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IMPACT ATTRIBUTION MODELS TO EVALUATE DROUGHT EFFECTS: ECONOMIC IMPACTS, RISK ANALYSES AND MANAGEMENT STRATEGIES IN SPAIN AND CHILE

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RESUMEN

La sequía es un fenómeno natural que se origina por el descenso de las precipitaciones con respecto a una media, y que resulta en la disponibilidad insuficiente de agua para alguna actividad. La creciente presión que se ha venido ejerciendo sobre los recursos hídricos ha hecho que los impactos de la sequía se hayan visto agravados a la vez que ha desencadenado situaciones de escasez de agua en muchas partes del planeta. Los países con clima mediterráneo son especialmente vulnerables a las sequías, y, su crecimiento económico dependiente del agua da lugar a impactos importantes.

Para reducir los impactos de la sequía es necesaria una reducción de la vulnerabilidad a las sequías que viene dada por una gestión más eficiente y por una mejor preparación. Para ello es muy importante disponer de información acerca de los impactos y el alcance de este fenómeno natural. Esta investigación trata de abarcar el tema de los impactos de las sequías, de manera que plantea todos los tipos de impactos que pueden darse y además compara sus efectos en dos países (España y Chile). Para ello se proponen modelos de atribución de impactos que sean capaces de medir las pérdidas económicas causadas por la falta de agua.

Los modelos propuestos tienen una base econométrica en la que se incluyen variables clave a la hora de evaluar los impactos como es una variable relacionada con la disponibilidad de agua, y otras de otra naturaleza para distinguir los efectos causados por otras fuentes de variación. Estos modelos se adaptan según la fase del estudio en la que nos encontremos. En primer lugar se miden los impactos directos sobre el regadío y se introduce en el modelo un factor de aleatoriedad para evaluar el riesgo económico de sequía. Esto se hace a dos niveles geográficos (provincial y de Unidad de Demanda Agraria) y además en el último se introduce no solo el riesgo de oferta sino también el riesgo de demanda de agua. La introducción de la perspectiva de riesgo en el modelo da lugar a una herramienta de gestión del riesgo económico que puede ser utilizada para estrategias de planificación. Más adelante una extensión del modelo econométrico se desarrolla para medir los impactos en el sector agrario (impactos directos sobre el regadío y el secano e impactos indirectos sobre la Agro Industria) para ello se adapta el modelo y se calculan elasticidades concatenadas entre la falta de agua y los impactos secundarios. Por último se plantea un modelo econométrico para el caso de estudio en Chile y se evalúa el impacto de las sequías debidas al fenómeno de La Niña.

Los resultados en general muestran el valor que brinda el conocimiento más preciso acerca de los impactos, ya que en muchas ocasiones se tiende a sobreestimar los daños realmente producidos por la falta de agua. Los impactos indirectos de la sequía confirman su alcance a la vez que son amortiguados a medida que nos acercamos al ámbito macroeconómico. En el caso de Chile, su diferente gestión muestra el papel que juegan el fenómeno de El Niño y La Niña sobre los precios de los principales cultivos del país y sobre el crecimiento del sector.

Para reducir las pérdidas y su alcance se deben plantear más medidas de mitigación que centren su esfuerzo en una gestión eficiente del recurso. Además la prevención debe jugar un papel muy importante para reducir los riesgos que pueden sufrirse ante situaciones de escasez.

ABSTRACT

Drought is a natural phenomenon that originates by the decrease in rainfall in comparison to the average, and that results in water shortages for some activities. The increasing pressure on water resources has augmented the impact of droughts just as water scarcity has become an additional problem in many parts of the planet. Countries with Mediterranean climate are especially vulnerable to drought, and its water-dependent economic growth leads to significant impacts.

To reduce the negative impacts it is necessary to deal with drought vulnerability, and to achieve this objective a more efficient management is needed. The availability of information about the impacts and the scope of droughts become highly important. This research attempts to encompass the issue of drought impacts, and therefore it characterizes all impact types that may occur and also compares its effects in two different countries (Spain and Chile). Impact attribution models are proposed in order to measure the economic losses caused by the lack of water.

The proposed models are based on econometric approaches and they include key variables for measuring the impacts. Variables related to water availability, crop prices or time trends are included to be able to distinguish the effects caused by any of the possible sources. These models are adapted for each of the parts of the study. First, the direct impacts on irrigation are measured and a source of variability is introduced into the model to assess the economic risk of drought. This is performed at two geographic levels provincial and Agricultural Demand Unit. In the latter, not only the supply risk is considered but also the water demand risk side. The introduction of the risk perspective into the model results in a risk management tool that can be used for planning strategies. Then an extension of the econometric model is developed to measure the impacts on the agricultural sector (direct impacts on irrigated and rainfed productions and indirect impacts on the Agri-food Industry). For this aim the model is adapted and concatenated elasticities between the lack of water and the impacts are estimated. Finally an econometric model is proposed for the Chilean case study to evaluate the impact of droughts, especially caused by El Niño Southern Oscillation.

The overall results show the value of knowing better about the precise impacts that often tend to be overestimated. The models allow for measuring accurate impacts due to the lack of water. Indirect impacts of drought confirm their scope while they confirm also its dilution as we approach the macroeconomic variables. In the case of Chile,

different management strategies of the country show the role of ENSO phenomena on main crop prices and on economic trends.

More mitigation measures focused on efficient resource management are necessary to reduce drought losses. Besides prevention must play an important role to reduce the risks that may be suffered due to shortages.

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LIST OF ABBREVIATIONS

ADU: Agricultural Demand Unit

ARIS: Annual Relative Irrigation Supply

CAP: Common Agricultural Policy

CDF: Cumulative Distribution Function

CDI: Combined Drought Indicator

CGE: Computable General Equilibrium

CHE: Confederación Hidrográfica del Ebro

CLP: Chilean Pesos

DF: Distribution Function

DG: Directorate General

DMP: Drought Management Plans

EC: European Commission

ECHO: Humanitarian Aid and Civil Protection

EDMI: Economic Drought Management Index

EEA: European Environment Agency

EGU: European Geosciences Union

ENSO: El Niño Southern Oscillation

EU: European Union

FAO: Food and Agriculture Organization

FAPAR: Fraction of Photosynthetically Active Radiation Absorbed by the Photosynthesizing Tissue in a Canopy

GDP: Gross Domestic Product

GNP: Gross National Product

GVA: Gross Value Added

IO: Input Output

IPCC: International Panel for Climate Change

NDVI: Normalized Difference Vegetation Index

OECD: Organization for Economic Co-operation and Development

PDF: Probability Distribution Function

R&D: Research and Development

RBA: River Basin Authorities

RBMP: River Basin Management Plan

SAM: Accounting Matrix

SAMEA: Accounting Matrix and Environmental Accounts

SDMP: Special Drought Management Plan

SPI: Standardized Precipitation Index

SWAP: Statewide Agricultural Production Model

UN: United Nations

USA: United States of America

VIF: Variance Inflation Factor

WEAP: Water Evaluation and Planning System

WFD: Water Framework Directive

WMO: World Meteorological Organization

WS&D: Water Scarcity and Drought

WTA: Willingness to Accept

WTP: Willingness to Pay

Part I:

General introduction and literature review

1 INTRODUCTION

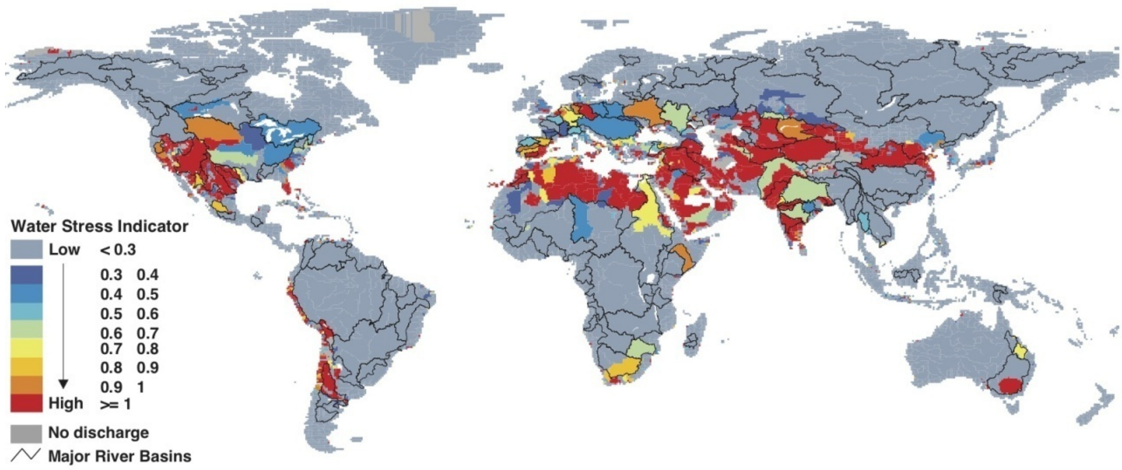
1.1 Problem's statement: droughts and water scarcity

Drought is a complex phenomenon that can be characterized in many ways, and therefore has multiple definitions. From a general perspective a drought can be defined as a natural hazard initially caused by abnormally low precipitations that result in an extended period of water supply deficiency (WMO 1975). The deficiency in water supply is measured as a drop below average or normal indicators. Therefore, drought's definition must be always related to normal conditions of a specific geographical area and within a time frame. However as normal can be understood in many ways, and may be misleading under non-stationary conditions, we can also talk about water scarcity, and assert that the problem is more related to the way water is being used with respect to water resources availability in general.

There are three general types of drought: meteorological, agricultural and hydrological (Wilhite and Glantz 1985) that can be complemented with the socioeconomic and environmental droughts defined by the American Meteorological Society (AMS Council 1997). Meteorological drought refers to a precipitation deficit over a period of time. Agricultural drought refers to water deficit for crop production, and it generally occurs when precipitation, water flows or soil moisture are insufficient to meet crops' requirements. Hydrological drought occurs when water levels in reservoirs, river flows or groundwater tables are reduced by the effect of prolonged periods of precipitation shortfalls. And, lastly, the socioeconomic and the environmental droughts are defined by their impacts. While the first one has its repercussions on society and on agricultural or non-agricultural activities such as tourism, recreation, urban water consumption and energy production, the second one threatens the ecosystems conservation.

Total available freshwater water on earth amounts to 55 thousand Km^3/year (renewable water), but its distribution is not regularly spread (Pacific Institute 2010a). From that amount of water around 70% is used for agriculture in Mediterranean climate countries (Pacific Institute 2010b). Vulnerability of the agricultural sector is relevant, and small variations of water availability could lead to critical shortages for agriculture and other purposes.

Map 1. Water stress indicator (Withdrawal to availability ratio: water withdrawals as the proportion of the balance of mean annual river flow and environmental water requirements)

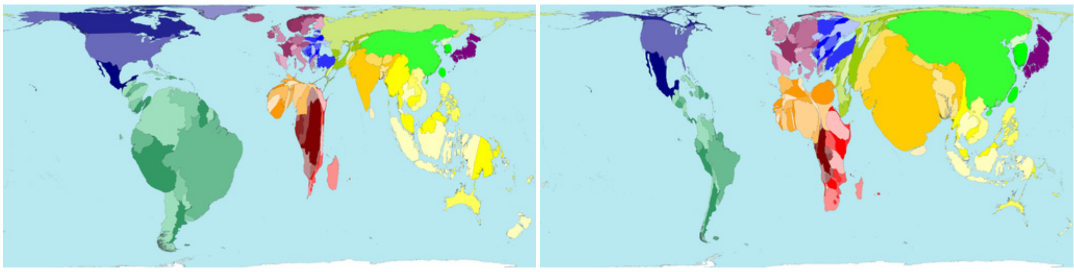


Source: Smakhtin et al. (2004)

Water shortages occur as a result of the unbalance between water supply and water demand (water resources and water uses), when there is not enough water to produce crops or for other uses, a variety of impacts is triggered. World Water Council (2012) characterizes water shortages through a water stress indicator. Map 1 highlights world regions by the proportion of water withdrawals with respect to total renewable resources around the world. With regard to countries with Mediterranean climate it can be seen how the stress ratio is high or very high, which indicates a structural problem of water scarcity, exacerbated in those countries where more agricultural productions are developed. Mediterranean-climate countries, like Spain or Chile (which are the concern of this research), use for agriculture 25.33 Km^3/year and 8.04 Km^3/year respectively (AQUASTAT 2009, Pacific Institute 2010b). Agricultural water use in Spain has been reduced by a 10% during the last ten years (Camacho 2012).

The University of Sheffield and the University of Michigan (2012) jointly developed a method to draw maps that graphically represent the relation between territory and water resources. They calculate the percentage of total freshwater showing that South America has the 30% of the total freshwater resources while Western Europe has the 4%, from total world resources (Map 2). However, the focus countries of this work have their water resources stored in very different ways, Chile has most of them as snow or ice reservoirs and therefore not easily available.

Map 2. World's water availability (left) and population (Right)



Source: Worldmapper (http://www.worldmapper.org/, U. of Sheffield and U. of Michigan)

The importance of the lack of resources to meet growing water demands is highlighted by the fact that economic activities share available resources with non economic ones. The increasing trend of drought occurrence due to both climate change (IPCC 2007) and increases in population (Wilhite 2005) makes extremely necessary to assess their impacts and consequences, and enhance adaptation strategies (Iglesias et al. 2007b). Furthermore, it is important to remark that, from the water management perspective, present water shortages may turn into an unacceptable risk in the near future (Iglesias et al. 2007c, Martin-Carrasco et al. 2012).

Water scarcity and drought are different phenomena though they are liable to aggravate the impacts of one another. In some regions, the severity and frequency of droughts can lead to water scarcity situations, while overexploitation of available water resources can exacerbate the consequences of droughts. Water scarcity occurs where there are insufficient water resources to satisfy long-term average requirements. It causes long-term water imbalances due to human and economic increasing water demands, it is therefore the result of the combination of low water availability with a level of water demand exceeding the supply capacity of the natural system. Droughts can be considered in contraposition as a temporary decrease of the average water availability due to changing climatic conditions and with no human-related action (European Commission 2012b). However, special attention has to be placed in the interrelations between those two phenomena that sometimes cannot be treated separately.

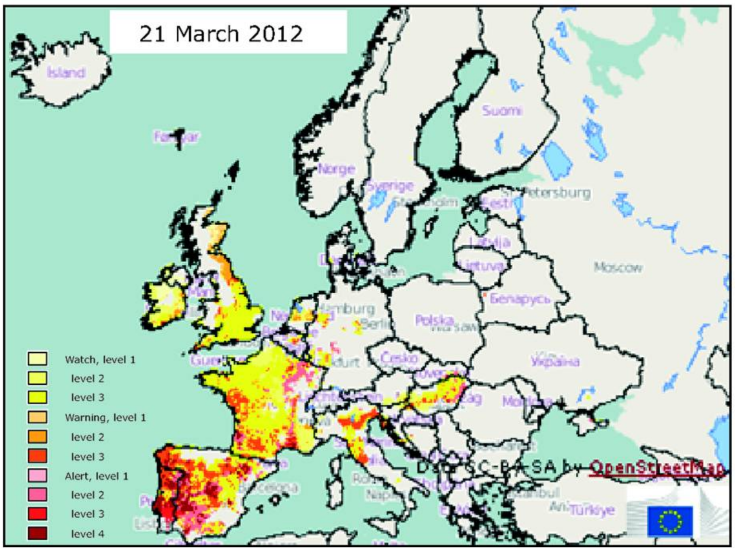
1.1.1 Droughts' importance relative to their impacts

Drought is a recurrent phenomenon (Wilhite and Glantz 1985) and a natural hazard that is a normal part of the climate of virtually all countries (Wilhite 2007), although Mediterranean climates are especially prone to extreme drought periods. Spain has suffered four significant and country-wide hydrological droughts since the beginning of systematic hydrologic monitoring (1941): in 1941-1945; 1979-1983; 1990-1995; 2005-2008 (MMA 2007), while in Chile drought has been the most common climatic risk faced between 1998 and 2008 (MINAGRI 2009, Báez 2010).

This recurrence demands that the attention be more focused on drought management and preparedness within water management strategies, just as how water scarcity for different uses amplifies the effects of drought periods. Water management has been traditionally designed to increase water availability, Gisansante et al. (2002) encountering increasing difficulties for the management of a limited natural resource. In the case of Spain water scarcity is partially produced by inefficient allocation of water resources (Lopez-Gunn and Ramón Llamas 2008, Aldaya et al. 2010, De Stefano and Llamas 2012), in spite of the amount of water reservoirs being quite large and drought policies quite mature. While drought consequences and problems in Chile are produced more by drought management rather than by water management, the latter is conducted by liberalized allocation mechanisms and rules that presumably achieve efficient uses (Bauer 2005, Donoso 2006). Drought and water scarcity are managed in Chile as an emergency situation, which does not necessarily contribute to decrease the vulnerability with no previous proactive strategies.

Map 3 shows the Combined Drought Indicator (CDI) for agricultural drought in Europe designed by the European Environment Agency (EEA 2012). This indicator measures the agricultural impact or damaged suffered on each analyzed area, and is based on the cause–effect relationships between rainfall deficit (Standardized Precipitation Index, SPI), soil moisture anomaly, and impact on the vegetation canopy anomaly (Fraction of Photosynthetically Active Radiation Absorbed by the Photosynthesizing Tissue in a Canopy, FAPAR). According to the severity of the recorded impact, a watch, warning, or alert is issued. The CDI is targeted to agricultural drought impacts. A precipitation shortage is reflected in a watch. When the rainfall deficit translates into a soil moisture deficit, it is reflected in a warning. Finally, when reduced vegetation production is identified an alert is issued. The Iberian Peninsula is shown for its high drought occurrence in March 21st.

Map 3. Map of drought conditions in Europe as calculated by the CDI (based on SPI, soil moisture and FAPAR) for March 2012



Source: EEA (2012) http://www.eea.europa.eu/data-and-maps/figures/mapping-of-drought-conditions-in-europe

Despite having adequate management strategies, droughts can cause impacts as a result of extreme and extended drops of precipitation. Droughts differ from other natural or induced disasters in two special features related to their impact: (i) droughts' spatial and temporal boundaries are not easily to delimit, and therefore their scope and relevance are difficult to anticipate (Kallis 2008, CCSP 2008, ISDR 2009, MEDROPLAN 2009) and (ii) a drought phenomenon definition is also difficult to delimit and therefore the impacts become also difficult to be isolated. Droughts propagate slowly in time and space, and thus their effects on the economy are difficult, but not impossible, to identify and quantify (Wilhite 1993).

