatic Change, 38, 261–287.

Yilmaz, B., Harmancioglu, N.B., 2010. An Indicator Based Assessment for Water Resources Management in Gediz River Basin, Turkey. Water Resources Management, 24, 4359–4379.

Yohe, G., Tol, R.S.J., 2002. Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity. Global Environmental Change, 12, 25–40.

Young, C.A., Escobar-Arias, M.I. , Fernandes, M., Joyce, B., Kiparsky, M., Mount, J.F., Mehta, V.K., Purkey, D., Viers, J.H., Yates, D., 2009. Modeling the hydrology of climate change in California's Sierra Nevada for sub-watershed scale adaptation. Journal of The American Water Resources Association, 46 (6), 1409–1423.

8. Annexes

8.1 Annex A

Farm questionnaires

WATER SCENARIOS FOR EUROPE AND FOR NEIGHBOURING

ESCENARIOS DE AGUA PARA EUROPA Y PARA LOS PAÍSES VECINOS

COMISIÓN EUROPEA – UNIVERSIDAD POLITÉCNICA DE MADRID

ENCUESTA DE EXPLOTACIONES AGRARIAS

PROVINCIA DE BADAJOZ – CUENCA MEDIA DEL GUADIANA

Nombre de la Explotación / Referencia:

Código: CCRR_TM_N (Comunidad de Regantes_Término Municipal_Número)

Localización:

- Municipio:

- Comunidad de Regantes:

Titular de la explotación:

- Género: ☐ hombre ☐ mujer

- Tipo de actividad:

  ☐ La agricultura es la actividad principal (ATP)

  ☐ La agricultura es actividad secundaria

- Tipo de empresa agraria:
  - ☐ Propiedad personal
  - ☐ Sociedad anónima u otra sociedad
  - ☐ S.A.T.
  - ☐ Otras

- Régimen de tenencia:
  - ☐ Propiedad → nº hectáreas:_____
  - ☐ Arrendamiento → nº hectáreas:_____
  - ☐ Otros → nº hectáreas:_____

- Edad:

☐ < 25 ☐ 25-34 ☐ 35-44 ☐ 45-54 ☐ 55-66 ☐ > 65

- Nivel de educación:
  - ☐ Sin estudios
  - ☐ Enseñanza primaria
  - ☐ Enseñanza secundaria
  - ☐ Formación profesional
  - ☐ Enseñanza universitaria
  - ☐ Otros

- Recibe asesoramiento técnico: ☐ Si ☐ No

- Es miembro de alguna cooperativa: ☐ Si ☐ No

- Número de miembros de la familia: _____

Características de la explotación:

- Tamaño de la explotación (has): ________

- Cultivos en la explotación:

Cultivo	SECANO (has)	REGADÍO (has)
Trigo		
Cebada		
Maíz		
Arroz		
Girasol		
Otros herbáceos		
Alfalfa		
Otros forrajeros		
Tomate		
Melón		
Brócoli		
Otros hortícolas		
Viña		
Olivar		
Melocotonero		
Ciruelo		
Otros leñosos		

- Sistema de riego:

☐ Gravedad (a pie) → nº hectáreas:_____

☐ Presión - Aspersión → nº hectáreas:_____

☐ Presión - Goteo → nº hectáreas:_____

☐ Otros → nº hectáreas: _____

- Origen del agua de riego:
  - ☐ Superficial → dotación (m^3/ha): _____
  - ☐ Subterránea → cantidad extraída media (m^3/ha): _____

- Consumo medio por hectárea (m^3/ha): ___________

- Tipo de motor:
  - ☐ Eléctrico
  - ☐ Gasoil

<u>Estructura laboral:</u>

- Número de miembros de la familia que trabajan en la explotación: ______

- Número de contratados fijos: ______

- Número de contratados eventuales: ______
  → Periodo de contratación:______

<u>Otros datos:</u>

- Contratación de seguros
  - ☐ Si
  - ☐ No

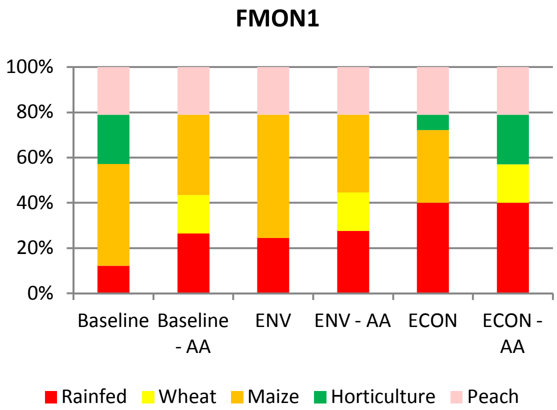
- En caso de tener seguros contratados:
  - o Tipo de seguro:
  - o Producción asegurada:

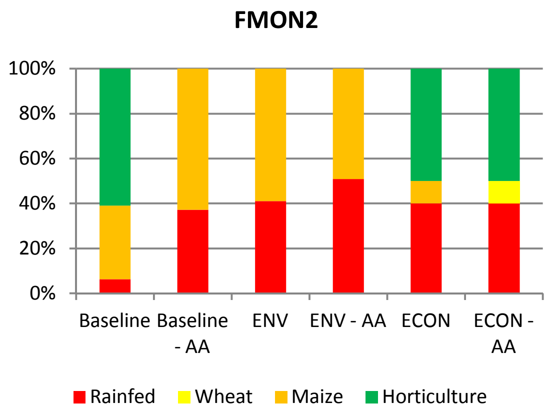
- Acceso a créditos / financiación:
  - ☐ Si
  - ☐ No

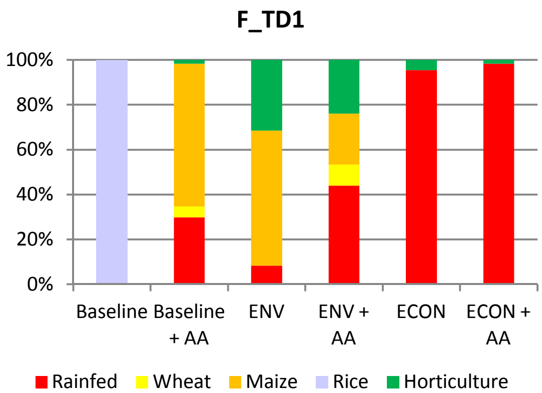
8.2 Annex B

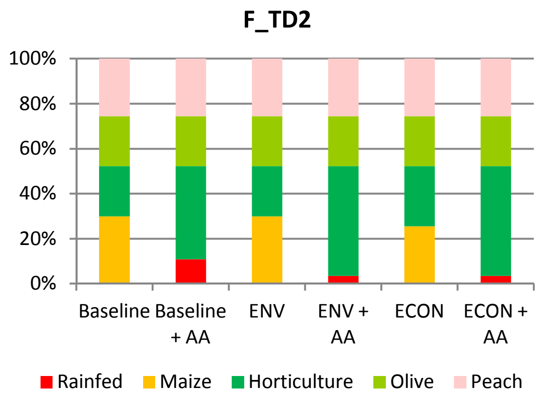
Middle Guadiana basin - Results of the hydro-economic model at farm level

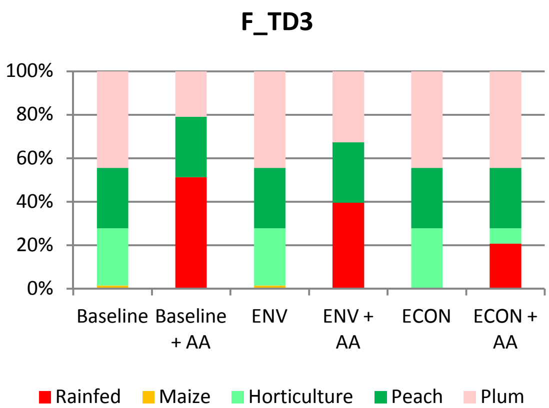
Cropping patterns

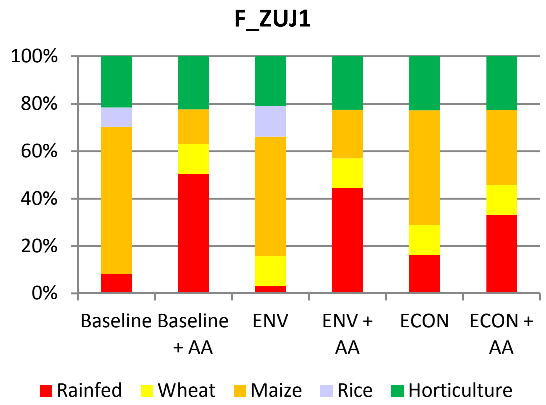


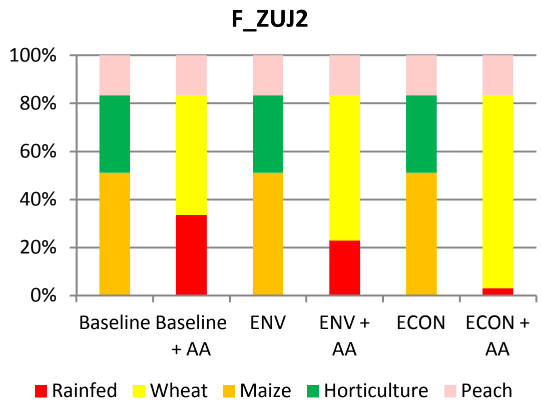


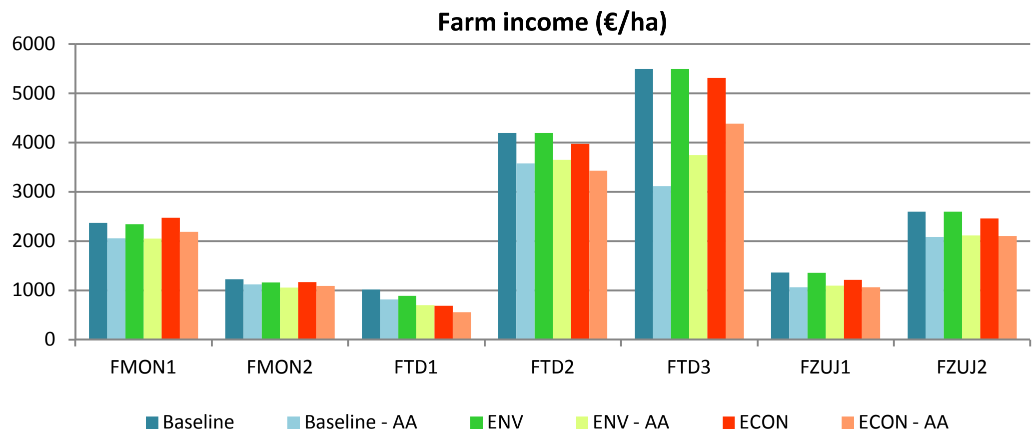


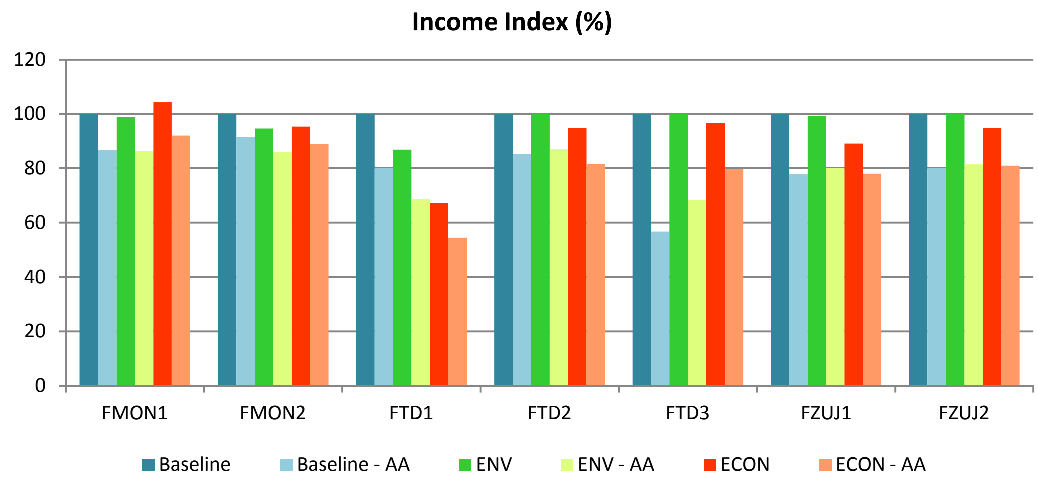


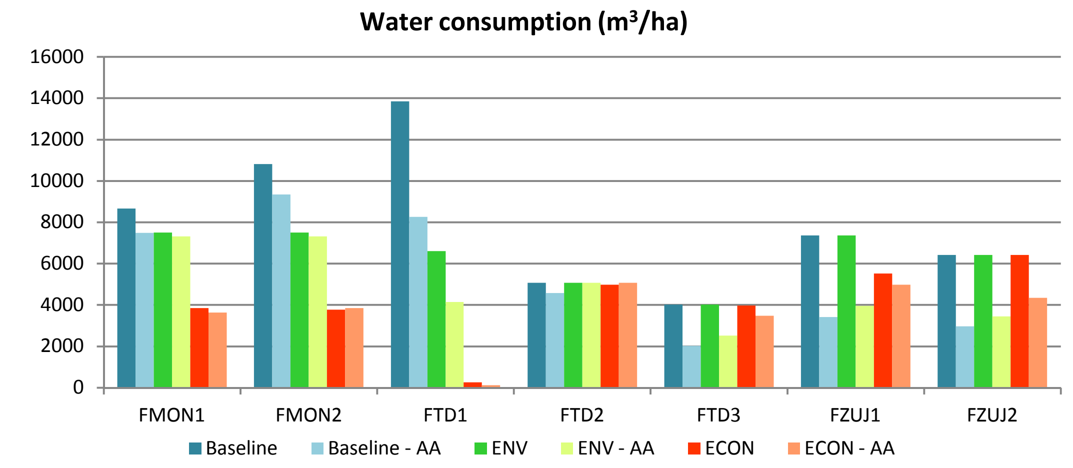



F_ZUJ1
100%
80%
60%
40%
20%
0%
Baseline
Baseline + AA
ENV
ENV + AA
ECON
ECON + AA
Rainfed
Wheat
Maize
Rice
Horticulture


F_ZUJ2
100%
80%
60%
40%
20%
0%
Baseline
Baseline + AA
ENV
ENV + AA
ECON
ECON + AA
Rainfed
Wheat
Maize
Horticulture
Peach

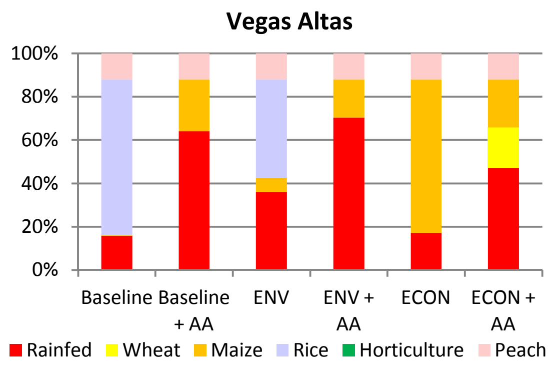