Droughts and water scarcity can cause economic losses in key water-using sectors and have environmental impacts on biodiversity, water quality, deterioration and loss of wetlands, soil erosion, land degradation and desertification. Those negative impacts can be categorized into direct, indirect, tangible and intangible losses, all of them measurable in economic terms (see Chapter 3). Identifying an adequate definition for direct and indirect impacts is important for economic impact assessments because the bounds set by such definitions dictate the scope of impacts that may or may not be included (Ding et al. 2010). Furthermore, those impacts are directly or indirectly affecting society and systems inside and outside the areas prone to them.

In the last decades drought impacts have increased, its recurrence is more frequent and their impacts have also grown because economic development and growth was supported in water reliability, which obviously has not increase. In the European Union, between 1976 and 2006 the number of areas and people affected by droughts went up by almost 20% and the total costs of droughts amounted to 100 billion euros (European Commission 2012a). Increasing exposure of people and economic assets has been the major cause of long-term augment in economic losses from weather- and climate-related disasters (IPCC 2007). All these facts and the trend followed by the Mediterranean climates suggest that more efficient management strategies could accomplish significant impacts reduction.

Finally, to better inform policy makers, more knowledge must be generated. Drought assessments should be based on simpler, clear and transparent information to provide the best possible choices sustained in improved assessments. This is important as a principle of good governance, smart regulation and better law making (PREEMPT 2011). But also the financial and economic value of knowledge must be taken into account: (i) the financial value is referred to the hazard and risk assessment services, and (ii) the economic value to the identification of the factors affecting vulnerability or to the development of cost-effective and efficient risk mitigation solutions (Mysiak 2012). Quiroga Gomez et al. (2011) evaluate the economic value of information on drought events taking into account the risk aversion of water managers, and concludes that the availability information is relevant for the management responsible agencies and the farmers affected by their decisions. Therefore a balance needs to be found between knowing better and the opportunity cost, by the prioritisation of scarce resources, the identification of those most in need, the transparency and the environmental liability. That way a commitment of accountability for having better drought information and knowledge can be achieved.

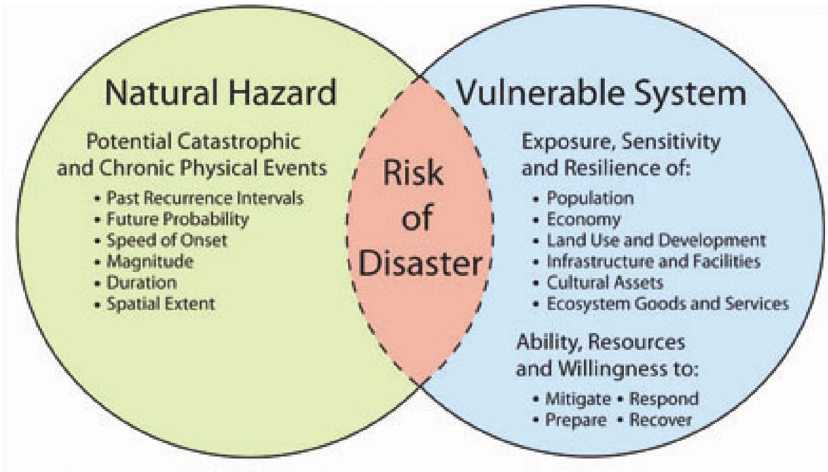
A better knowledge about past losses of droughts can inform measures for prevention, protection and preparedness, as well as response and recovery. Looking into the past to draw lessons learned for the future actions is useful, but surely the exact losses produced in the past would not translate into exactly the same losses into the future. However, the availability of the previous numerical estimations gives a range or order of magnitude, or at least the direction of changes.

1.1.2 Socio-economic Systems' vulnerability to droughts

Vulnerability to natural hazards is always framed with respect to the extent to which the system is susceptible to suffer negative impacts. Even though it has many definitions, researchers from the natural sciences tend to focus on the concept of risk, while those from the social sciences and climate change field often prefer to frame the issue in terms of vulnerability (Downing et al. 2003, Allen 2003). Since our work has the two components (social and natural) both meanings have to be taken into account. Vulnerability in the natural sciences is understood as the likelihood of impacts occurring as a result of weather and climate related events (Nicholls et al. 1999). From the social sciences perspective, it is represented as a set of socio-economic factors that determine people's ability to cope with stress or change (Allen 2003).

Figure 1 visually represents how risk is the result of the combination between being vulnerable and being exposed to a natural hazard. It also shows the characteristics that determine the intensity of the natural hazard, in this case droughts, and the characteristics of the system that makes the vulnerability vary and that influence the magnitude of the damage caused. According to the UN (2004), vulnerability is defined as the conditions determined by physical, social, economical, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards. Resilience is denoted as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and sustain an acceptable level of functioning and structure (UNISDR 2004). Vulnerability is a function of sensitivity, exposure and adaptive capacity or resilience to the natural disasters. Exposure is usually considered in terms of the position of the threatened system in relation to the position of the threat. Exposure in this sense can be understood as a geographical attribute (ENSURE 2009). Sensitivity is the degree to which a system is affected by natural disasters, whereas resilience or adaptive capacity is the ability of a system to adjust to natural disasters, moderate potential damages, take advantage of opportunities or deal with the consequences (IPCC 2001). Exposure and sensitivity are interrelated, and the adaptive capacity is similar to resilience.

Figure 1. Conceptual framework of risk, vulnerability and natural hazard



Source: USGS-ONHW Research collaboration, 2006

Vulnerability to drought in the Mediterranean regions is increasing because of socio-economic and technological changes that increase the pressure on its already structural water deficit situations and question the ability to maintain the current management philosophy (Iglesias et al. 2007c, De Stefano and Llamas 2012). In European Mediterranean countries also the environmental needs expected to be met by the WFD's mandate and some of the shared water in transboundary river basins has increased drought vulnerability (Iglesias et al. 2007b) together with the need to prioritize the uses. All of these reduce the availability of water for irrigation or urban water uses. PREEMPT project[1] (2012) has identified the main drivers enhancing or reducing the vulnerability to droughts in Spain and Italy (as an example of Mediterranean countries). It concluded that, excluding the characteristics of the event, the order of allocation priorities, that also reduces the use of water in times of drought, is the main factor enhancing vulnerability. Table 1 shows main drought drivers classified into five groups (biophysical, institutional, economic, social/community and infrastructural), and distributed according to which vulnerability parameter they influence the most.

[1] PREEMPT Project (2012). Policy-relevant assessment of socio-economic effects of droughts and floods. http://www.feem-project.net/preempt/

Table 1. Main drivers of drought and their effect on vulnerability

VULNERABILITY PARAMETER	BIOPHYSICAL	INSTITUTIONAL	ECONOMIC	SOCIAL/ COMMUNITY	INFRAS-TRUCTURAL
EXPOSURE	Drought characteristics: duration, extension, intensity & timing		Evolution of international commodity prices		
	Pre-hazard soil conditions		Dependence on local agricultural producers		
	Pre-hazard ecosystem health		Diversification of farm income		
	Reservoir storage		Importance of recreational activities		
SENSITIVITY		Agricultural policies & measures		Public awareness of water scarcity/ conservation	
EXPOSURE & ADAPTIVE CAPACITY	Groundwater availability	Water resources allocation			
ADAPTIVE CAPACITY	Type of land cover	Forecasting & early warning systems	Insurance coverage	Professional experience & know-how	Infrastructure maintenance (network losses)
	Type of agriculture	Basin & drought management plans	Financial & economic wealth	Environmental consciousness	Water source diversification
	Type of livestock production	Water (demand) management		Labor and age structure	Degree of regulation in basin
	Climate change	Land use planning		Social capital & social networks	Type of irrigation technology
		Institutional robustness & risk governance			

Note: Adaptive capacity can be assumed equal to Resilience
Source: PREEMPT Project Guidance Document (2012)

As it happens with the order of allocation priorities, institutional factors prevail among the ones on other categories, and therefore any impact assessment can be conducted to motivate institutional changes in order to reduce vulnerability. The institutional factors affecting the adaptive capacity (Table 1) can be transformed into useful tools to prevent drought impacts, such as forecasting, early warning systems or risk governance. The development of more comprehensive and integrated drought monitoring and early warning systems is an essential component of a more proactive, risk-based management system (Wilhite 2007). Regarding economic vulnerability, the forecasting of both macro- and microeconomic variables is a step to achieve economic risk management (Adams et al. 2002). Other important factor often mentioned by the competent institutions that is related to the projected decrease on water availability is the increase of use efficiency. According to the EEA irrigation efficiency can reduce irrigation water withdrawals to some degree but will not be sufficient to compensate for climate-induced increases in water stress (EEA 2012).

Therefore, vulnerability to droughts could be partially reduced by making more efficient use of water or by managing the main drivers of vulnerability. But to entirely face the challenge of reducing the vulnerability to droughts and shortages, to mitigate the impacts and to be able to recover with a relative ease, it is also necessary to generate applicable knowledge to reach a more sustainable situation in terms of water management. In this direction Varela-Ortega et al. (2007) indicate the need of the integration of more realistic vulnerability analysis into water resource planning.

1.2 A missing element within policies: drought risk management approaches

Countless studies have been developed to enhance the understanding of droughts, but not many attempted to obtain accurate evaluations of the impacts on the economy. Drought impacts can be measured in different ways, economic estimations have been made through different approaches and they will be reviewed and explained in detail in Chapter 3 of the thesis. And yet, these studies continue to highlight shortcomings, especially in connection to the real impact of droughts with coherent estimations of agricultural outputs.

Although there is a growing concern on the risk of running unbalances between water supply and demand, and to the extent to which they affect society, drought management is still a challenge for many regions of the world. Despite numerous efforts to develop policy strategies that mitigate or prevent drought impacts and risk, significant knowledge gaps persist.

In 2007 a Communication on Water Scarcity and Drought (WS&D)[2] was adopted by the European Commission to be reviewed in 2012. Seven main policies addressing efficient use of water resources were identified: (i) putting the right price tag on water,

[2]European Commission (2007a). Communication to the European Parliament and the Council–Addressing the challenge of water scarcity and droughts in the European Union, 2007, COM/2007/04141 final, Brussels.

(ii) allocating water and water-related funding more efficiency, (iii) improving drought risk management, (iv) considering additional water supply infrastructures, (v) fostering water efficient technologies and practices, (vi) fostering the emergence of a water-saving culture in Europe, and (vii) improving knowledge and data collection. In 2012 the need of enforcing those strategies supporting further policy development was highlighted (EC, 2012).

The 2012 Report[3] shows how Member States of the European Union are implementing some strategies identified in the WS & D 2007 Communication. It also mentions the role of the Water Framework Directive (WFD) in contributing to the management of water in terms of reducing drought vulnerability. Although water tariffs are listed as an important issue concerning water scarcity, and they are calculated with the aim of setting right prices to the resource by taking into account the cost recovery, it is not clear how effective they are in combating drought impacts. Although some authors have been highlighting the efficiency of water pricing in water scarce countries (Varela-Ortega et al. 1998) from over a decade ago, not many results have been seen in the practice. Currently, as the WFD is implemented primarily by means of River Basin Management Plans, it must be part of drought policies (European Commission 2012a).

Common Agricultural Policy (CAP) also includes measures to reduce water scarcity and drought vulnerability. Two mechanisms can be specially mention to this aim: (i) cross compliance integrates water quantity and efficiency aspects in irrigation projects and (ii) direct payments are proved to be a rent stabilizer that reduces farmers' vulnerability to reduced yields (PREEMPT 2011, CONHAZ 2012). The reform of the CAP post 2013 is still under discussion.

Concerning water allocation mechanisms that tend to alleviate the conditions of those basins or areas where water scarcity is more severe, Chile is at the forefront with one of the most developed water markets in the world (Bauer 2005). And Spain is the only country in Europe where trading water use rights with a diversity of informal and formal trading mechanisms is possible (Garrido et al. 2012, European Commission 2012a).

[3] European Commission (2012a). Report on the Review of the European Water Scarcity and Droughts Policy

Risk management is considered one of the major weaknesses of current drought policies (Bakker 2012). Iglesias et al. (2007a) provided the essential guidelines to develop adequate drought management plans in some Mediterranean countries, especially in Spain. They put the emphasis in a robust system of indicators that can provide information for early detection of drought episodes. They placed relevance to drought monitoring as a network of interrelated issues and pre-specified drought mitigation measures.

A Spanish National Drought Indicator System and Drought Management Plans were approved in 2007 have been put in place. They represent strategic tools with positive results in drought warning and impact mitigation (Estrela and Vargas 2012). The indicators are used for foreseeing different water scarcity situations and to establish thresholds according to the drought intensity and therefore to accordingly develop mitigation actions. But most of the indicators have limited knowledge on different water sources apart from surface ones. This leads to a bias because most of Spanish irrigation areas depend on water diversification for irrigation.

Besides this, drought indices must incorporate the economic perspective to reduce the vulnerability. If losses are measured in economic terms, then the vulnerability of the water dependent sector would be measured in those terms too. Iglesias et al. (2007d) developed an Economic Drought Index (EDMI) to assist water managers in their reservoir allocation decisions by evaluating different institutional arranges. As it is based on an optimization model, it becomes unsuitable to be used as an early warning system that faithfully represents the reality. EDMI is a performance indicator that suggests courses of action, but does not provide ex-ante economic impacts. However the design of similar approaches is coherent with early warning efficient systems.

Risk assessment must be implemented to reduce negative impacts of drought. But if the impacts are not correctly assessed then the strategy may fail. Although there have been efforts to economically assess drought impacts, there is still missing an accurate methodology to clearly identify which part of the loss is attributable drought, to which extent the losses are produced by the lack of water and what other sources are responsible for the remaining fluctuation of key economic variables. For this aim it is very important to establish a link between quantitative drought indicators and concrete measures (Iglesias et al. 2007a).

The implementation of risk management has been a challenge in all drought affected regions. In 2007 Chilean Agricultural Ministry fostered the development of a "Risk Management Unit" that assessed the possibility of developing vulnerability maps all over the country and to encourage the outsourcing of drought risk by augmenting food markets size and by diversifying agricultural activities (INDAP 2009). But eventually many of the proposals were not carried out, and as a result there still is a lack of strategic measures in contrast with the predominance of reactive measures.

In order to set policies in the correct direction, it is also very important to distinguish both the sectors mostly affected and the cause of the impact. Drought-induced losses cause negative supply shocks, but the amount and distribution of economic losses depend on the market structure and the interaction between supply and demand of agricultural products (Ding et al. 2011).

A set of complementary reports also concluded that there is a need of better implementation and integration of water policy objectives. A report of the European Commission assessing the rationale to safeguard Europe's water resources (European Commission 2012c) according to the review of the Commission assessment of the Member States River basin management Plans (RBMPs) and some reports on Water Scarcity and Drought policies conform with such reports.

Under current implemented policies, Varela-Ortega et al. (2011) posed the conflict between irrigated agriculture and ecosystem conservation. By analyzing different scenarios they conclude that drought prone countries like Spain are being led to overexploitation of groundwater. This kind of studies highlights also the importance of considering both economic and environmental impacts in the design of drought policies.

Finally it is important to mention that in all possible scenarios, where climate change may (IPCC 2007), or may not (Sheffield et al. 2012), alter drought consequences by increasing its occurrence and intensity, it is a phenomenon with which both developed and developing countries have to deal.

2 OBJECTIVES, OUTLINE AND RESEARCH CONTEXT

2.1 Objectives

The general objective of this thesis is to carry out a thorough study of the socio-economic impacts of drought, including a global and complete view of their impacts, risks and political and management implications. Associated with this overall objective there are other specific goals that are presented in this chapter. These specific objectives can be classified according to five main groups: (a) the general conceptual framework of the thesis; (b) the econometric models that are the basis of the methods applied; (c) objectives related to the measurement of impacts and risks; (d) the set of objectives related to some insights from the analyses, particularly the ones concerning the differences management and policies; and lastly, (e) the differential lessons one can draw from the study of two distinct geographical and institutional contexts: Chile and Spain.

a) Objectives related to the overall conceptual framework

- The thesis attempts to **contribute with information and insight on droughts' socio-economic impacts and consequences**. The work describes social and environmental consequences and performs risk analyses of that natural hazard, extending the risk evaluations to the economic performance. All this information may be useful for policy makers and water managers, in order to assist them when taking decisions on water allocation issues, and when planning drought responses and preparedness, as well as risk in management strategies.

- The problem of **drought and water scarcity** will be posed, putting special emphasis on the Mediterranean climate. IPCC (2007), Iglesias et al. (2007c) and many other researchers have suggested that there might be increases on the frequency and intensity of droughts in the regions characterized by this type of climate[4]. The thesis, thus, responds to the need of having more information about this phenomenon and its consequences on these regions.

- With the aim of improving the available information and of expanding the knowledge about drought impacts, it is also fundamental to clearly identify and differentiate between **direct, indirect, tangible and intangible impacts**. Climatic natural hazards like droughts cause direct impacts as a result of not being able to meet all regular water demands (Wilhite 2005). These direct impacts can be transmitted to other interrelated sectors, whose impacts can be measured in economic terms and job losses. Therefore within this objective, our work will identify and assess what methodologies have been commonly used to measure and describe those impacts.

- After thoroughly reviewing the impacts, **knowledge gaps must be identified**. The areas where impacts have not been assessed, or where estimations are not sufficiently accurate will be identified and brought into focus. The implications of these gaps will be extended to risk analysis and management strategies.

- All the previous objectives are going to be reached by developing a theoretical and empirical framework to analyze **the scope of droughts** in different sectors and different geographical areas. This framework is going to be provided by both previous literature and the author's own contributions. The **methodological framework** of the thesis will be oriented to three main issues: economic impacts, risks, and drought management.

b) Objectives related to the methods

- With respect to drought impacts, a general approach will be developed to evaluate the economic impacts of drought. The formulation of **econometric models** that permit the identification of the economic, hydrological and climatic factors particularly affecting the agricultural sector under water deficit situations will be posed, and statistically fitted. Those models must be simple and general

[4] A very recent article by Sheffield et al. (2012) seems to refute the conclusion that droughts will be exacerbated as a result of climate change.

enough in order to be useful and applicable at different levels and different sectors.

- The main objective related to the econometric models is the **attribution of drought effects on the economy**. This requires an approach that is capable to represent the linkages between drought and observed economic losses. This linkage must reproduce the real, or at least an accurate, relation between decreases in water availability and decreases in economic outputs, thus establishing statistically proven causality relations.