Farm income (€/ha)
6000
5000
4000
3000
2000
1000
0
FMON1
FMON2
FTD1
FTD2
FTD3
FZUJ1
FZUJ2
Baseline
Baseline - AA
ENV
ENV - AA
ECON
ECON - AA

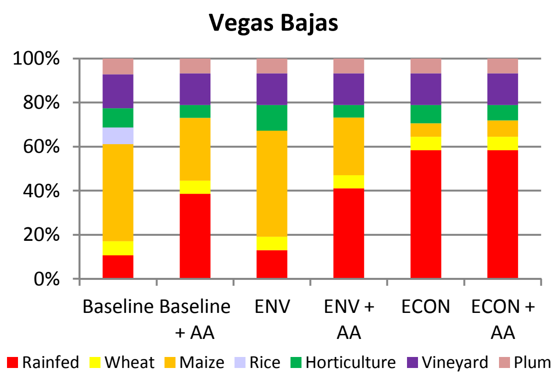

Income Index (%)
120
100
80
60
40
20
0
FMON1
FMON2
FTD1
FTD2
FTD3
FZUJ1
FZUJ2
Baseline
Baseline - AA
ENV
ENV - AA
ECON
ECON - AA

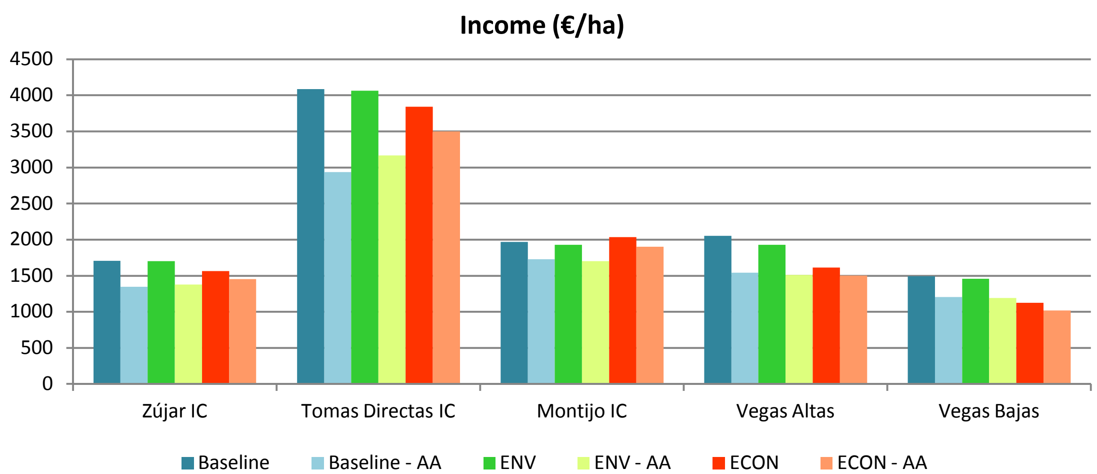


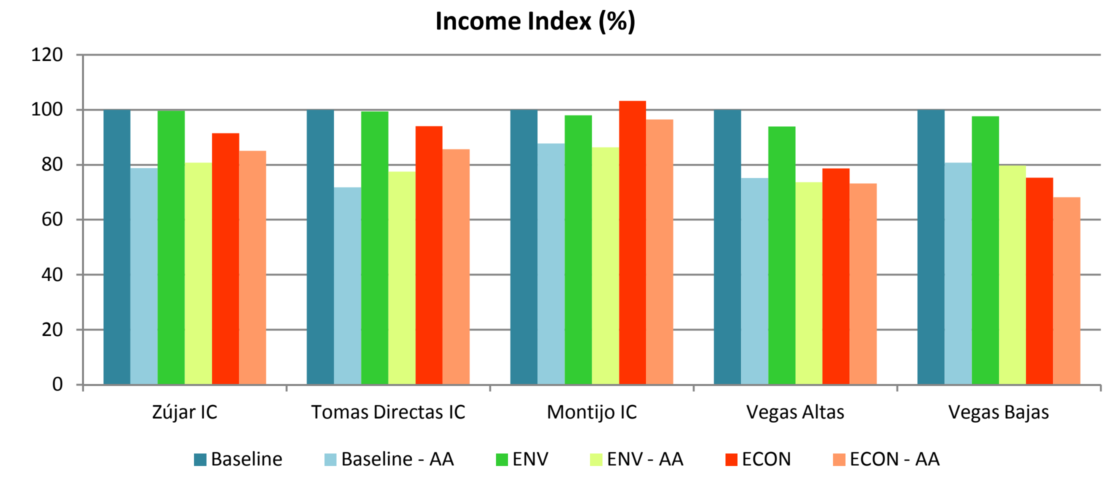
Middle Guadiana basin - Results of the hydro-economic model for the aggregated Vegas Altas and Vegas Bajas irrigation districts

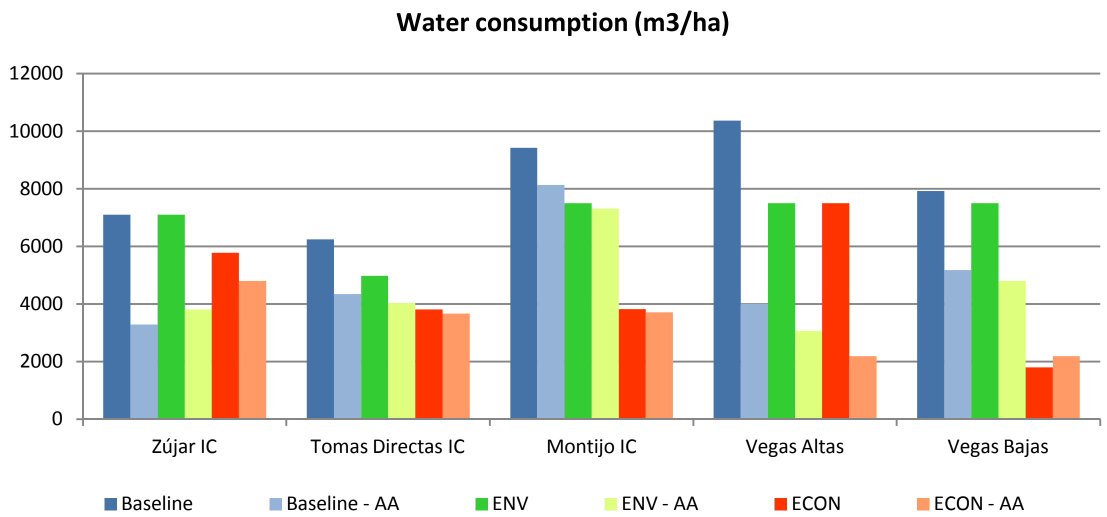
Cropping patterns








Income Index (%)
120
100
80
60
40
20
0
Zújar IC
Tomas Directas IC
Montijo IC
Vegas Altas
Vegas Bajas
Baseline
Baseline - AA
ENV
ENV - AA
ECON
ECON - AA

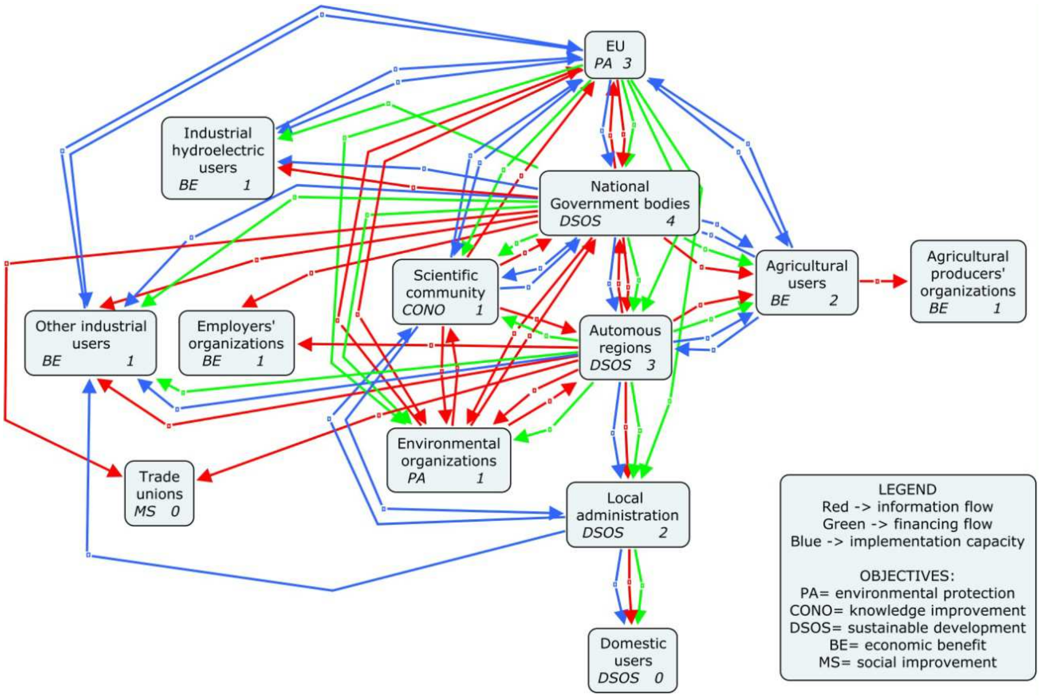

Water consumption (m3/ha)
12000
10000
8000
6000
4000
2000
0
Zújar IC
Tomas Directas IC
Montijo IC
Vegas Altas
Vegas Bajas
Baseline
Baseline - AA
ENV
ENV - AA
ECON
ECON - AA

8.3 Annex C

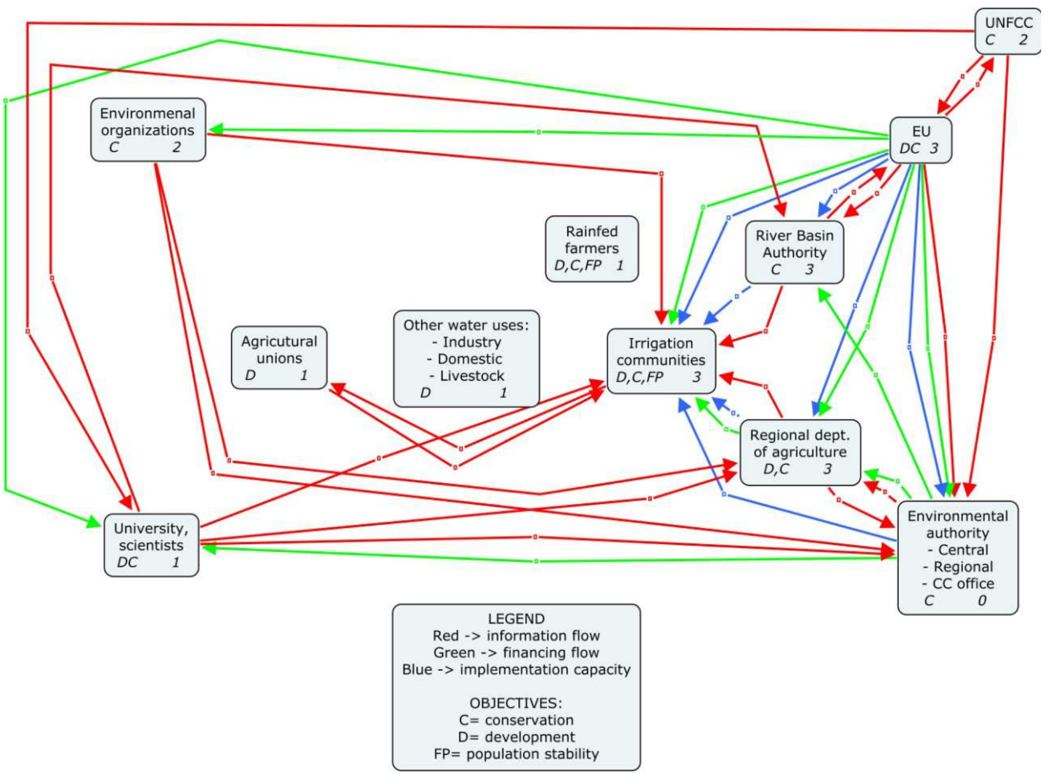
Social Network Maps produced in SH workshop.