- To measure different types of drought impacts (direct, indirect, and at different scenarios) it is required to **identify the main water explanatory variables** to be used in the econometric models for each application performed in this thesis. This process will take into account the type of agriculture that is going to be assessed, the available information and data, and the management implications of the water variable to be used.

- The proposed models must permit also assessing and comparing the impacts of water scarcity and water shortages at **different levels of influence**, including the evaluation of direct impacts at a river basin, the province or the irrigation district levels in Spain, or at the sub-basin level in Chile.

- The models must allow for differentiating the impacts of drought from the impacts caused by different sources. The **prices of products and production trends** will be used to identify whether the market fluctuations and the structural changes in a given sector covariate with the interested economic performance. In addition to the models' error terms, water availability will be capturing the remaining unexplained variance, thus accomplishing a major goal of the thesis.

- A final specific objective is to **integrate the econometric models into risk management models**. For this aim, the intrinsic variability of hydrologic variables will be introduced into the impact attribution models. A tool, based on Monte-Carlo simulations, will be developed to evaluate the probability of suffering losses on each application performed on this study.

c) Objectives related to the measurement of impacts and risks

- The thesis attempts to **measure in economic terms** the direct and indirect impacts of water shortages on the agricultural sector by using the proposed econometric approach. This measurement should provide a range of values where past drought events have had their impacts and therefore it might provide information in order to take either preventive or reactive measures to cover drought losses.

- Since direct and indirect impacts will be identified, it is very important to analyze how the impacts of water scarcity **are transmitted across the economy**. The analysis of transmission of supply shocks between primary production and the processors of those productions provides relevant insights to assess vulnerability of each sector in different geographical contexts.

- Once economic impacts are measured, the need of risk assessments will be justified by developing methodological frameworks to measure **water availability risk and water demand risk** under water uncertainty situations. Those risk profiles for each application made in the thesis are used to transform the hydrologic risk into potential economic losses attributable to that sort of risks. This should provide the basis for sound drought risk management and the development of risk-sharing and risk-transferring mechanisms.

- To perform **ex – ante simulations** of the possible direct economic impacts of drought to evaluate the risk posed by farmers. For this aim, the methodological framework that provides the tools to evaluate risk will be used and the results will be given in probability terms.

d) Objectives related to the management and policy strategies

- With respect to some of the practical applications of this work, certain aspects of different policy performances can be analyzed. Therefore the first objective included in this category is to analyze and evaluate **water and drought management** through the different case studies. This analysis would allow for determining which factors influence more the final economic impacts of drought events.

- The overall results of this research are focused on giving emphasis to the **difference between droughts and water scarcity**, which is required to reach the clearly identification of either droughts or water scarcity effects.

- Some of the findings will help in assessing economic, social and environmental **vulnerability** to drought and water scarcity as well as to evaluate the risk profiles produced by the differences in vulnerability between the different case studies analyzed.

- Final statements are used to assess current efficiency of **drought measures** and to propose possible **policy alternatives** to mitigate drought impacts and to achieve better levels of adaptive capacity to face droughts.

e) Objectives related to the empirical contexts

- The geographical scope of the thesis takes an important role in defining the final group of objectives. First of all there is an aim to **analyze drought in different geographical areas** and to compare the impacts obtained at these different locations.

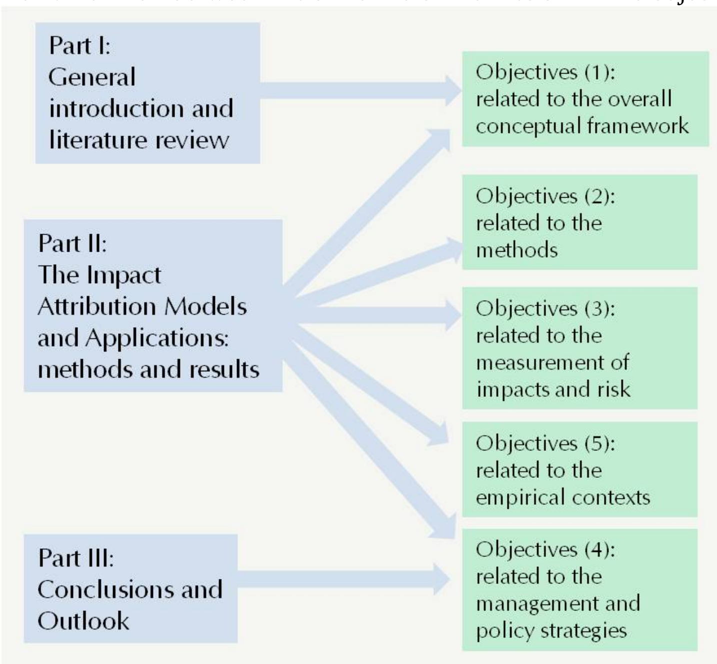
- Different geographical areas provide different climatic and policy scenarios. By setting out a methodology to assess drought losses in Spain and in Chile, the context differences are tested. **Hydrological droughts** are the main type of drought to be analyzed in Spain, while **agricultural droughts and El Niño Southern Oscillation** effects are the main objective of analysis in Chile.

2.2 Thesis Outline

This thesis is structured in three parts: the first part (Chapters 1, 2 and 3) serves as an introduction and literature review, containing the problem's statement and the review of drought impacts models (direct, indirect, tangible and intangible). Part II (Chapters 4, 5 and 6), which is the longest of the thesis, contains its main conceptual and empirical contributions, explains the methodological approaches along with the results obtained for each application proposed and some specific conclusions for each application. And Part III (Chapter 7) summarizes the overall conclusions of the thesis along with some political recommendations obtained from the study.

Figure 2 provides an overview of the relation between the listed groups of objectives and the structure of this research. The first part of the thesis is basically related to the first group of objectives, since it will provide the overall conceptual framework of this work. Part II is basically focused on the second group of objectives, the ones related to the methods, but it also shares objectives with the first group, the third and the firth ones. Finally the concluding part (Part III) will mainly summarize the objectives collected in the third and fifth groups.

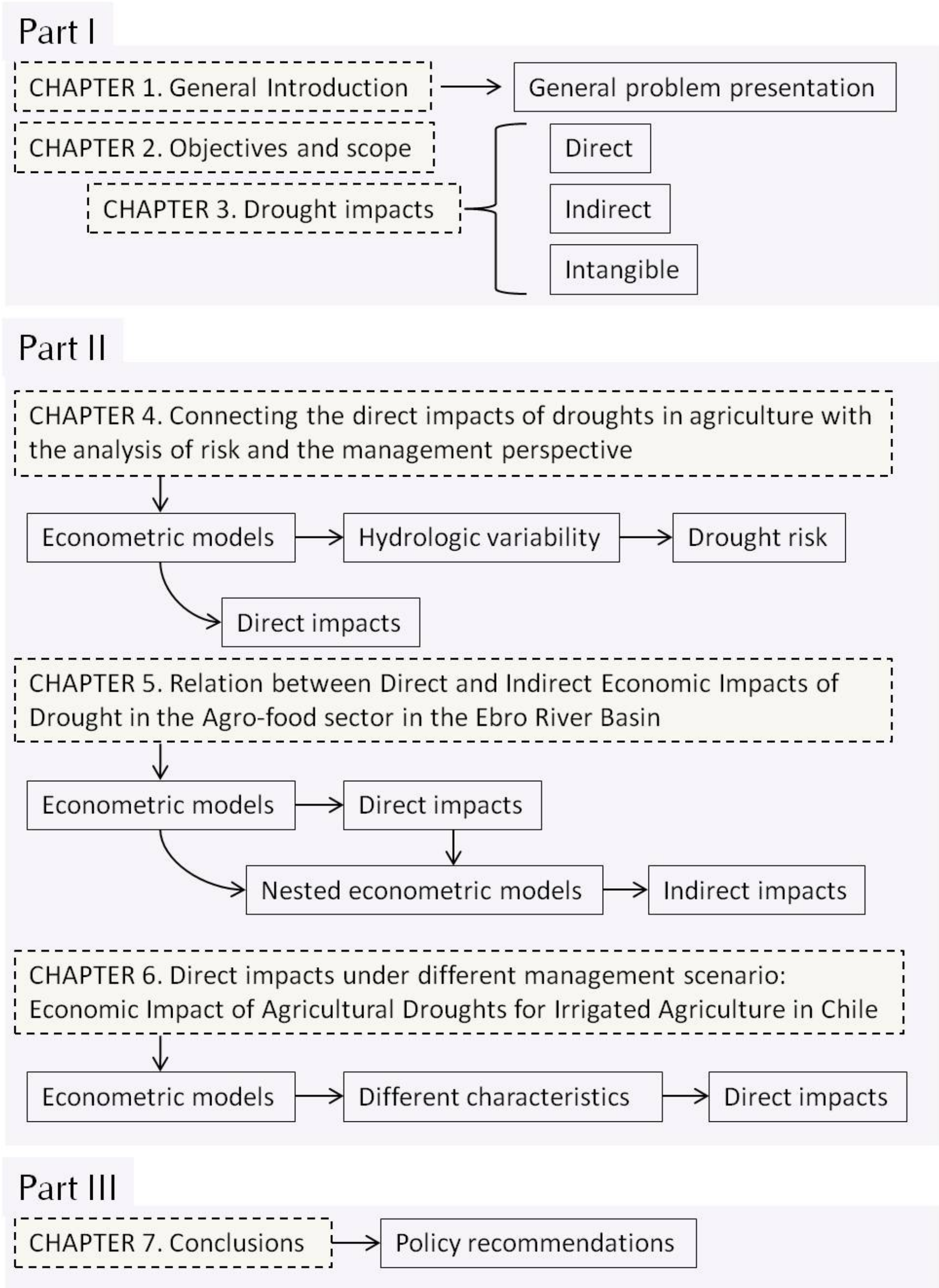
Figure 2. Relation between the structure of the thesis and the objectives



Source: Own elaboration

Figure 3 visually relates the three parts of the thesis with their chapters and the keywords describing its contents. Part II contains three applications of the econometric models proposed on this study. The first one (Chapter 4) uses the econometric models to both measure the attribution of drought direct impacts and to calculate the losses suffered by irrigated agriculture. The risk is calculated at two different geographical levels (provincial and irrigation community, in Spain). The second application (Chapter 5) measures the direct impacts on agriculture (through the impact on irrigated and rainfed productions) and the indirect impacts on the Agri-Food industry and on employment. This application also uses econometric models formulated at two steps, one for the direct and the second one for the indirect. The last application (Chapter 6) uses the econometric models to measure the relation of water shortages and economic outputs of irrigated agriculture under a different policy and climatic scenario for the case of Chile.

Figure 3. Thesis outline



Source: Own elaboration

2.3 Research context

This thesis is the result of the author's involvement in various research projects in Spain and Chile in the course of five years, starting in 2008. These research periods do not overlap perfectly with the thesis' parts and chapters, as some of its results were first developed and stopped, and the taken in a subsequent period.

In the **first stage** the author worked in the Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM), a R&D Research Centre of the Universidad Politécnica de Madrid, in a Spanish research project called "*Análisis económico de los planes de sequía*" (Economic analysis of Drought Management Plans) funded by the General Directorate of Water of the Ministry of Environment of Spain (Project OTT number P070220C106). The project run from January 2008 until January 2010 and the main researcher was Prof. Alberto Garrido. Prof. A. Gómez-Ramos, from the University of Valladolid worked in this project, and the team was assisted by Josefina Maestu and Teodoro Estrela, senior officers in the Ministry of Environment, during the project execution. This project aimed to assess the economic drought impacts on the most important Spanish River basins. At that time the Drought Management Plans were being developed and there was a need of filling the economic gaps the Ministry thought they contained. This objective set the motivation for the starting point of the thesis, as there was a need for better measurement of the impacts as well as the need of knowledge enrichment. The Ministry had the need to enhance its knowledge on drought impacts on irrigated agriculture, and the project helped in developing initial impact attribution models, which were expanded, improved and data updated in the author's third stage.

After that, the **second stage** began with a research stay funded by the Agencia Española de Cooperación Internacional para el Desarrollo (Spanish Agency for International Development Cooperation, AECID) in the Pontificia Universidad Católica de Chile under the supervision of Prof. Guillermo Donoso Harris. The investigation title was: "*Evaluación del impacto económico de las sequías en Chile: una comparación entre España y Chile*" (Economic impact assessment of droughts in Chile: a comparison between Spain and Chile) and was developed between January 2010 and September 2011. The aim of this project was to measure drought impacts under two main different factors in comparison to Spain: these factors were (i) El Niño Southern Oscillation, as the natural hazard threatening the region, and (ii) the different institutional and policy implications of Chile´s water and drought management. During the research an assessment of irrigation water needs was made for the World Bank, and the data obtained was introduced into the study to improve drought impacts assessment. In the context of this project, the author contributed to the Red de Expertos en Sequía (Drought experts' network) from the Centro del Agua para Zonas Áridas y Semiáridas de América Latina y el Caribe (Water Center for Arid and Semi-Arid Zones in Latin America and the Caribbean).

The last and **third stage** was developed within a European Project titled "*Policy relevant assessment of socio-economic effects of droughts and floods (PREEMPT)*", European Commission, DG Humanitarian Aid and Civil Protection – ECHO [grant agreement 070401/2010/579119/SUB/C4] Leaded by Dr. Jaroslav Mysiak from Fondazione Eni Enrico Mattei (Venice, Italy), under the coordination of Alberto Garrido for the CEIGRAM-UPM team, formed by Nuria Hernández-Mora, Roberto Rodríguez Casado and the author. PREEMPT is a policy directed assessment exercise, setting to assist the relevant authorities to better appreciate the risks posed by droughts and floods. It does so by collecting the data about past disasters, filling-up the knowledge gaps – in particular about indirect and intangible losses, both economic and social ones, and by improving risk assessment methods and approaches in place in four participating countries: Italy, Spain, Belgium and Germany. CEIGRAM-UPM team focused on the Ebro basin. The main objective of this project is to collect, harmonize and improve data about past drought events. This project gave a global view for the thesis framework, highlighting the importance of drought impact analyses and including an accurate characterization of the impacts.

2.4 Thesis publications

Chapter 3 forms part of the paper:

Nuria Hernández-Mora, Marina Gil, Roberto Rodríguez and Alberto Garrido. (2013) A Comprehensive Assessment of the Socioeconomic Impacts of Droughts: The 2004-08 drought in the Ebro River basin, Spain. In preparation.

Chapter 4 have been published in different parts and scope in

Gil, M., A. Garrido and A. Gómez-Ramos (2010). How to link agricultural productivity, water availability and water demand in a risk context: a model for managing hydrological risks. *Spanish Journal of Agricultural Research*, 8 (2). 207-220.

Gil, M., A. Garrido and A. Gómez-Ramos (2011). Economic analysis of drought risk: An application for irrigated agriculture in Spain. *Agricultural Water Management*, 98, 823-833.

Chapter 5 gave rise to the following paper:

Gil, M., A. Garrido and N. Hernández-Mora (2013). Direct and Indirect Economic Impacts of Drought in the Agri-food sector in the Ebro River Basin (Spain). Submitted to *Natural Hazards and Earth Systems Sciences* to be part of the Special Issue "Costs of Natural Hazards", and presented in the EGU General Assembly 2012.

Chapter 6 gave rise to the following paper:

Gil, M. and G. Donoso (2012). Economic Impact of Agricultural Droughts for Irrigated Agriculture in Chile. Presented to the *III Congreso Regional de Economía Agraria* in Valdivia, Chile (9-11 November 2011). And now is under review by the authors to be submitted to a Journal.

Other author's publications are:

Gil, M., A. Garrido and A. Gómez-Ramos. (2009). Análisis de la productividad de la tierra y del agua en el regadío español. In Gómez-Limón, J.A., J. Calatrava, A. Garrido, F.J. Sáez y Á. Xabadia (Eds.). *La economía del agua de riego en España*. Fundación Cajamar, Almería, Spain. 95-114.

Garrido A., M. Gil. and A. Gómez-Ramos (2010). Disentangling the social, macro and microeconomic effects of agricultural droughts: An application to Spanish

irrigated agriculture. In: Options Mediterranéenes and CIHEAM (Editors), *Economics of Drought and Drought Preparedness in a Climate Change Context*, Zaragoza, Spain. 149-158.

3 REVIEW OF DROUGHT IMPACTS

This chapter contains a review of drought impacts and the methodologies commonly used to assess them. The chapter distinguishes between direct and indirect impacts, as well as between tangible and intangible effects. For those easily measurable in economic units, another distinction is specified differentiating among micro- and macroeconomic impacts. The chapter begins with a discussion about conceptual difficulties associated with impacts' assessments and continues with the review of the methods.

3.1 Conceptual difficulties surrounding the evaluation of drought economic impacts

The economic assessment of drought-induced losses is a difficult and ongoing topic that involves the intrinsic complexity of the natural hazard and countless methodological challenges regarding the attribution of water supply shocks. Most of the studies have been carried out in the United States and in Australia, although there has been a renewed interest in the EU, especially since the publication of the 2007 EC Communication of Water Scarcity and Droughts, and significant funding effort in the Scientific Framework Programmes. In Mediterranean countries, like Spain, severe droughts are generally followed by renewed political interest in learning about the impacts and improve preparedness and planning[5]. Therefore, a complete estimation of the losses with reliable information, regarding the real scope of droughts has become a high priority to inform mitigation and risk management policies in Spain, Europe, and in Chile.