January 12th 2012, Madrid, Spain – MEDIATION Project

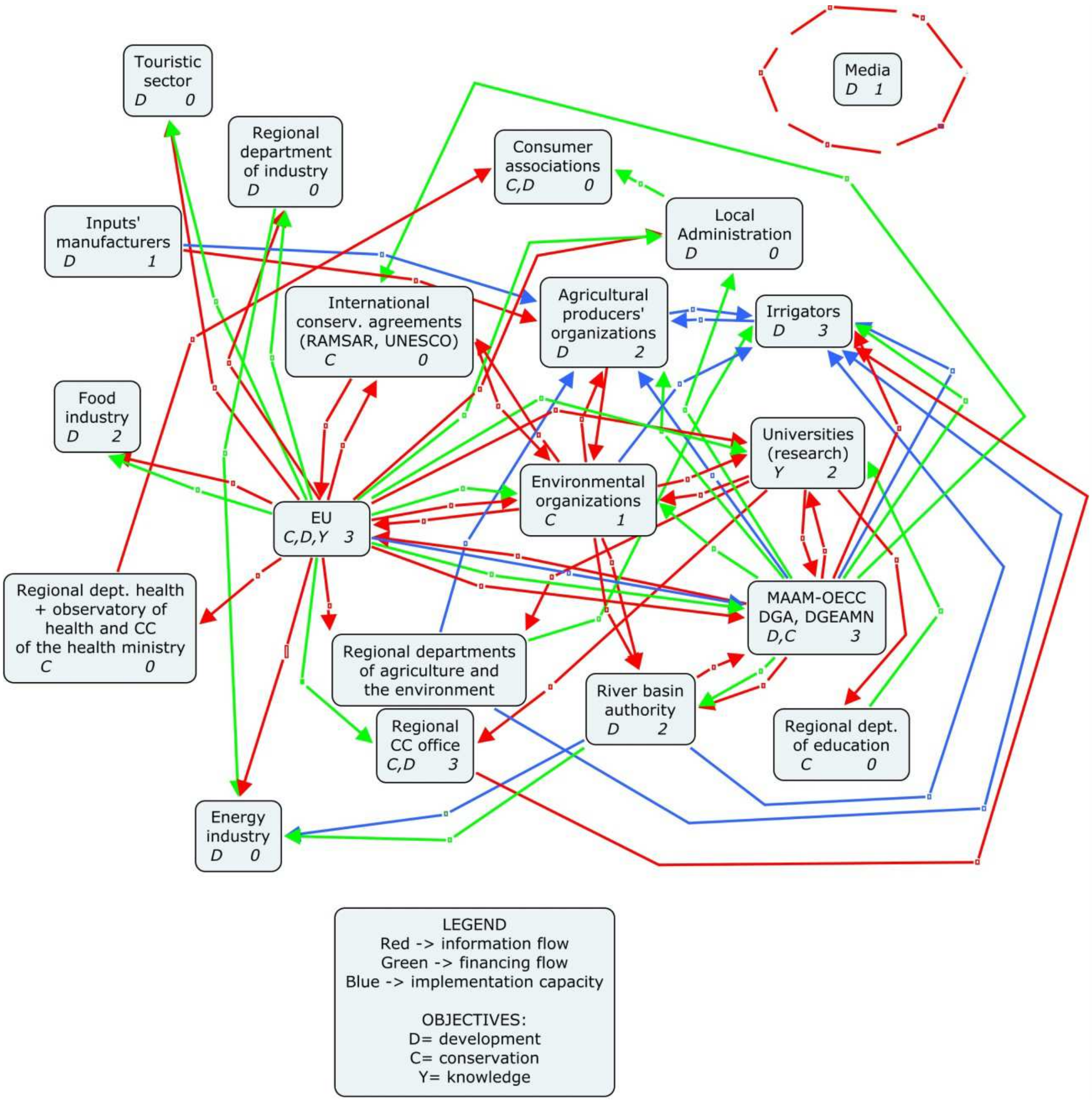
Group 1: Water administration



Group 2: Farmers



Group 3: Environmental groups



8.4 Annex D

Social networks validation and barriers to adaptation questionnaire

POLITÉCNICA

Mediation

Estudio de las redes socio-institucionales para la adaptación al cambio climático

El estudio de las redes socio-institucionales analiza cuales son los actores más importantes para la adaptación al cambio climático, cuales son las relaciones entre ellos, y que sinergias, lagunas o barreras puede haber. Nos centraremos en las relaciones entre actores en cuanto a:

- Flujos de información (mapas, datos, documentos…)
- Flujos de financiación (presupuestos, subvenciones, incentivos económicos…)
- Flujos de capacidad de implementación (capacitación, apoyo, establecimiento de mecanismos o procedimientos…)

1. ¿Cree que todos los actores importantes están representados en la red?

2. Con respecto a los flujos de información para la adaptación:
- ¿Cree que todos los flujos importantes están representados?
- ¿Está de acuerdo en la importancia de los actores señalados?

3. Con respecto a los flujos financieros para la adaptación:
- ¿Cree que todos los flujos importantes están representados?
- ¿Está de acuerdo en la importancia de los actores señalados?

4. Con respecto a la capacidad de implementación para la adaptación:
- ¿Cree que todos los flujos importantes están representados?
- ¿Está de acuerdo en la importancia de los actores señalados?

Reflexionando sobre el sistema que hemos representados de la adaptación al cambio climático en los sectores del agua y la agricultura:

5. ¿Cree que hay alguna relación entre actores que debería fortalecerse o que debiera darse en caso de no existir en la realidad? ¿Qué podría hacerse para crear o fortalecer esas relaciones?

6. ¿Cree que hay algún actor que tiene demasiadas conexiones con otros actores?

7. ¿Cree que hay algún actor central en la red? ¿Qué implicaciones puede tener esto?

8. ¿Cuál cree que es el actor más influyente? ¿Cree que hay algún conflicto entre influencia e importancia de algún actor sobre la adaptación?

9. ¿Cree que existe conflicto entre los objetivos de diferentes actores que pueda tener una repercusión negativa sobre la red socio-institucional de adaptación al cambio climático?

<u>Análisis de estrategias de adaptación al cambio climático en el Guadiana medio y barreras para su implementación</u>

Prácticas de adaptación: ajustes reales o cambios en los contextos de toma de decisión, que pueden mejorar la resiliencia o reducir la vulnerabilidad a los cambios observados o esperados del clima (IPCC, 2007)

En la Cuenca del Guadiana, se prevé que el cambio climático afecte de forma especial a la disponibilidad de recursos hídricos, pudiendo reducirla en un 20% en el último periodo del siglo XXI. Por tanto, parece evidente la necesidad de medidas de adaptación que reduzcan la vulnerabilidad de la agricultura y de los ecosistemas acuáticos.

En esta investigación analizamos la efectividad de diferentes medidas de adaptación relacionadas con la aplicación de la directiva marco del agua.

Las medidas de adaptación consideradas provienen del Plan de Adaptación al Cambio Climático del Sector Agrícola de Extremadura así como de otros planes y políticas relacionadas con la gestión de los recursos hídricos.

OBJETIVO	ESTRATEGIA	MEDIDA
Reducir la vulnerabilidad de los regantes	Aumento de la oferta	Aumentar la capacidad de embalse
		Otras:
	Gestión/reducción de la demanda	Control/Disminución de cuotas
		Tarificación – recuperación de costes
		Cambio/adaptación de cultivos
		Otras:
	Mejora de la eficiencia	Modernización regadíos
		Mejora infraestructuras distribución
		Otras:
	Estabilización de la renta	Fortalecimiento seguros agrarios
		Otras:
Reducir la vulnerabilidad de los ecosistemas acuáticos	Mantenimiento de caudales ambientales	Fijación y cumplimiento de caudales ambientales
		Otras:

- **Análisis de barreras a la adaptación**

Del análisis de las redes socio-institucionales, se derivan algunas conclusiones en cuanto a posibles barreras que pueden surgir en la aplicación de estrategias de adaptación:

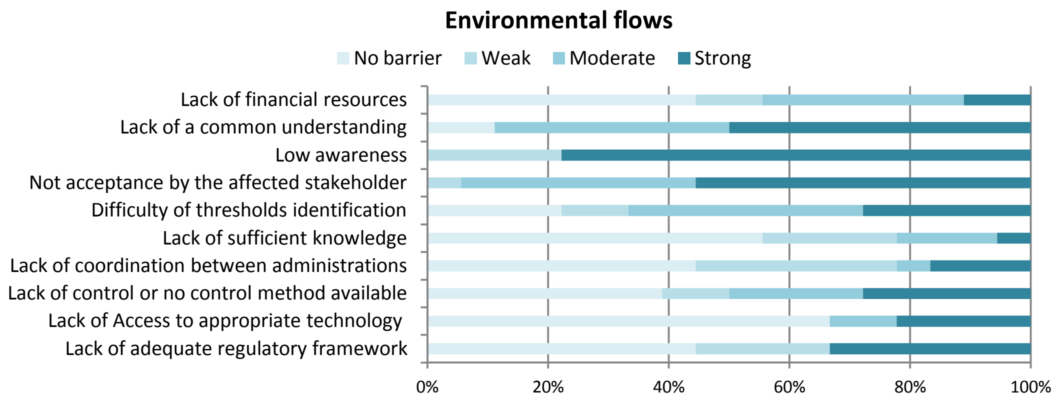
¿Podrías evaluar de 0 a 5 como afecta cada una de las barreras a las medidas de adaptación planteadas?

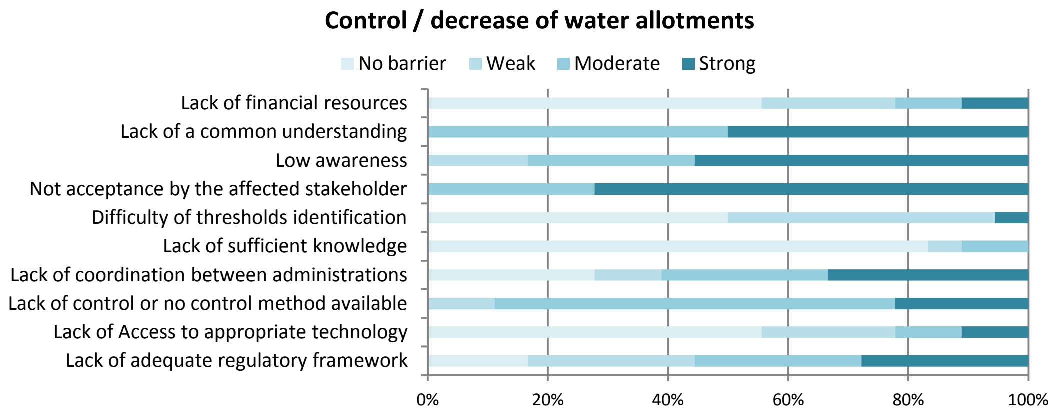
0 = no afecta nada 5 = es una barrera de máxima importancia para la aplicación de esta medida