Bridging the knowledge gaps requires an improved understanding of society's exposure and vulnerability, which are key determinants of droughts risk and impacts. However, our knowledge in this area is partial and limited, and subject to methodological issues and considerable data limitations. Although it is often claimed that the economic losses associated with climatic risks in general, and drought in particular, have increased in the

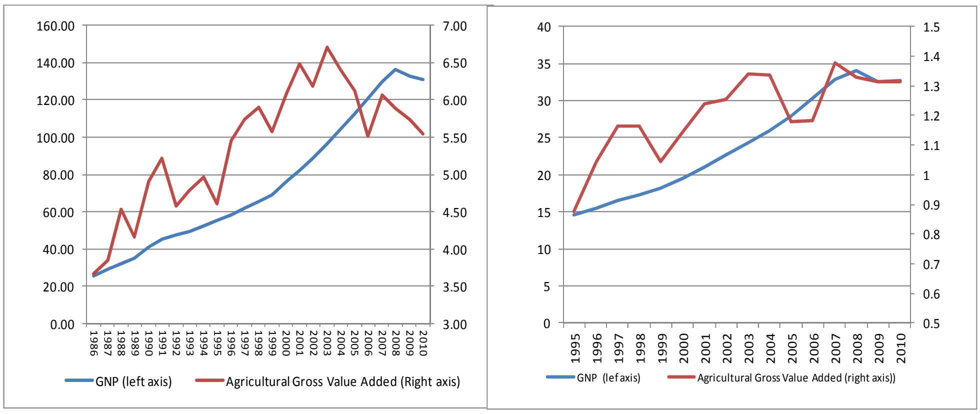
[5] See projects Medroplan, DEWFORA, Xerochore and PREEMPT (listed in the references of this document). The EU Communication on Water Scarcity and Drought 2012 recognizes the need to 'know better'.

recent past (European Commission 2012a), there is very little guidance from the literature about direct costs even on direct water user sectors such as agriculture or hydropower generation, and hardly in any other sectors or non-market services.

Droughts impacts evolve slowly and follow uncertain propagation processes in the time-space dimensions (Tallaksen and Van Lanen 2004, Wilhite et al. 2007). It is known from numerous previous works that the socio-economy responds to water scarcity, adjusting to reduced water availability (Iglesias et al. 2003, 2007d). In advanced and industrialized economies, the macro-economic effects of a drought, even at the regional or provincial level, is almost indistinguishable within the normal variation of GNP and employment. However, the European Commission, for instance, claimed that "*Over the past thirty years, droughts have dramatically increased in number and intensity in the EU. The number of areas and people affected by droughts went up by almost 20% between 1976 and 2006. One of the most widespread droughts occurred in 2003 when over 100 million people and a third of the EU territory were affected. The cost of the damage to the European economy was at least € 8.7 billion. The total cost of droughts over the past thirty years amounts to € 100 billion. The yearly average cost quadrupled over the same perio*d" (European Commission 2007a). Logar and van den Bergh (2012) summarizes the most of the existing literature on droughts impacts, and show that drought impacts in the EU typically represent less than 0.5% of GDP on the European Union.

Graphical evidence is shown in Figure 4, and has been documented by Garrido et al. (2010). The right panel in Figure 4 reports total economic activity and Agricultural Gross Value Added in constant Euros (1986-2010) for the region of Andalusia (representing about 13% of Spanish GNP), showing the impacts of the 1994-95 and 2005 droughts in the Agricultural sector, and no impact in the region's GNP. In the case of Aragón, left panel (representing about 3% of Spanish GNP), the drought of 2004-2007 is clearly marked in the reduced turn-out of the primary sector (Agriculture, livestock and fisheries), but literally unnoticeable in the Gross National Product of the region. In both regions the economic recession began in 2008 as clearly shown in the figure.

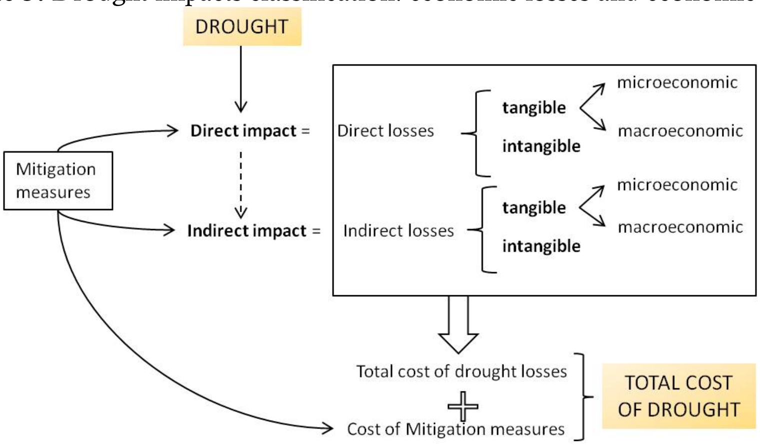
Figure 4. Total GNP and Agricultural Gross Value Added in (constant billion €, referred to year 2005) of Andalusia (Right) and Aragón (Left), deflated with inflation index)



Source: INE (various years)

Drought impacts are usually grouped into three principal areas: economic, environmental, and social (Wilhite and Glantz 1985, Wilhite 1993). In this section, the costs of droughts are categorized following Figure 5. This figure shows how drought causes direct impacts (computable in economic losses) and these damages cause indirect impacts (indirect losses), and how the measures applied to mitigate drought impacts generate extra economic costs attributable also to the drought event in case. The classification of the losses is based on (Table 2), which is similar to the one used on PREEMPT project (2011) and on the EU Project CONHAZ (2012). Both direct and indirect losses are classified into tangible and intangible, and the tangible economic losses into micro and macroeconomic losses.

Figure 5. Drought impacts classification: economic losses and economic costs



Source: Own elaboration

The term impact is interchangeably used with loss. In this study we will then refer to impact as the economic losses produced by the external shock on water availability.

However, it is important to indicate that the impact is the physical or visible consequence of the drought, and the consequential losses are the measurable evaluations of that impact in the socio-economy sphere. Therefore, the direct impacts are those whose events affect directly the sector and last during the event, because of impaired or reduced access to water resources. And the indirect or higher order impacts are those that are not directly impacted by the event and result from the direct damages to other domains or sectors. Indirect effects arise when the reduction of supply for one sector (in goods or services) generates a reduction of the purchases of other sectors[6]. Droughts reduce assets' productivity putting firms and markets under dire situations, reducing income and employment. Tangible impacts are easier to be revealed in prices, income or revenue directly or indirectly attributable to the droughts. And the intangible impacts refer to the impacts that have no price on markets but whose value should be accounted for in the social welfare variations and environmental deterioration. Both tangible and intangible impacts can be direct or indirect. Table 2 shows the main examples of drought impacts within the proposed classification.

Table 2. Categorization of drought impacts

	Type of impacts	
	Tangible (Market impacts)	**Intangible (Non-market impacts)**
Direct	Urban Water Supply Agricultural and Livestock Sector Hydroelectricity Fish farm Recreational Uses	Welfare impacts Environmental impacts - Aquatic ecosystems - Forest ecosystems
Indirect	Impacts on the Agro-industrial sector Agricultural Employment Tourism and service sector	Humans health and disease exposure

Source: PREEMPT and CONHAZ

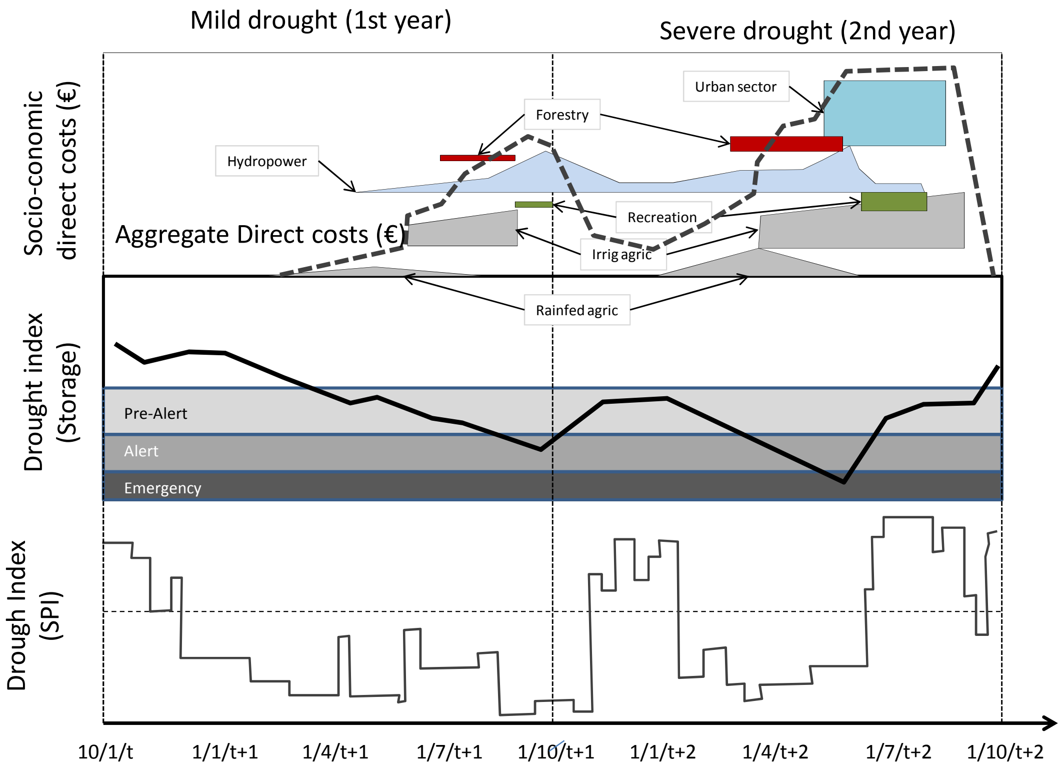
In addition to data limitations and methodological issues, there are at least four types of conceptual problems associated with economic evaluation of droughts. First, drought impacts occur despite drought preparedness and planning, which entail costs to the economy. Infrastructures are often built in emergency situations at a higher cost but can also be used in future droughts. Other measures, including agricultural insurance, involve multi-annual risk spread schemes that may or may not require government

[6] The good and services produced by the sector A (supply side) are thus intermediate goods and services for sector B (demand side).

outlays. This means that drought impacts also include measures undertaken to avoid, compensate, alleviate or offset its expected consequences. Martín-Ortega and Markandya (2009) conducted an in-depth analysis of the consequences of a drought suffered in Barcelona between 2007 and 2008, a detailed compilation of the cost of the measures undertaken on that period was included in the assessment. There were significant avoided costs caused by the implementation of the measures. The European Commission (2007b) summarized the positive and negative impacts of the implementation of their proposed drought and water scarcity mitigation strategies as a way to achieve an impact assessment of the possible consequences.

Second, there is a compositional problem. Accepting that macro effects are negligible or very difficult to analyze in detail, there must be some impact transmission mechanisms in the economy which diminish the costs of droughts. Reduced water supplies can impact direct users severely, but the costs of direct users do not sum up additively to obtain the impact on the regional or even national economy. To better target policies and programmes, evaluations must identify the sectors and markets that suffer droughts the most. This kind of specifications must be used to design appropriate measures for each sector. Input-Output and CGE models have been used to analyze water scarcity impacts (Goodman 2000, Gómez et al. 2004, Berrittella et al. 2007, Pérez y Pérez and Barreiro-Hurlé 2009, Calzadilla et al. 2010), and the relation between sectors (but avoiding time line occurrence) and little is known about their ex-post prediction accuracy.

Figure 6. Schematic representation of a generic drought onset (SPI, at the bottom; Drought Storage Index, in the middle; Socio-economic Impacts, on Top; dates are reflected in the horizontal axis starting on Oct 1, of a generic year t)



Source: Own elaboration

Third, droughts propagation occurs slowly, from low precipitation to reduced soil moisture to lower run-off to reduced water storage, and finally, to water shortage. While economic impacts occur in parallel to droughts onset, little attention has been set on inter-annual losses of droughts and the propagation along time (Peck and Adams 2010). Figure 6 depicts the idea of preparedness and the relation between drought indices and drought impacts. The evolution of events in time and the starting point of each type of impact is determinant when illustrating this relation. It shows a generic representation of the evolution of a drought event and its related socioeconomic impacts. The bottom panel of the figure shows the evolution of a common meteorological drought indicator, the Standard Precipitation Index (SPI). The middle panel represents the evolution of a hydrological drought index based on the evolution of reservoir storage in generic basin as a result of a decrease in precipitation, with its four levels (normal, pre-alert, alert, emergency). Finally the top panel represents the temporal appearance of the costs and losses associated with the drought event, with a dotted line representing the flow of costs as a sum of the reduced direct welfare and income caused in five sectors (rainfed agriculture and livestock, irrigated agriculture, hydropower, forestry, recreation and tourism and the urban sector).

And fourth, drought characteristics vary depending on the geographical location of the natural hazard occurrence, and hence the impacts and the spreading of them will be always dependent on the climatic and economic characteristics of the particular area under consideration. The consequences of a drought are never the same in Africa, for instance the examples from in Ethiopia (Helldén and Eklundh 1988, Tagel et al. 2011) than in Spain, consequently their impacts cannot be generalized, requiring context-specific studies.

As it has been said in the introductory section, this study focuses on the impacts of drought in two countries with Mediterranean climates, Spain and Chile. Both of them belong to the OECD, so they can be considered developed. Drought impacts in developing countries are totally different and more severe than in developed ones. Vulnerability aspects are the main drivers for causing those differences and therefore the management strategies applied on those countries follow also a separate line (UNISDR 2004). Vicente-Serrano (2012) outlines the possibility of changing the old drought risk management based on a reactive crisis-response approach, by promoting drought mitigation and preparedness in Africa. Recently, the European funded DEWFORA project (2012) has provided an approach to Drought preparedness and adaptation through early warning systems to deal with droughts in Africa. And Rosegrant and Binswanger (1994) studied water allocation for gains in developing countries. But nevertheless, the differences remain large to be treated the same way and over the same assessment.

3.2 Categories of impacts

3.2.1 Direct impacts

Evaluations of direct impacts of drought are commonly found in the literature, with a variety of methodologies to calculate them. The majority of the studies are focused on the losses generated on the agricultural sector, as it is the main water user in almost all river basins around the world. Agriculture is therefore the most vulnerable sector according to direct water scarcity and drought impacts, but nevertheless there are other sectors affected by droughts and with high vulnerability status, such as urban water supply. Next to agriculture, drought impacts on households have also been thoroughly studied.

Microeconomic impacts of drought in agriculture have been the most commonly assessed. The evaluations are generally performed by measuring the effects of lower water availability and/or lower soil moisture causing reduced plants' growth. Production functions are formulated in order to obtain the losses, and crop prices are used to monetize them. Impacts at a microeconomic level can be found on a crop single basin or in an aggregate form (measuring production values of the combination of many crops in a given area). On the other hand, macroeconomic effects are measured on GDP (Gross Domestic Product) and on GVA (Gross Value Added) among other indicators.

As a matter of simplicity, some authors have measured the decreases in yields as a response of drought conditions, these methodologies directly measure the physical damaged suffered by crops. This was used to measure single crop (Ritcher and Semenov 2005) or multiple crop yields decreases. Nonetheless these methods had evolved by relating yield failures to drought indices like NDVI (Normalized Difference Vegetation Index) as Hartmann et al. (2003) does using Geographic Information Systems. Or by measuring yield decreases in relation to the followed trend for a long time series like Xiao-jun et al. (2012). But, unfortunately none of them measures the impact on economic terms. Similar procedures incorporating the economic aspect are for example the study by Klein and Kulshreshtha (1989) who measured income decreases per acre as a result of lower yields, or Fernández el at. (1997) who assigned an economic value to the damage by considering the decrease in yields and using regional prices of products in

Chile. Martínez-Cachá (2004) relates yield decreases with drought years and crop prices to calculate direct impacts from the production loss. She also uses these production losses results to calculate higher order impacts. The most recent study by Kirby (2012) in the Murray-Darling basin in Australia assesses the economic impact of a drought in the yields of the main planted crops.

In addition to this literature, many authors have used mathematical programming models to simulate water availability constraints and water allocation alternatives in order to draw the best outcomes of several drought scenarios. These methods are based in the construction of deterministic models, and can feature both linear and nonlinear programming techniques, static or dynamic, deterministic or stochastic. Regarding past drought estimations on this group of methods there are a wide amount of studies of non linear programming using the CALVIN model in California (Koss and Khawaja 2001, Jenkins et al. 2003, Booker et al. 2005, Quenani-Petrela et al. 2007, Harou et al. 2010) and the linear models have been also used, but generally in more specific studies, and more often to inform decision making processes (Dono and Mazzapicchio 2010, Peck and Adams 2010).

Specific technical limitations of the CALVIN model are fairly discussed (Draper et al. 2003). The most significant drawbacks relate to (i) the use of a network flow formulation that limits ability to represent important physical phenomena like the relations between stream and aquifers, or the dynamic pumping costs, and (ii) the non consideration of flood control and recreational benefits. In the use of linear models, the disadvantages are extended to one more: (iv) the objective function is even simpler because of a rather unrealistic representation of the production technologies.

Mathematical programming models can be seen then as a useful tool in order to compare different alternatives. The simulation processes can perform different scenarios and compare the most distant results. Some authors have used them to evaluate policy and water strategies, such as Booker (2005) in the USA for testing economic tradeoffs among water uses, regions, and drought control strategies, or Lorite et al. (2007) by assessing deficit irrigation strategies in Spain. Another two examples can be found in Spain (Iglesias et al. 2007d, García-Vila et al. 2008). The first one uses it to simulate the benefits and economic gains of an irrigated area by imposing water restrictions, and in the second authors perform crop production simulations and the linked agricultural losses produced by limited water supply.

Among the most recent stand (i) Qureshi (2012) who integrates the long-term drought impacts on gross value or irrigated agriculture with predictive capacity within the mathematical model, and (ii) Sidibé (2012) who simulates the representative farmers' optimal behavior under innovative pricing systems. Both of them use mathematical programming models to assess farmers' adaptation options and water policies including water markets or water pricing.

Other methods are the hydro-economic models that integrate climate, hydrological and socio economic aspects to dynamically simulate human-environment systems under uncertainty. They permit the representation of the complexity of water resources systems within a coherent framework. These models have been used in integrated water resources management and planning and in policy development. Although they measure the direct impacts of drought, these models have been more oriented to cover the gaps of knowledge concerning environmental impacts (Krol and Bronstert 2007) or social implications (Lozano et al. 2007, Ward and Pulido-Velázquez 2008, 2012).

The most recent contributions to hydro-economic models are provided by Blanco (2010), Varela-Ortega (2011) and Howitt et al. (2012). Blanco (2010) performs a hydrology water management simulation model built using WEAP (Water Evaluation and Planning System) and combines it with economic models. Varela-Ortega (2011) proposes a hydro-economic model to evaluate the consequences of policy implementation in groundwater conservation and rural livelihoods under climate uncertainties. Howitt (2012) uses the mathematical linear program SWAP (California Statewide Agricultural Production Model) to combine it with exponential cost functions and constant elasticity of substitution production functions, showing that a more flexible water market allocation can reduce revenue losses from drought up to 30%.

Accurate estimations of drought impacts from many studies tend to reduce the amount of losses produced by drought from estimations performed by farmers, or institutions. Simple calculations frequently ignore the external shocks that agriculture suffers from many other causes. In Craik and Cleaver (2011) it is shown that the impact of 20% lower water allocation in annual farm profit reduced total income less than 6% in the

Murray-Darling basin in Australia. This calculation was made for farm profits during the 2007-2009 drought through an optimization water trade model combined with a general equilibrium economic model. Ward and Pulido-Velázquez (2012) found that the economic cost of protecting the sustainability of the Rio Grande basin's water stocks can be achieved at 6-11% of the basin's average annual total economic value of water over a 20-year time horizon.

Although drought assessments based on Input-Output (IO) tables are used to assess indirect impacts, they also present estimations of direct losses (the indirect consequences of drought assessed by IO will be explained in the following section). The IO approaches are based on the idea that changes in product demand lead to changes in the economic structure of a region and therefore to production variations (Leontief 1986). In order to measure the economic impacts of a drought the method is applied backwards: the decrease in production generates changes in the entire economic structure dependant on it, and therefore decreased revenues and incomes can be calculated in many sectors. Adaptations of IO are the Computable General Equilibrium (CGE), and the Social Accounting Matrix (SAM) or Social Accounting Matrix and Environmental Accounts (SAMEA). A potential serious problem of this methodology is that even if the transmission of the impacts across the economy can be calculated, the initial decrease in production is usually overestimated with no precise attribution measurement. In addition, the direct impact is measured over macroeconomic variables, on which the drought impacts are difficult to identify (Garrido et al. 2010). This is the case of Feng et al. (2007) who use CGE for decision support at assessing vulnerability to drought in the conduction of a water transfer in China, and they support the vulnerability assessment by calculating the impacts on GDP.

Macroeconomic assessments are also performed by mathematical programming (Salami et al. 2009), statistical analyses (Rosine and Walraven 1989) and econometric models (Alcalá Agulló and Sancho Portero 2002, Garrido et al. 2010). The last are the most precise in attributing the effect of constrained water availability but even they still showing that there is little economic losses at this level. But, de Stefano and Llamas (2012) show overwhelming evidence of the fact that the agricultural water footprint is very high in comparison to the economic productivity of the sector, so drought should have a modest impact on the macro-economy.

Uncertainties are always involved when methodologies deal with the precisely attribution of the real impact of drought. More emphasis should then be put on mechanisms to achieve this aim, especially for the methodologies that were developed to estimate the direct costs of drought. Although drought definitions entails difficulties to define the boundaries and scope, an effort must be made to better measure what actually occurred as a result of water lacks.

3.2.2 Indirect impacts

Indirect impacts, secondary impacts, or higher order effects are the costs or economic losses derived from the direct impacts, either because the dependence on the sectors directly affected is large (producing indirect tangible impacts), or because the losses in these sectors are able to generate indirect intangible losses (the latter will be treated separately). Therefore, the direct economic impacts on an individual sector would spread through the upstream or downstream linkages to other sectors or industries, causing secondary impacts, and other multiplicative effects in the economy. In the same way than in previous section, the indirect tangible losses of drought are generally measured in the literature over the agricultural related sectors. Because it is one of the most significantly hit by water drops, it also has the most significant indirect impacts. In spite of this, there can also be drought related indirect losses in other sectors, but the most commonly considered indirect impacts are calculated over agricultural employment, and over the Agri-food industry.

For calculating employment losses there are a variety of methods ranging from approaches that assume theoretical employment or labor losses per hour directly linked to the yield loss of the crop (Martínez-Cachá 2004) to econometric analyses relating the decrease in water availability to the number of workers (Schuh 1962, Garrido et al. 2010) or even through discrete stochastic programming (Dono and Mazzapicchio 2010). Changes in employment are reported at a reduced geographical level, studies regarding farms or irrigation districts are able to measure variations in employment. But in all of them employment losses are simulated under theoretical hypothesis, but when they have been measured with the official data no significant employment loss is found, at least in Spain (Garrido et al 2010, Hernández-Mora et al. 2013).

On the other hand, Agri-food industry has been mostly considered within the IO (Pérez y Pérez and Barreiro-Hurlé 2009) and the CGE (Gómez et al. 2004, Berrittella et al. 2007) models. These models calculate a wide variety of indirect impacts over the most productive sectors of a region as they simulate the interrelations of the economy by applying multiplier effects to project the impacts. The major disadvantage of these simulations is that the complexity of the model is formulated for a static representation of the economy, from which parameters are obtained. The analyses are generally based on outdated parameters, which are difficult to update and so the usefulness of their simulations becomes doubtful. It should be mentioned also that the use of the IO tables for the estimation of indirect costs implies not accounting for behavioral changes and their results may be seen as an upper bound estimate of the losses (Markandya et al. 2010).

As it has been said, drought impacts tend to dilute at the macro level, especially when trying to measure them through macroeconomic aggregated variables like GDP or GNP. But, it is important to remark that water supply shocks could be appreciated on disruptions of trade balances (Berrittella et al. 2007, Cavallo and Noy 2009) and this macro level cannot be negligible. Berrittella et al. (2007) analyze the virtual international markets of foods and products on the world economy and identifies the interrelations that generate regional winners and losers from water constraints.

The perdurability of direct impacts has been documented (Peck and Adams 2007), but this subject is much more important when dealing with indirect impacts. As indirect impacts show up after direct impacts occur, they may start even when meteorological droughts are finished. Cavallo and Noy (2009) report the existence of short- and long-run indirect economic effects of the natural hazards. The time division between short and long can be made under different parameters, but for droughts the most logical should be the consideration of one season for the short-run, hydrological year for the medium-run, and more than one for the long-run (see Figure 6). Not only the time dimension is important, but also depending on the duration and intensity of the drought, more sectors could be affected by indirect impacts.

3.2.3 Intangible impacts

The intangible or non-market costs of natural hazards are those with no economically established value and so their losses are neither internalized nor revealed in market economy. Regarding droughts, the intangible losses produced by an event can be environmental and social. Environmental losses are the result of natural and biophysical degradation of the ambiance produced by the lack of water. And social costs of droughts are the reductions of welfare as a result of different impacts (losses imposed by water use restrictions or by increased risk perception). Both of them are generally obtained through contingent evaluation techniques, first proposed by Ciriacy-Wantrup (1947), which are survey-based economic techniques for the valuation of non-market natural resources. Although stated preference models have created controversy, they afford an economic approach to value intangible elements. Surveys evaluate either individuals' willingness to pay (WTP) for improvements or willingness to accept (WTA) for deteriorations. The economic valuation of numerous water quality aspects and supply reliability has been widely addressed with stated preference methods.

Environmental losses of drought performed through contingent valuation are focused on the calculation of the non-market benefits that society attaches to different alternatives. For instance Alcon et al. (2010) calculates the WTP for the use of reclaimed wastewater for agricultural purposes in the Segura river Basin (Spain) as a possible measure to be implemented in order to reduce water use in a water scarce Spanish area. But, the most common valuations are related to environmental benefits. Surveys are conducted to evaluate water scarcity through the non-market value of allocating enough water to the environment to ensure environmental services, or to guarantee water supply for household uses (Blamey et al. 1999, Bateman et al. 2006, Del Saz-Salazar et al. 2009, Martin-Ortega and Berbel 2010).

Social impacts of droughts are evaluated through measurements of WTP or WTA for increased supply reliability and for establishing water supply options. It is assumed that drought can cause water supply interruptions or quality declines that would result in welfare losses, the avoidance of which would produce welfare gains. Depending on the country, the policy choices analyzed on each study are different. For example in India and Mexico access to water and safety issues prevail (Raje et al. 2002, Vásquez et al.

2009) while in more developed countries, with more trustworthy supply systems, the reliability of the water supply system is evaluated in different ways.

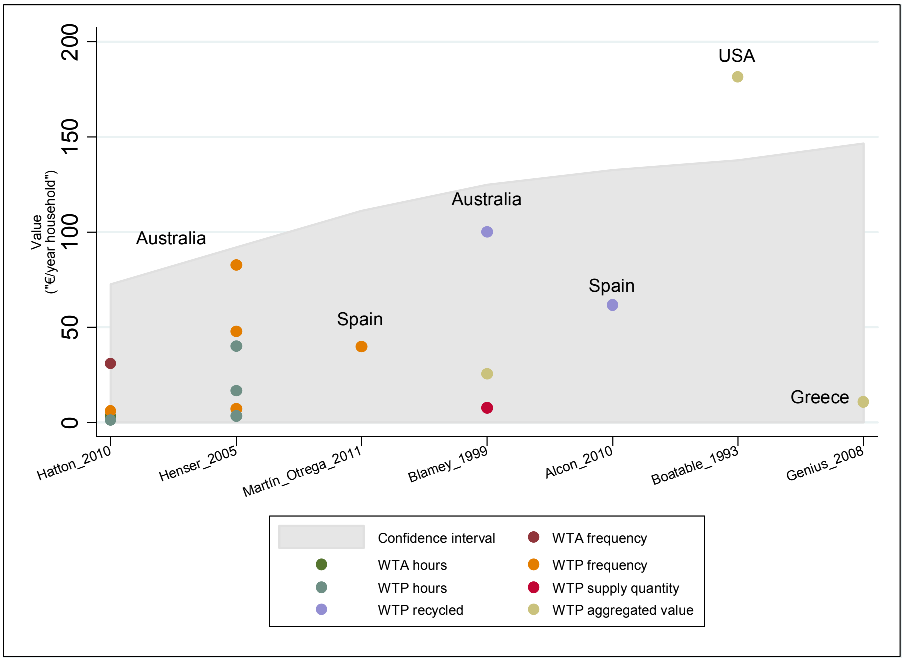
In the social context, the family of contingent valuation method is again the most popular method to evaluate this kind of preferences and, as customers pay water tariffs, the monetization turns out to be understandable and credible as payment vehicle. Koss and Khawaja (2001) value supply reliability in California, by performing a contingent valuation to evaluate the WTP in order to avoid the occurrence of water shortages of a given frequency and severity, while Haider and Rasid (2002) evaluates in Ontario (Canada) the percentages of reduction in different domestic water uses. When a society is facing a drought, water supply interruptions can occur, and therefore, the value of the welfare loss produced by these disruptions is evaluated through the WTP or WTA to avoid or to reduce changes in welfare. The previous studies (Koss and Khawaja 2001, Haider and Rasid 2002) can be seen as two examples of drought social impacts assessment examples.

However there are some other methods to evaluate the social losses derived from water restrictions. They are based on water demand functions and consider water price elasticities, based on which consumer welfare losses are calculated. In Spain a couple of studies by Roibás et al. (2007) and Valiñas (2003) documented the drought suffered during 1992-1995. The city of Seville was selected to conduct the estimations because it suffered severe water restrictions as well as water quality deteriorations during that period. Apart from this example, Woo (1994) analyzed water management options in times of drought or scarcity in Hong Kong. He concludes that service interruptions are inefficient for water shortage management, and to support this conclusion he uses the concept of compensating variations to compare service interruptions to water tariffs increasing policies. Lastly, Jenkins (2003) also uses benefit functions to estimate water losses within the CALVIN model (mentioned in previous sections). In this study, the author designs drought management functions with residential water demand elasticities to be integrated within drought assessments to highlight the importance of managing drought economic and social impacts.

Intangible impacts must be considered in drought assessments, as this kind of evaluations require significant efforts, resources and time, benefit transfer can be used in order to give a monetary value to an existent loss that is commonly forgotten. This can be performed in three ways: (i) by single point value transfer, where a single value is transferred without adjustment from source study to target site, (ii) by marginal point value transfer where a single value that allows for site differences is transferred and (iii) by benefit function transfer, where a valuation function is transferred allowing adjustment for variety of site differences.

Benefit transfer generally provides limited information and can over- or underestimate economic values. Supporters of benefit transfer argue that the benefit function transfer is more robust than transfer of average site benefits (Loomis 1992, Kirchhoff et al. 1997). But the problem lies in the huge variability between experimental results. Figure 7 shows a selection of studies with shared objectives, the estimation of social welfare losses derived from drought. Differences can be appreciated between countries, river basins and authors. Legend illustrates the type of value shown, for example "hours" indicates WTP or WTA for services cuts lasting hours, or "frequency" indicates the frequency of restrictions among days, months or within a year. To a better understanding of the figure, Table 3 provides more details of the reviewed sources.

Figure 7. Welfare losses related to impacts on social water uses from various sources and authors (data expressed in € per year and household, at market exchange rates of each year study, the 95% confidence interval has been obtained by a quadratic regression of the values for each study)



Source: Own elaboration

Table 3. Selection of studies that analyzes the social-intangible cost of drought

Category	**Type**	**Author**	**Country**		**Value (€/year household)**
Urban Water Use Restrictions	WTA frequency restriction	Hatton et al. (2010)	Australia	# occurrences/yr	30.86
	WTA hours restriction	Hatton et al. (2010)			3.14
	WTP frequency restriction	Hatton et al. (2010)	Australia	# occurrences/yr	5.96
		Hensher et al. (2005)		12 times/yr	82.61
				once/year	47.69
				once/10 years	6.99
		Martín-Ortega et al. (2011)	Spain	once/10 years	39.53
	WTP hours restriction	Hatton et al. (2010)	Australia		1.09
		Hensher et al. (2005)			16.36
					3.20
					39.96
	WTP supply quantity	Blamey et al. (1999)	Australia		7.67
	WTP recycled water	Blamey et al. (1999)	Australia	all uses	-116.90
				outdoor uses	99.89
		Alcon et al. (2010)	Spain	improved wastewater for agriculture	61.58
Improvement	Aggregated value	Blamey et al. (1999)	Australia		25.41
		Boatable (1993)	USA	improved quality for recreation	181.53
		Genius et al. (2008)	Greece	improved quality and quantity for drink	10.64

Source: Own elaboration

Studies regarding environmental intangible losses of drought generally evaluate quality environmental losses. These losses can be assessed in many ways. Figure 8 compiles different studies that permit getting an idea of the type of these evaluations. Specific studies within the WFD evaluate the WTP for the allocation of water for the environment to maintain or improve its quality (Martin-Ortega et al. 2011). For instance, other study regards the environmental loss related to the loss of uncommon species (Blamey et al. 1999) as a possible impact of a prolonged or severe drought.

Figure 8. Representative studies of environmental intangible losses (data expressed in € per year and household, at market exchange rates of each year study, the 95% confidence interval has been obtained by a quadratic regression of the values for each study)

Source: Own elaboration

Innovative methodologies to assess social impacts have been recently used. Carroll et al. (2009) and Frey et al (2009) value the decreases in life satisfaction produced by the changes in the perception of people threaten by droughts. Carroll et al. found that an Australian rural household living in an area suffering a drought would experience a loss of 18,000 AUS dollars, which amounts for the 1% of GDP. This measurement results excessively high because it is based on the expectations of people happiness. Although this is a measurement of well-being and has been shown to be closely related to the measurement of happiness, its reliability raises doubts. And yet, it may assist in giving an alternative point of view to value the social implications of drought.

Yun et al. (2012) proposes a categorization of the victims' perception of drought impact in relation to the stages of drought responses of different subjects (government, social organizations, and the public). Social related losses produced by drought have received renewed political attention and presents significant opportunities for change (Askew and Sherval 2012)

Finally, complete assessment of drought losses are recently found on the literature, a few examples can be compiled by the study carried out in Barcelona by Martín-Ortega and Markandya (2009), the XEROCHORE project (2010) the CONHAZ project (2012)or the PREEMPT project (2012) for some representative river basins around Europe. All of them illustrate the value of quality studies for assessing the scope of droughts, including cost of the measures undertaken and the even more important, the efficiency of them that has been primarily assessed on a few. This kind of analyses is extremely valuable to inform policy makers.

Part II:

The Impact Attribution Models and Applications: methods and results

Part II: Impact Attribution Models and Applications: methods and results: General introduction for chapters 4, 5 and 6

Part II presents a general approach, based on econometric model specifications, to relate drought impacts with the economic output of agriculture. Therefore, a family of attribution models to evaluate direct drought impacts for Spain and Chile is proposed and presented. These modeling approaches provide the foundation for assessing drought impacts, evaluating drought risk profiles, and analyzing management strategies, as developed in Chapters 4, 5, and 6.

The impacts of drought can be measured in terms of the lost economic output of agriculture that is measured at different scope levels. The macro economic variables like GDP (Gross Domestic Product) or GVA (Gross Value Added) have been used to assess either major drought events (Adams et al. 2002, Martínez-Cachá 2004), or to show that such large impacts are spread and reduced at that level of analysis (Garrido et al. 2010). On the other hand, a farm level approach has been also used to evaluate the impact of drought and to design small-scale mitigation strategies (Klein and Kulshreshtha 1989, Lorite et al. 2007). Nonetheless the regional level has also been used generally in Computable General Equilibrium Models (Goodman 2000, Berrittella et al. 2007) introducing into it economic estimations of agricultural productions. Variations of agricultural economic indicators are suitable to be used for identifying drought or scarcity signals if the signals can be isolated from other causes.

The method proposed here is designed to explain drought direct impacts through a simple formulation. Eq. 1 defines the agricultural economic output *Z(€)* to be dependent on a set of control variables of interest. Therefore, x_1, x_2, … and x_n are climatic, biophysical, and economic variables for instance.

$$Z(€) = f(x_1, x_2 \dots, x_n) \qquad (1)$$

Some authors used this kind of econometric models to measure the impact of extreme events on the economic indicators, but they generally include dichotomous variables to identify whether or not there has been an extreme event (Cavallo and Noy 2009).

However, climatic and economic variables are also needed, the latter are related to the vulnerability of the system and the firsts to risk or exposure levels.

This general approach can be seen as formulated in Eq. 2 where specific explanatory variables are identified. The econometric model explains the variation in the agricultural economic indicator as a function of water related variables, climatic characteristics, a time variable and a price index. These are the main relevant variables considered in order to capture drought effects, market fluctuations and the time evolution. ε is an error term that can be estimated through panels (if the model is being applied at a national level), or through the estimation of cross sections of regional observations where suitable.

This model is proposed to be used at different levels of influence and at different geographical areas. Depending on where and to which context the model is applied there can be obviously other sources of economic impacts, but the aim of this method is to provide a general tool that can be simply adapted according to the research parameters.

$$V_{it} = a_i + b_i T_t + c_i W_{it} + e_i P_{it} + \varepsilon_{it} \qquad (2)$$

On Eq. 2 T_t is the time variable (trend) expressed generally in years, W_{it} is the hydrological variable (that can be expressed in a wide variety of forms, depending if the agriculture relays mainly on water from reservoirs, or in groundwater or even in accumulated precipitations), this water variable will be succinctly named in the following chapters as it will be different depending on the application, and P_{it} is a variable related to the price variations (a price index calculated for each application presented in the following chapters). V_{it} is the economic variable on which the impacts are measured (again, each chapter in Part II will measure different economic variables, mainly related to production values).