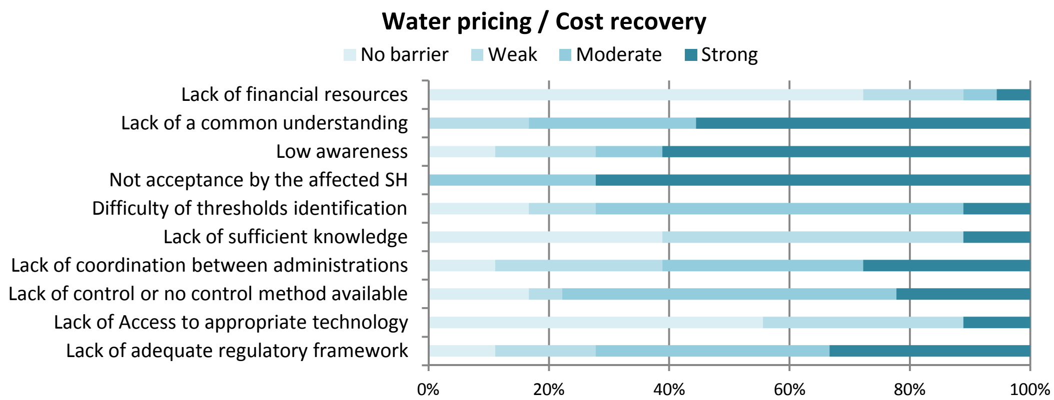
POSIBLES BARRERAS	Aumento de la capacidad de embalse	Control / disminución de cuotas	Tarificación / Recup. de costes	Cambio / adaptación de cultivos	Modern. Regadíos y distribución	Seguros agrarios	Caudales ambientales	Otra:
No hay leyes adecuadas o hay conflicto con las leyes actuales (I,F,C)								
No hay acceso a la tecnología necesaria (I,F,C)								
No hay control suficiente o no hay método de control disponible (I,F,C)								
No hay suficiente coordinación entre administraciones (I,F,C)								
No hay conocimiento suficiente (I,C)								
Dificultad para identificar los niveles adecuados de una determinada medida (I,C)								
No aceptación por parte del actor afectado (I,C)								
Bajo nivel de concienciación (I)								
No hay una visión o entendimiento común (I)								
No hay recursos financieros suficientes (F)								
Otra:								

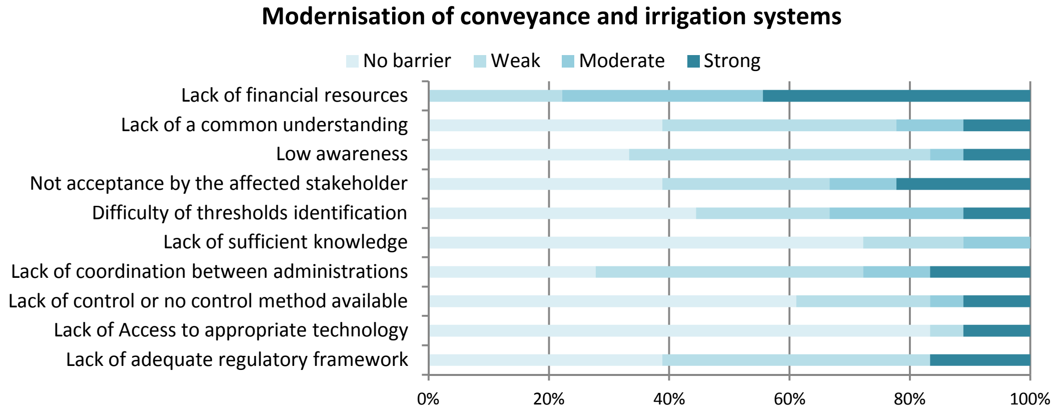
8.5 Annex E

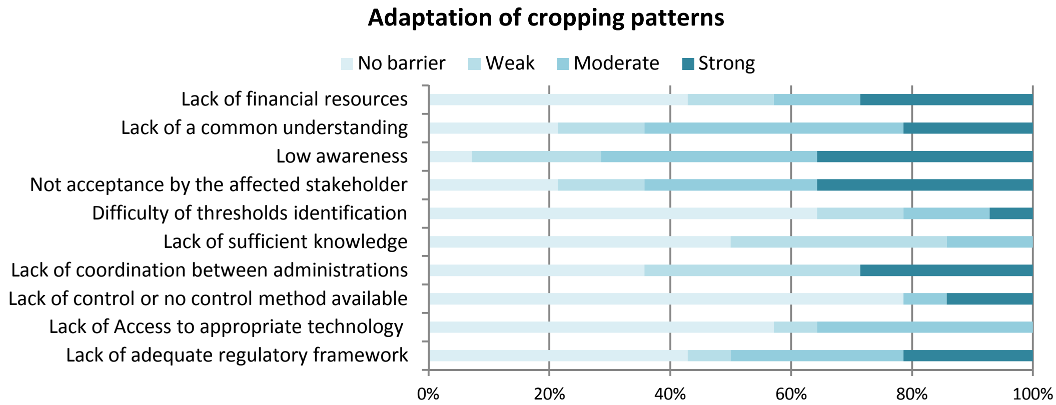
SH perceptions on the strength of barriers for the implementation of specific measures