This model measures the variations of the economic output dependent on crucial explanatory variables. If the model fits well and it has enough explanatory power, it allows for differentiating between impacts produced by drought and variations produced by other important factors.

Once the impacts are determined, the estimated models will be used as a basis for the different objectives of the thesis. It will be adapted for each application (in the following chapters) to determine both direct and indirect drought losses, as well as the economic risk of drought. Therefore, Chapters 5, 6, and 7 are the different applications proposed with the Impact Attribution Model, and they are related to it as it is graphically showed on Figure 9.

Figure 9. Methodological framework for Chapters 4, 5, 6 and 7

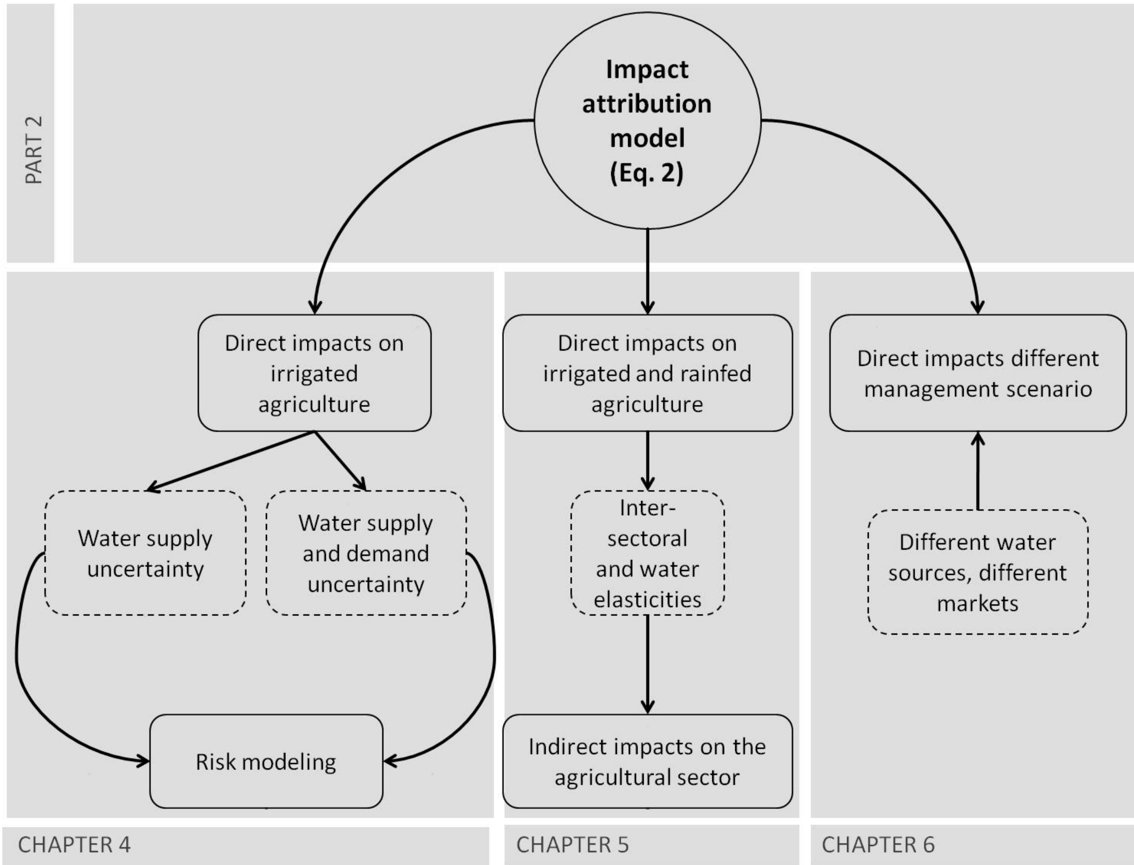


Figure 9 shows how the impact attribution model is used in the different chapters of Part II. In Chapter 4 as the direct impacts are identified, two sources of uncertainty are introduced into the Impact Attribution Model to generate two different risk modeling approaches. These will be: in Chapter 5 the indirect impacts on the agricultural sector are calculated by an adaptation of the Impact Attribution Model to identify and calculate the existent elasticities between the use of water and the impacts in the primary production (Agricultural production) and in the Agri-food Industry. And, in Chapter 6 the direct impacts are evaluated under different policy and water scenario, in this last chapter the Impact Attribution Model has been adapted to fit with the characteristics of the case study (Chile).

4 CONNECTING THE DIRECT IMPACTS OF DROUGHTS IN AGRICULTURE WITH THE ANALYSIS OF RISK AND THE MANAGEMENT PERSPECTIVE

4.1 Introduction: Risk management of drought impacts

This chapter contains two applications for managing and measuring drought risks on irrigated agriculture. The first one deals with water supply risk and is referred to the regional level (provincial) in Spain. The second one incorporates crops' water demand variability, setting up stochastic water balances, with the analyses and simulations performed at a local level (Demand Management Unit) where specific and detailed data are available. Both applications are organized as follows: first, the methods and the case studies are presented. These include 1) the econometric models, which provide the attribution model of economic drought effects and 2) the risk analysis at the provincial (in the first example) and the lower level of agricultural demand unit (the second example). Subsequently, the most relevant results of each case are presented, and at the end of the chapter the impact on water management of economic drought risk is summarized as a way of conclusions.

Droughts create periods of water scarcity that affect all urban, industrial, and agricultural water supply systems, and they disturb the flow of environmental services. The prevention of these effects must be done through managing the risk of suffering them, but risk models have rarely been used to evaluate the economic impact of droughts or water scarcity periods. This, in a sense, is awkward because numerous efforts to develop hydrological and operation models have been made in the last 25 years (Vogt and F. Somma. 2000, Rossi et al. 2007, Iglesias Martínez and Blanco Fonseca 2008). Very often, shortages occur because droughts are poorly managed, and droughts are the consequence of precipitation anomalies that last longer than expected. They are extreme events that are subject to risk evaluation and assessment. Managing droughts is managing the risk of suffering water shortages, with the objective to avoid them or reduce their duration and magnitude.

Until now, the increase in regulating infrastructures has been seen as a measure to prevent drought impacts. Water infrastructure indeed alleviates the effects of meteorological droughts for the urban and agricultural sector, but it has different effects on the environment or on other uses, and it also requires the efficient management of reservoirs and aquifers together with demand management (Iglesias et al. 2007c). Counting on the infrastructures already built in Spain, water management must be focused on reducing drought risk through an efficient use. However, any model or protocol designed to mitigate the effects of water scarcity requires, among other things, updated information about the social and economic consequences of drought. The incorporation of risk analyses into resource management thus requires the precise and timely knowledge of the economic impacts of droughts at the level of basins and even at smaller domains (Iglesias et al. 2007b). This knowledge must be combined with environmental information to mitigate both the economic and the environmental effects of drought.

Southern Europe is more prone to suffer increasingly drought risks, at least under most common global change scenarios (Lehner et al. 2006). Drought risk models have normally been seen apart from economic impacts of this natural hazard. Many authors developed risk models based on climatic projections, for example, Incerti et al. (2007) or Hao et al. (2012) who develop models for drought ex – ante risk assessment using climatic data. Both of them introduce the geographical dimension, but the economic one is missed. Dankers et al. (2006) also developed an assessment framework to evaluate drought risk within the climate models simulations but together with floods and at a European level. Other authors evaluate the adaptive capacity of crop yields under drought risk situations (Wu and Wilhite 2004, Quiroga and Iglesias 2009, Quiroga Gomez et al. 2010). Risk analysis and assessment is obviously necessary to reduce vulnerability, and to improve water supply reliability (Nebiker 2006). Drought risk management would therefore lead to a decrease in disaster incidence (Boterril and Wilhite 2005). Martin-Carrasco et al. (2012) developed indexes to assess water scarcity risk based on supply and demand obtaining demand reliability curves at the river basin level.

Garrido and Gómez-Ramos (2008) reviewed possible economic instruments that can be applied to manage drought risks. One of these economic instruments, proposed by Gómez-Ramos and Garrido in 2004, is an option contract to transfer supply risks between users with different levels of flexibility to accommodate lower application rates by irrigators. Drought risks can be analyzed by linking scarcity risks with the economic value generated by water, expressed in terms of social, environmental or economic services (Iglesias et al. 2003). Uncertainty about future water availability is transferred to the value and commercial uses of the eco-system.

A number of studies analyzing the economic impact of droughts use mathematical programming models to simulate economic impact (Iglesias et al. 2003, Calatrava and Garrido 2005, Salami et al. 2009, Peck and Adams 2010). Others use econometric models fitted at the macroeconomic level (Alcalá Agulló and Sancho Portero 2002, Martínez-Cachá 2004) or at the level of the irrigation district (Lorite et al. 2007), the irrigated farm (Rubio Calvo et al. 2006) or single crops (Quiroga and Iglesias 2009). Input-output models have also been used to study the regional effects of water scarcity (Pérez y Pérez and Barreiro-Hurlé 2009). Finally, other authors have used computable general equilibrium models (Goodman 2000, Gómez et al. 2004, Berrittella et al. 2007). With the exception of Iglesias et al. (2003), none of these authors has used a model to predict the impact of future droughts.

The use of mathematical programming models must overcome the calibration problem, which, in most cases is performed with reference to a number of representative units (typically farms) (Iglesias Martínez and Blanco Fonseca 2008), one or very few periods (in most cases), or behavioral features such as risk aversion (Mejías et al. 2004). In these models, the simulated economic value results from optimizing the allocation of available resources (land, water, and labor) subject to observed constraints. The resource constraint can be assumed to be stochastic (Iglesias et al. 2003, Calatrava and Garrido 2005), which enables dynamic models for optimizing water allocation over a number of seasons (Iglesias et al. 2007d).

Computable general equilibrium models (CGE) serve as an analytical tool, but most of the parameters, such as elasticities and the coefficients of production functions, quickly become outdated. Gómez et al. (2004) evaluated the economic impacts of various allocative criteria in the Balearic Islands using the National Agricultural Accounting Network and the input-output tables for 1997, on which future scenarios were evaluated. The simulation results of Berrittella et al. (2007) are based on a version of the

Global Trade Analysis (GTA) using data for 1997. The potential to productively inform actual management criteria for scarce resources diminishes as the lapse between the reference year used for model calibration and the projection period expands.

In a global context, climate change would alter drought risks (Quereda Sala et al. 2005, Lehner et al. 2006). However, suitable methodologies to evaluate this kind of risk must work on a smaller scale (Adams et al. 2002, Cunderlik and Simonovic 2007, Feng et al. 2007). Some specific models have been developed, but most of them take a crop perspective. Wu and Wilhite (2004), for example, set out a model to prevent drought risk that is specific to corn and soybeans.

4.2 Economic analysis of drought risks: an application for irrigated agriculture in Spain at provincial level[7]

This first section includes a two-part methodology for managing the risk posed by water supply variability to irrigated agriculture. First, an econometric model is used to explain the variation in the production value of irrigated agriculture. The explanatory variables, proposed for this application, include an indicator of irrigation water availability (surface storage levels), a price index representative of the crops grown in each geographical unit, and a time variable. The model corrects for autocorrelation and is applied to 16 representative Spanish provinces in terms of irrigated agriculture. In the second part, the fitted models are used for the economic evaluation of drought risk. Inflow variability in the hydrological system servicing each province is used to perform ex–ante evaluations of economic output for the upcoming irrigation season. The model's error and the probability distribution functions (PDFs) of the reservoirs' storage variations are used to generate Monte Carlo (Latin Hypercube) simulations of agricultural output 7 and 3 months prior to the irrigation season. The results of these simulations illustrate the different risk profiles of each management unit, which depend on farm productivity and on the probability distribution function of water inflow to reservoirs. The potential for ex–ante drought impact assessments is demonstrated. By

[7] Most of the section has been published in Gil, M. A. Garrido and A. Gómez-Ramos. "Economic analysis of drought risk: An application for irrigated agriculture in Spain" *Agricultural Water Management* 98(5) March 2011, Pages 823-833. doi:10.1016/j.agwat.2010.12.008.

complementing hydrological models, this method can assist water managers and decision makers in managing reservoirs.

This approach complements previous analyses in two ways. The economic impacts are calculated directly from observed cropping patterns, yields, and water consumption and are evaluated with the prevailing prices in each season. They are not estimated and do not result from optimization models. By focusing the analysis on observed economic output at the provincial level, we avoid assuming fixed production technologies (as in Computable General Equilibrium models) or fixed resource constraints (as in optimization models). Furthermore, this modeling approach isolates the effects of economic production of the passage of time (trend) and crop price variations (farm products) from the effect of actual water availability which is the basic variable controlled by water managers.

The second feature that differentiates this approach from previous works is that the stochastic water sources are analyzed in detail and are linked with the economic drought impact model. As a result, water and irrigation managers not only have easily interpretable ex-ante probability measures of water availability that can be revised periodically, but they also have ex-ante probability measures of the economic output that can be obtained from the available water. By breaking up the period between the end of one irrigation season (October) and the beginning of the next (spring) into sub-periods, the risk analysis model provides a variety of distribution functions for the irrigated farms' expected productivity, which can be revised on a monthly basis before the beginning of the irrigation season. The methodological approach is applied to the 16 most important Spanish provinces in terms of irrigation, which are representative of all major geographic Iberian basins.

4.2.1 Methods: water supply risk for irrigated agriculture at the provincial level

To measure the economic effects of drought on irrigated agriculture, the main variables that explain the observed variation in irrigation production value need to be identified. A water variable is needed to identify droughts and scarcity periods. On this section the storage levels of reservoirs are selected as a clear and simple index for water availability at the provincial level. Two main reasons can be underlined: they are the main variable used in the Spanish Drought Plans and they are monitored and updated on a weekly basis. This variable also provides the most objective and transparent indicator of farmers' irrigation water availability, as current existent drought indices that are fundamentally based on reservoir levels, but they are built at a more specific geographical scope. Although groundwater resources provide a significant amount of water for irrigation in a few of the analyzed provinces, the dynamics of groundwater levels, storage and pumping rates span longer time periods than those of surface storage reservoirs, but they have been considered too.

The methodological approach has two components. First, an econometric model is fitted in an attempt to explain the variation in the irrigated production value due to water availability. This general model is subsequently applied to each of the 16 provinces studied. The province level is the unit of analysis because specific storage capacity can be almost unambiguously linked. Because there are no reliable databases for production costs at the level of these analyses, the focus is only placed on farmers' revenue. However, for the purpose of this study (obtaining ex-ante economic projections), the only relevant sources of variation are crop yield, crop price, available water (which informs cropping patterns and acreage decisions) and other non-controllable factors. In the immediate short term, crop costs can be assumed to be constant.

Therefore the explanatory variables are the availability of irrigation water (assumed here as the capacity of surface reservoirs before the start of the irrigation season), a price index that captures the variation of product prices at the farm level, and a time variable. The second methodological component takes the econometric model as a basis for the risk model, which introduces the current variability of water inflow to each storage system. The economic risk of drought is simulated based on the stochasticity of the supply source of irrigation water to obtain ex-ante economic projections.

4.2.1.1 *Econometric model: impact attribution basis*

The econometric model explains the variation in the economic value of harvests from an irrigated area (irrigated production value) as a function of water availability, a time variable and a price index. This is a general model in which the variable to be explained is Ipv_{it} (irrigated production value) estimated for each year (index t) and each province (index i). The statistical model is defined for each province i as follows:

$$Ipv_{it} = a_i + b_i T_t + c_i R_{it} + d_i G_{it} + e_i P_{it} + u_{it} \quad (1)$$

$$\text{With } u_{it} = \varepsilon_{it} + \rho_i \varepsilon_{it-1};\ E(\varepsilon_t) = 0 \text{ and } \sigma^2_{\varepsilon i} = \sigma^2_i,$$

where T_t is the time variable expressed in years, R_{it} is the hydrological variable expressed in % reservoir capacity, G_{it} are groundwater levels (only in the provinces where groundwater provides a significant proportion of irrigation water) and P_{it} is a price index for each province.

Ipv_{it} is the production value calculated from data on irrigated area and crop yields along with annual crop prices. Therefore, it is expressed in thousands of nominal euros and is calculated as the sum of the 94 irrigation crops as follows:

$$Ipv_{it} = \sum_{j=1}^{94} Suf_{jt} * Yield_{jt} * p_{jt} \quad (2)$$

where Suf_{jt} is the irrigated surface in province i, year t, and crop j (j=1,…,94), $Yield_{jt}$ denotes the yield of each crop in province i and year t, and p_{jt} is the national price for each crop in year t evaluated at the farm gate.

The explanatory variable R_{it} corresponds to the percentage storage level of reservoirs in the basin where each province is located as measured on May 1 every year. R_{it} is calculated from actual levels measured in cubic hectometers (hm3) divided by total capacity in hm3. The data are obtained from the MAGRAMA hydrological Bulletin between 1994 and 2009. The selected date (May 1st) for the econometric model is considered a valid indicator of the total water available before irrigation starts. In the provinces where groundwater is the main irrigation source, R_{it} corresponds to underground water levels measured on May 1st.

A weighted price index for each geographical unit (denoted by P_{it}) has been calculated to capture the variations in product value due to crop price variations. This index takes into account the importance of each group of crops within each unit and is calculated using the following formula:

$$P_{it} = \frac{\sum_{k=1}^{12} Ipv\_tc_{ikt} * P_{kt}}{Ipv_{it}} \qquad (3)$$

where Ipv_tc_{ikt} is the total value of crop group k (k=1,..,12), which is representative of the crops grown in each province. All 94 crops were included in these 12 groups so that each group has a specific price index, P_{kt}, which is published by the official statistical source (MAGRAMA 1995-2007). An alternative option would be to evaluate the variable Ipv_{it} in real euros (constant euros) by dividing it with a price index such as P_{it}. However, a nominal evaluation (in current euros) of Ipv_{it} as defined by Eq. 2 has two advantages. First, both farmers and water managers understand economic evaluations better in nominal terms. Second, the effect of price variation is isolated from the effects of time and of water availability.

Estimates of Eq. 1 were performed using the Prais-Winsten method for time series data. The Durbin-Watson statistic was calculated and the effect of serial correlation errors was corrected. Multicollinearity between *R*, *P* and *T* was tested by measuring the Variance Inflation Factor (VIF).

The econometric model has been formulated to measure the relationship between the availability of water and the final economic output independent of farmer decision processes. We assume that farmers optimize the resources they are given to irrigate their crops, and we take past observed productivity as the basis for predicting farm productivity in the short term. However, in the second part of the methodology, the work is focused on risk assessment. For this purpose, we will take into account the conditions prior to the start of each irrigation season to predict both the economic result and the strategic options of irrigators and water managers.

4.2.1.2 *Analysis of economic drought risk: water supply scarcity*

The explanatory model described above (Eq. 1) is the starting point for the analysis of economic drought risk in each province. If the goodness-of-fit in each geographical unit is robust enough, then the fitted equation can be used to define the distribution function of the harvest's value for the upcoming irrigation season based on the estimated parameters and the model variables known at the time of calculation. Thus, Monte Carlo (Latin Hypercube) simulation models yield distribution functions of production value for the year *t+1* ($\widetilde{Ipv}_{i,t+1}$) under different scenarios of water availability with particular attention to situations of water scarcity. The procedure allows the distributions ($\widetilde{Ipv}_{i,t+1}$) to be revised months before the irrigation season *t+1* begins. These revisions can be performed because the variable R_{it} is monitored at least monthly in each watershed and historical data series are available.

Let $\tilde{R}^{h}_{i,t+1}$be the random variable that defines the increase in reserves between the end of season t (in October) and the start of season *t+1* on May 1st, estimated *h* months before that date, in province *i*. Thus, the random variable that defines the availability of water for the irrigation season of year *t +1*, evaluated in month *h*, is given by:

$$\tilde{R}^{h}_{i,t+1} = \bar{R}^{h}_{i,t} + \Delta\tilde{R}^{h}_{i,t+1} \quad (4)$$

Where $\bar{R}^{h}_{i,t}$ is known (stock levels *h* months before May 1st) and $\Delta\tilde{R}^{h}_{i,t+1}$ is a random variable that can be estimated from historical data of the supply system servicing province *i*. Periods of risk analysis are referred to as *h*. In the application shown in this work, we obtained results for two sub-periods: 7 months before the beginning of the season (i.e., October 1st, 7 months before May 1st) and 3 months before the beginning of the season (February 1st). It should be noted that our modeling approach allows for weekly or monthly time steps because historical reservoir data are recorded on a weekly basis.

Thus, the simulated stochastic value of production $\widetilde{Ipv}_{i,t+1}$ for season *t*+1 of province *i* at *h* months before the beginning of the season is based on the following equation:

$$\widetilde{Ipv}_{it} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i \tilde{R}^{h}_{i,t+1} + \hat{d}_i G_{it} + \hat{e}_i \bar{P}_{it} + \tilde{u}_{it} \quad (5)$$

$\tilde{R}^{h}_{i,t+1}$ is defined according to Eq. 4 and accounts for the uncertainty related to water supply. The error model $\tilde{u}_{it}$ is based on the error structure assumed in Eq. 1. G_{it} is groundwater levels (only in the provinces where groundwater provides a significant proportion of irrigation water), projections of groundwater are the values obtained by the trend followed by data.

Because $P_{i,t+1}$ should be an ex-ante measure, the price index is assumed to be a simple moving average of the previous two seasons, as shown in Eq. 6. We have used the previous two seasons because they give a more accurate prediction of the price index in the following year (compared with historical data).

$$P_{i,t+1} = \frac{P_{i,t} + P_{i,t-1}}{2} \quad (6)$$

4.2.2 Drought characterization in the study areas

Prior to presenting the results of our ex-ante economic projections for irrigated agriculture, we provide a graphical and numerical description of the variation of water resource availability and of the production in six river basins where irrigated agriculture is the main use of water resources and is highly dependent on water management decisions by the River Basin Authorities. The selected basins are Guadalquivir, Guadiana and Duero (draining to the Atlantic Ocean) and Júcar, Ebro and Segura, which are Mediterranean basins (Map 4). The basins analyzed here have been grouped into two categories due to differences in climatic features between drainage areas. The percentage increases of reservoir levels described above are reported for two sub-periods: October (end of irrigation season *t*) through May (beginning of irrigation season *t+1*) and February through May. Thus, one can see how the probability of a certain increase in stock level changes as we approach the start of the irrigation season (Table 4).

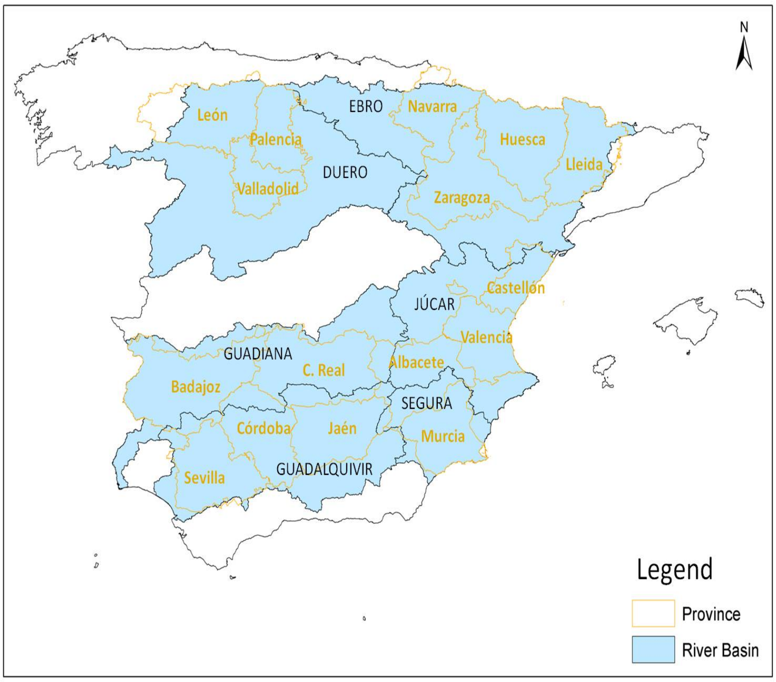
Table 4. Statistics for the percentage increase of storage levels between October and May (Δ oct_may) and between February and May (Δ feb_may) and fitted distribution functions (years 1995 and 2009)

RIVER BASINS		Mean (%)	st.dv.	VC	Var CF (%)	p5	p25	Distribution function (shape, scale)
GUADALQUIVIR	Δ oct_may	17.26	18.55	1.07	21.34	-22.46	4.83	Triang(-30,17.7,60)*
	Δ feb_may	5.69	7.42	1.30		-8.9	-0.42	Triang(-10,8.1,20)*
JÚCAR	Δ oct_may	10.25	10.14	0.99	21.26	-15.77	4.17	BetaGeneral(5.9219,4.414,-30,40)*
	Δ feb_may	4.41	5.29	1.20		-3.4	0.6	Triang(-10,2.7,20)*
EBRO	Δ oct_may	24.44	12.12	0.50	90.18	-12.36	16.98	BetaGeneral(7.2765,4.8665,-30,60)
	Δ feb_may	9.14	8.62	0.94		-3.02	3.6	BetaGeneral(2.7875,4.2768,-10,40)
SEGURA	Δ oct_may	11.11	9.45	0.85	21.86	-17.35	5	BetaGeneral(2.9289,1.9741,-20,30)
	Δ feb_may	4.93	5.11	1.04		-1.85	0.55	BetaGeneral(1.9923,2.8564,-5,20)
GUADIANA	Δ oct_may	13.43	15.79	1.18	37.42	-15.45	2.8	BetaGeneral(2.0549,2.7956,-20,60)*
	Δ feb_may	2.94	4.75	1.62		-2.52	-1.8	Triang(-5,-2.15,15)*
	Δ oct_may	24	20.3	0.85	8.34	-19.5	6.8	BetaGeneral(3.5429,1.6999,-50,60)*
DUERO	Δ feb_may	9.33	8.55	0.92		-10.11	2.8	BetaGeneral(14.502,11.967,-40,50)

*p<0.1
Source: own elaboration based on data reported by the Boletín Hidrológico Mensual (MARM, various years)

The seasonal pattern of rainfall determines the variability of reservoir inflows across the basins. Table 4 reports the statistical measures of the percentage change in reservoir storage levels in the selected Spanish basins. We also report fitted probability distribution functions (PDFs) for the percentage increase of reservoir levels calculated from monthly storage levels for each reservoir from 1995 to 2009. As an example, Figure 10 presents the cumulative distribution functions for the two sub-periods to illustrate the differential stochasticity between a river basin that drains to the Atlantic Ocean (Duero) and one that drains to the Mediterranean Sea (Segura). The graph includes four curves, two for each basin: the 7-month (October-May) storage gain and the 3-month (February-May) storage gain. Segura's storage gains are clearly less dispersed than Duero's.

Map 4. Maps of the analyzed provinces and basins



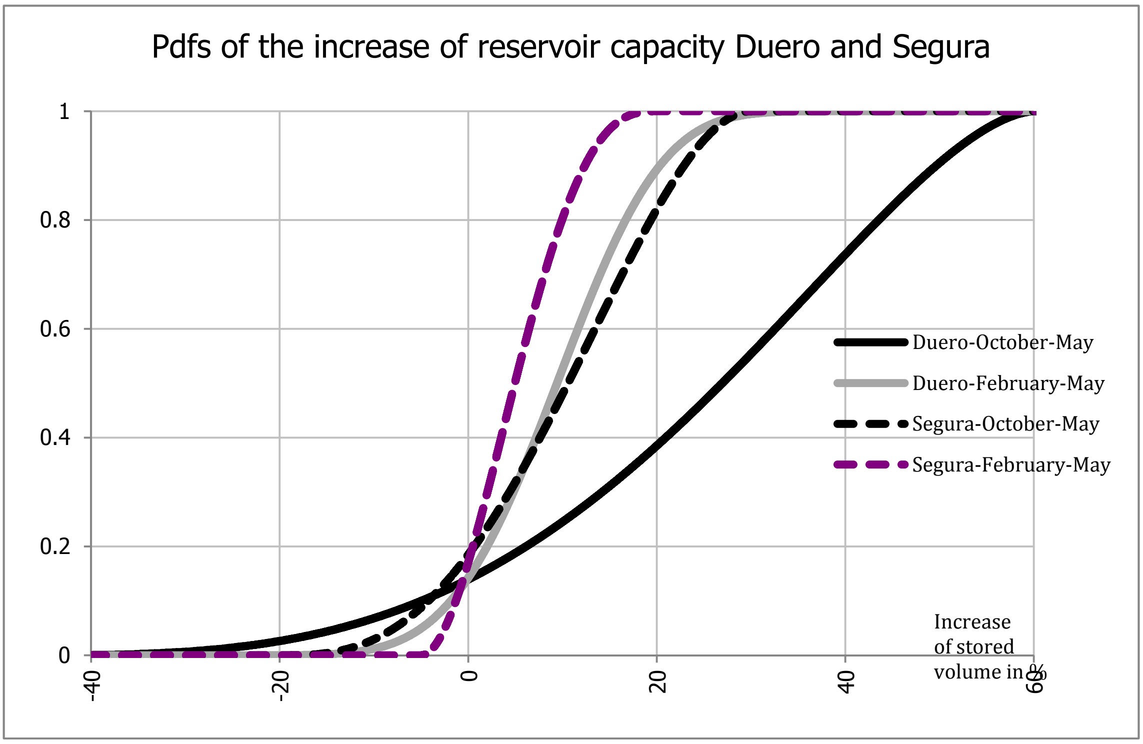
Source: (MARM 2009)

Table 4 shows that in all basins, the coefficient of variation in stock level increases is greater for the February-May period than for the October-May period, although the average increase is smaller. This means that in the short term, there is more variation in storage increases with a much smaller average. Duero and Ebro have the greatest average increases between October and May (both equivalent to about 24% of storage capacity), whereas the Mediterranean basins Júcar and Segura have the smallest (10.25% and 11.11%, respectively). Both the average and variance of winter storage increases are essential to our analysis because they describe the risk borne by irrigators at different times before land allocation decisions are made among competing crops.

Table 4 also reports the 5th and 25th percentiles of the storage increases. We focus on the percentiles in the left tail of PDFs because they are responsible for the downside of farmer productivity due to the shortage of water. In all basins, both the short term (February-May) and the long-term (October-May) 5th percentiles are negative, which means that storage levels can diminish with a probability of 5% each year. Only in Ebro and Duero are short-term left-tail increases quantitatively important and positive (3.60% and 2.80%, respectively), but these values differ for the 7-month period (16.98% and. 6.80%). This indicates that in the Ebro basin, inflows are most likely concentrated in winter (October to February), whereas in the Duero basin they are more evenly distributed between October and May. The main fact that is highlighted from this analysis is that the southern basins (Guadalquivir, Guadiana, Segura and Júcar) are more likely to have smaller increases in their reserve levels (even negative in the Guadiana basin), whereas the northern basins (Duero and Ebro) exhibit much higher storage increments. These differences can be explained by the different precipitation regimes, but they are also due to reservoir characteristics (the small reservoirs with less inter-annual carryover located in the Mediterranean basins would exhibit smaller changes between periods than the large reservoirs located in northern Spain).

Finally, the last column of Table 4 shows the distribution functions that best fit the percentage change in accordance with the $\chi2$ criterion. The PDFs that provided the best fit are General Beta and Triangular, which are bounded functions and allow for positive or negative asymmetries (see Figure 10). These functions are introduced in the Monte Carlo simulations using Eq. 5.

Figure 10. Probability distribution functions of the increase of reservoir capacity for Duero and Segura



Source: Own elaboration

In the second part of this section, the variability of the irrigated production value is analyzed. Irrigated production value (Ipv_{it}, expressed in current euros each year) is calculated according to Eq. 2 for the 16 provinces selected as the most important in terms of irrigated production in Spain. Figure 11 and Figure 12 show the production values of each province relative to its average production value across years (indexed to 100) as well as the water reserves in each basin measured on May 1 each year as a percentage of reservoir capacity. Again the provinces are separated as the basins into two groups: provinces located in basins that drain to the Mediterranean (Figure 12) and those in basins that drain to the Atlantic (Figure 13).

Figure 11. Production value in relative terms with reference to average (100) for the Mediterranean provinces and stock levels of the basin's reservoirs (in % over storage capacity) measured on May 1 (in the bottom right panel)

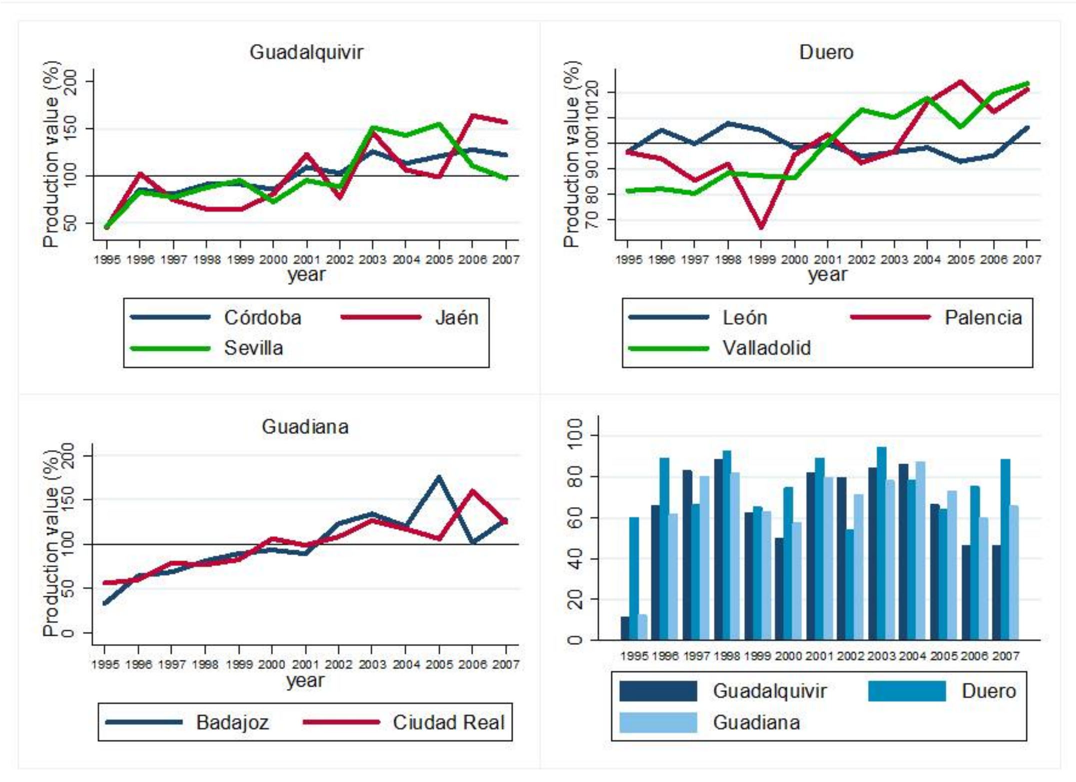
Source: own elaboration with data of the Anuario de Estadística Agraria and Boletín Hidrológico Mensual (MARM, several years)

The Ebro basin's output value varies by roughly 10% with no clear trend in the period under review. The average levels of the reservoirs servicing the provinces of Huesca, Lleida, Navarra and Zaragoza are above 60%. However, drops in reservoir levels in 2002 and 2005 were accompanied by lower production values in these provinces.

The provinces located in the Júcar basin exhibit higher variation in production value probably due to the price volatility of fruits and horticultural crops. However, Albacete exhibits an upward trend in production value due to the increased presence of vineyards in the province (Gil et al. 2009, Garrido et al. 2010). The storage levels of the reservoirs in this basin are highly variable but always run below 50%, which demonstrates the scarcity of surface water.

Finally, the province of Murcia, which is located almost entirely in the Segura basin, shows large variations in production value. However, the trend is clearly positive because of the growth in value added among irrigated surfaces in the province, especially due to the introduction of more profitable crops like vegetables. The variation in agricultural production value seems to not be a function of storage variation in this basin because in most years, the variation is around 20% of capacity. In this province groundwater resources contribute at least 30-40% of all water used in irrigated agriculture.