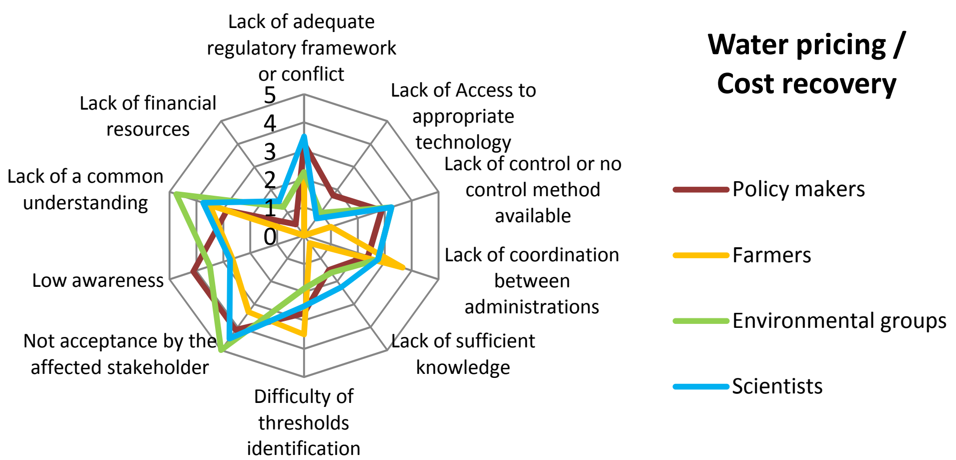


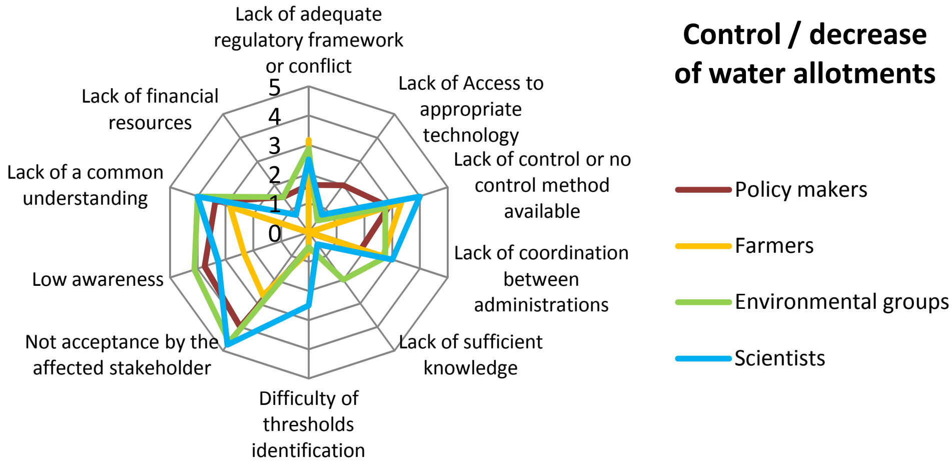


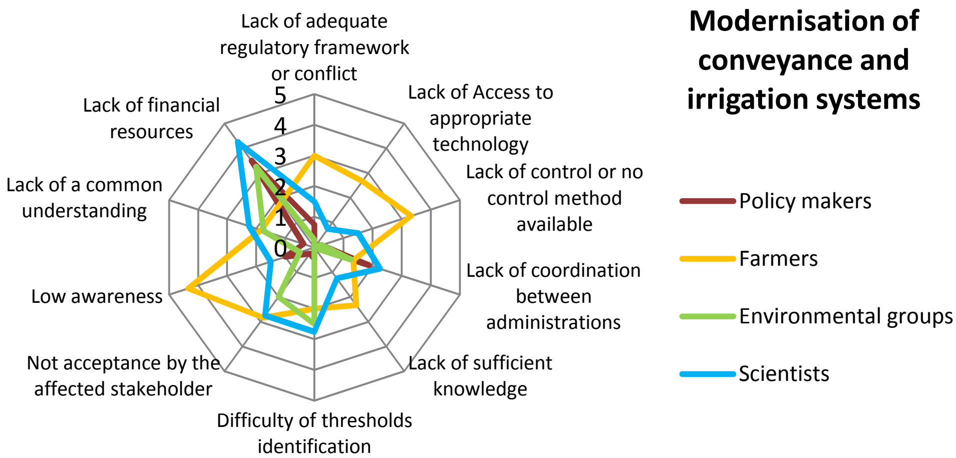


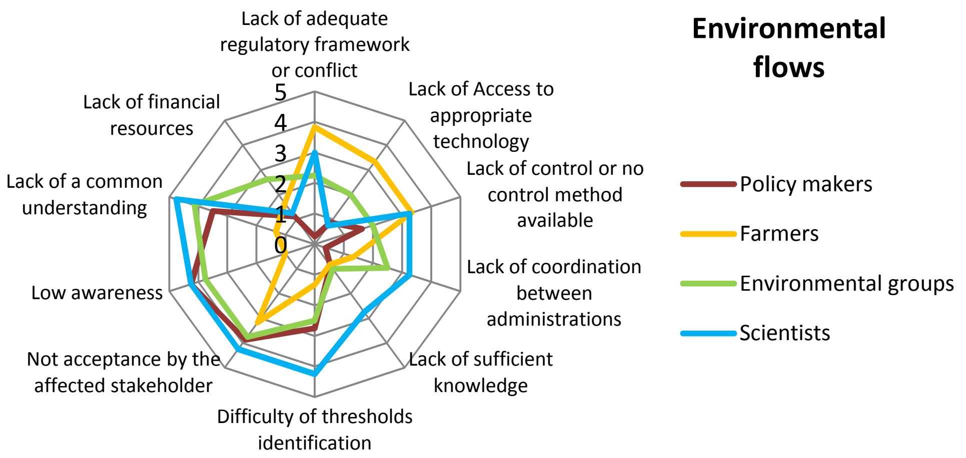


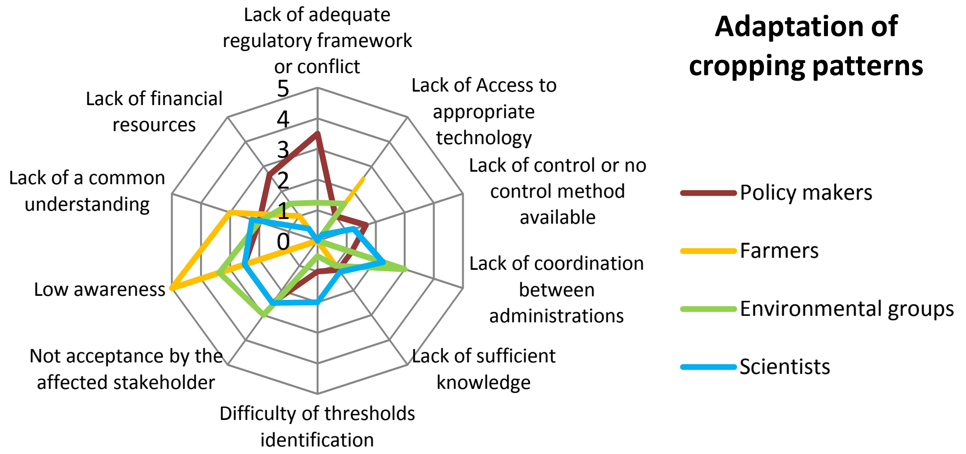
Strength of barriers for the implementation of specific measures – perceptions across groups




Lack of adequate regulatory framework or conflict
Lack of Access to appropriate technology
Lack of control or no control method available
Lack of coordination between administrations
Lack of sufficient knowledge
Difficulty of thresholds identification
Not acceptance by the affected stakeholder
Low awareness
Lack of a common understanding
Lack of financial resources
0
1
2
3
4
5
Control / decrease of water allotments
Policy makers
Farmers
Environmental groups
Scientists


Lack of adequate regulatory framework or conflict
Lack of Access to appropriate technology
Lack of control or no control method available
Lack of coordination between administrations
Lack of sufficient knowledge
Difficulty of thresholds identification
Not acceptance by the affected stakeholder
Low awareness
Lack of a common understanding
Lack of financial resources
0
1
2
3
4
5
Modernisation of conveyance and irrigation systems
Policy makers
Farmers
Environmental groups
Scientists


Environmental flows
Lack of adequate regulatory framework or conflict
Lack of Access to appropriate technology
Lack of control or no control method available
Lack of coordination between administrations
Lack of sufficient knowledge
Difficulty of thresholds identification
Not acceptance by the affected stakeholder
Low awareness
Lack of a common understanding
Lack of financial resources
5
4
3
2
1
0
Policy makers
Farmers
Environmental groups
Scientists


Adaptation of cropping patterns
Lack of adequate regulatory framework or conflict
Lack of Access to appropriate technology
Lack of control or no control method available
Lack of coordination between administrations
Lack of sufficient knowledge
Difficulty of thresholds identification
Not acceptance by the affected stakeholder
Low awareness
Lack of a common understanding
Lack of financial resources
5
4
3
2
1
0
Policy makers
Farmers
Environmental groups
Scientists