Figure 12. Production value in relative terms with reference to average (100) for the Atlantic provinces and stock levels of the basin's reservoirs (in % over storage capacity) measured on May 1 (in the bottom right panel)



Source: own elaboration with data of the Anuario de Estadística Agraria and Boletín Hidrológico Mensual (MARM, several years)

Figure 12 presents the data from the provinces located in basins that drain to the Atlantic Ocean. Despite an upward trend in economic productivity, the provinces of the Guadalquivir basin (Jaén, Córdoba and Seville) show strong inter-annual variations, especially in the provinces of Jaén (where olives are the principal crop) and Cordoba. These inter-annual variations are correlated with storage variations that range between 20% (1995) and 80% (2003 and 2005). The provinces located in the Duero basin also show changes in production value (Gil et al. 2009, Garrido et al. 2010).

Finally, the provinces of Badajoz and Ciudad Real (in the Guadiana Basin) exhibit small variations in production value (with a rebound at the end of the analyzed period) and a markedly positive trend. This trend does not correspond to the high variability of storage levels, indicating the strategic role of groundwater for mitigating water shortages, especially in the upper basin where the province of Ciudad Real is located.

4.2.3 Provincial results and discussion

This section first presents the results from the econometric models, one of which is fitted for each province. And then the simulation results for production value of various years in four distinct cases are reported: two cases in the north, represented by the provinces of Huesca (Ebro river basin) and Leon (Duero river basin), and two more provinces in the south, Cordoba (Guadalquivir river basin) and Murcia (Segura river basin). These provinces have substantially different hydrological and economic characteristics.

4.2.3.1 Results for the econometric models at the provincial level

The dependence of irrigated agriculture on water availability in the selected provinces was measured via econometric models (Eq. 1). The models take into account that the irrigated area has changed during the study years (a factor that is captured by the time variable) and that commodity prices also influence the production value (a factor captured by the price index). By using aggregate data, Eq. 1 provides an ex-post analysis that quantifies the economic variation directly related to the lack of irrigation water. Table 5 shows the regression results for the 16 provinces. The coefficients of determination (R^2) together with the level of significance of the explanatory variables provide generally good but somewhat ambiguous results. The last two columns reflect the auto-correlation coefficient (rho) and its statistical significance. The Variance Inflation Factor (VIF) suggests that multicollinearity is not significant in any of the regressions.

The hydrological variable together with the price indices allow the economic impact of drought to be measured in areas highly dependent on stored surface water. However, they also suggest that in some cases price drops are primarily responsible for economic losses even in periods of hydrological scarcity (see provinces like Navarra, Zaragoza, Murcia and Badajoz). Groundwater is an added explanatory variable for the provinces where irrigators use it intensively (Murcia, Albacete, and Ciudad Real), but it was significant only in Murcia. Overall, time (Year) is the most significant (positive) variable for most provinces, and %R (storage level) is significant (positive) in five provinces. The price index, *P*, is significant in seven provinces. The fact that its coefficient is negative in some provinces (Zaragoza and Huesca) suggests that crop price drops result from larger harvests (which in turn may be due to abundant water availability). Crop prices act as a natural hedge for farmers against smaller harvests due to irrigation water shortages.

We also report the elasticity (*Ipv*) with respect to the storage level variations (under the column "Elasticity %R" in Table 5). It was evaluated at the means of both variables, as shown by Eq. 7:

$$\eta_R^i = \frac{\Delta Ipv_i}{\Delta R_i}\frac{\bar{R}_i}{\overline{Ipv}_i} = \hat{c}_i\frac{\bar{R}_i}{\overline{Ipv}_i} \tag{7}$$

The estimated elasticities should be interpreted as follows: as R_i increases by 1%, Ipv_i increases by η_R^i percent. Elasticity is dependent on the estimated parameter $\hat{c}_i$. Among those that are significant (p>0.05), the lowest is in León with 0.141 and the highest is in Zaragoza with 0.597, closely followed by Seville (0.575) and Huesca (0.557). These elasticities suggest that storage level variation (and, by extension, water availability) has a larger impact in the Ebro and Guadalquivir basins than in the Duero basin.

In the Segura basin and (to a lesser extent) in the Ebro basin, crop prices also play an important role. To the extent that the model can isolate the effect of price variations over time, the rest of the explained variation is directly attributable to the hydrological variables.

Table 5. Regression results of the value of agricultural production (n=13 observations)

					Coefficients and Significance					
RIVER BASINS	**PROVINCES**	**R^2**	**Year**	**%R**	**G**	**P**	**Elasticity %R**	**rho**	**autocorr**	**mean VIF**
GUADALQUIVIR	Córdoba	0.99	11392.09(**)	624.94(**)		304.95	0,239	-0.69	- (*)	1.3
	Jaén	0.79	29134.07(**)	-181.26		702.21	0,076	-0.36	-	1.14
	Sevilla	0.85	30954.05(**)	6196.52(**)		16123.99(*)	0,575	-0.13	-	1.23
JÚCAR	Albacete	0.88	16783.51(**)	447.39	-9874.68	-9397.951	0,000	-0.22	-	1.38
	Castellón	0.69	-7357.52	-100.58		55.79	-0,002	0.53	+	1.7
	Valencia	0.79	184.57	-687.88		3700.34	-0,058	-0.49	-	1.79
EBRO	Huesca	0.95	18054.81(**)	4597.07(**)		-7320.83 (**)	0,557	-0.35	+	1.28
	Lleida	0.82	5070.76	2882.26		3460.86(*)	0,364	-0.16	+ (*)	1.2
	Navarra	0.97	7816.25(**)	247.43		2813.95(**)	0,071	0.11	+ (*)	2.02
	Zaragoza	0.97	32384.43(**)	4461.37(*)		-6496.18(**)	0,597	-0.72	- (*)	1.25
SEGURA	Murcia	0.95	-3559.17	3784.79	-459754.6 (*)	5937.66	0,062	-0.47	-(*)	1.21
GUADIANA	Badajoz	0.96	21938.28(*)	2305.27		12999.59(**)	0,192	-0.53	- (*)	2.16
	C. Real[(1)]	0.98	29910.07(**)	645.38	-6904.56	1168.70	-0,040	-0.95	- (*)	1.16
DUERO	León	0.70	-1506.14	403.35(*)		527.92	0,141	0.20	+ (*)	1.31
	Palencia	0.78	1526.66	307.89		2967.05(*)	0,186	-0.09	+	1.55
	Valladolid	0.83	6792.43(**)	-72.68		1013.63	-0,017	0.20	+	2.19

Note: VIF>5 indicates multicollinearity problems
(1) Ciudad Real
P<0.01 *
P<0.05 **
Source: own elaboration

4.2.3.2 Analysis of the projections of the economic drought risk

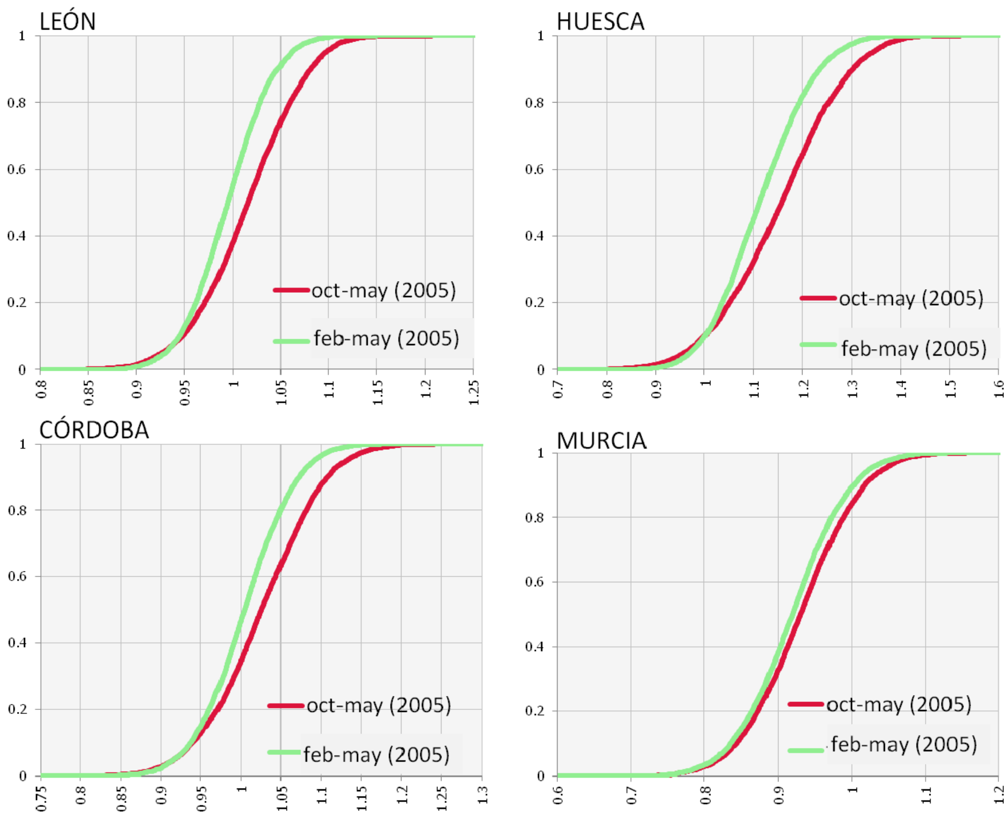
Based on Eq. 5 and the fitted PDFs, the estimated autocorrelation coefficient ρi, and the error variance σi, Monte Carlo simulations are performed to obtain 10,000 values of $\widetilde{Ipv}_{i,t+1}^{h}$ for both the short-term period (February-May) and the long-term period

(October-May). Note that there are two unique $I\widetilde{pv}_{i,t+1}^{h}$ curves for each year because the parameter $\bar{R}_{i,t}^{h}$ represents the initial reservoir storage levels.

The results of the economic drought risk analysis are presented with reference to two different hydrological years (2005 and 2007, a drought year and a wet year, respectively). Those two years have been selected as common for all the examples presented here, even if 2007 is not in all basins a typical wet year.

Figure 13 shows the probability distribution (cumulative probability) of the October-May and February-May production value forecasts expressed in percentage terms. The figure plots the results for the four selected provinces (León, Huesca, Córdoba and Murcia), with the October forecast marked in grey and the February forecast in black.

Figure 13. Cumulative probability of the economic output in relative terms for the two ex–ante projections (October and February) for a dry year (2005)



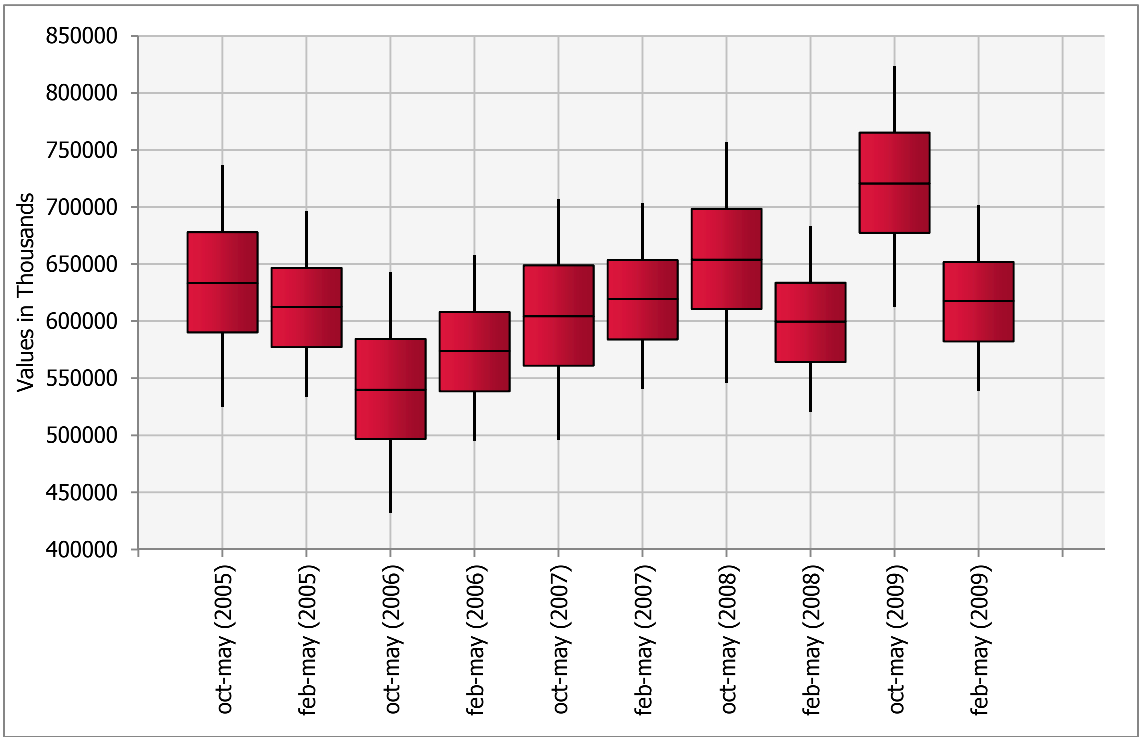
Source: own elaboration

The top panels of Figure 13 show the results for the two northern provinces. The graphs depict a similar situation for Huesca and León wherein the projections for the 2005 season worsen from October to February. However, a closer look reveals that the variability is much greater in Huesca (where 90% of the probability is concentrated between 90% and 120% of the historical average, equivalent to an output value of 489 and 694 million euros for the October to May prediction). By contrast, the range in León is limited to 95% to 100% of the historical average, i.e., about 40 million euros. Thus, the low availability of irrigation water in a dry year causes a downward revision in February of the expected results. However, Huesca is more vulnerable to droughts than León because its economic results are more dependent on the hydrological variable, as we anticipated in the drought characterization section (due to different elasticities, η_R^i, as shown in Table 5).

A more detailed risk analysis in the Ebro basin (represented by the province of Huesca in Figure 14) reflects the consequences of a dry period. The analysis for 2005 reported an average change in the expected production value between October and February of around -20 million euros. The actual production value of the province calculated from the official statistics was 548 million euros, but our ex-ante 5th percentile was approximately the same value. This means that Huesca had suffered a more severe drought than our model projected, although the projection was within our own prediction interval (5% - 95%). Figure 14 reports a drop of -100 million euros in the year 2009 (very dry for the Ebro basin) between the October and February projections. By contrast, in the wet year of 2007 (the end of 2007 was actually wet in the Ebro basin), as shown in Figure 15 the ex-ante 5th percentile estimates a production value increase of 50 million euros.

The bottom of Figure 13 shows the two provinces selected in the south of the Iberian Peninsula. Córdoba's projection in a dry year (2005) clearly shows that the October PDF is less favorable than the February PDF. By contrast, in Murcia, both projections are very similar. In this province, the joint use of surface and groundwater sources provides a much more secure water supply, leaving the price factor as the major source of economic instability (as shown by the coefficients of Murcia's regression model reported in Table 5).

Figure 14. Box-whisker plots of the production of Huesca province measured in 1000 € (2005-2009)



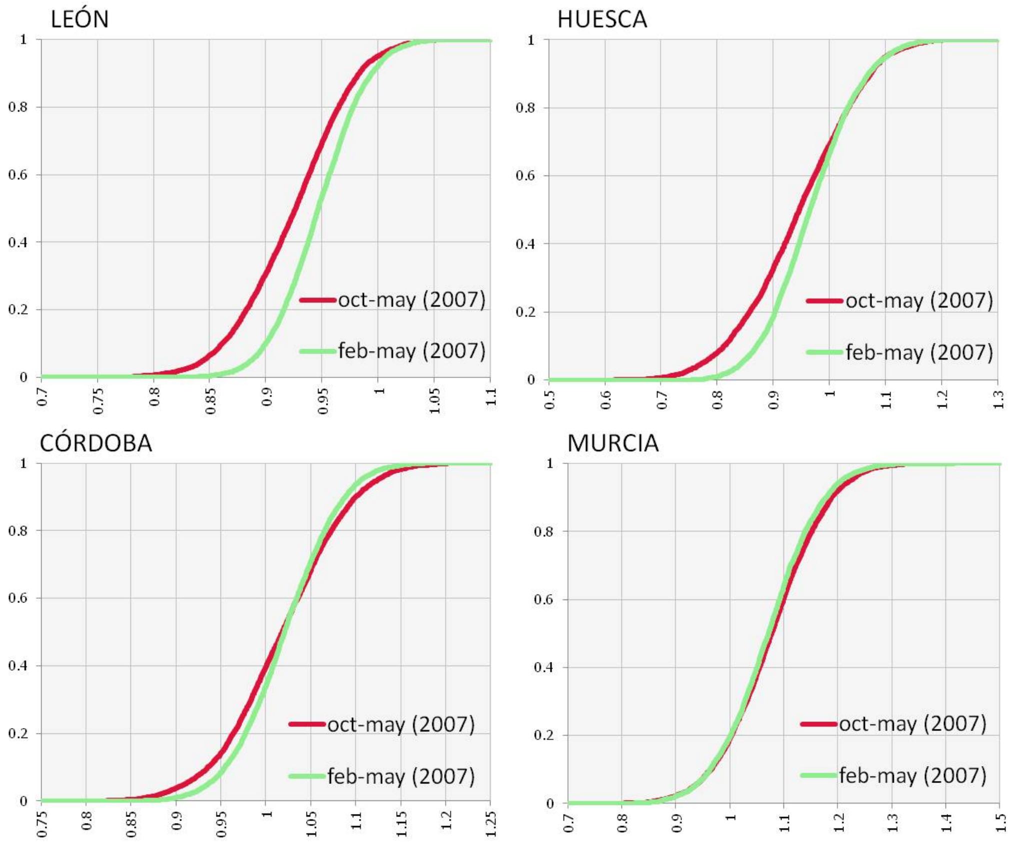
Source: own elaboration

The year 2007 is shown as an example of a wet year (Figure 15). We thus have a different setting than in 2005, with consequences for the risk profile anticipated for the 2007 irrigation season. On October 1, storage levels were running very low, so the economic expectations for the upcoming season were low (see Figure 15). The revision in February changes significantly but quite differently across provinces. In León and Huesca the curves move rightwards, showing a positive change.

However, the situations in Córdoba and Murcia are quite different. Murcia's results do not seem altered as the projection moves from October to February, even though reservoir levels increased from 9% of capacity in October to 17% in February. The province's general water scarcity does not entail greater economic variability because its tight water supply is predictable. This result is confirmed by Tobarra (2008), who shows that the insurance premium for a Murcian farmer to ensure water supply would be in the range of 150 €/ha (a small number compared to the average productivity values in the province in the range of 6,000 €/ha to 8,000 €/ha; Gil et al., 2009). In Cordoba, updating the projections from October to February results in a reduction of both tails and a negligible effect on the expected value, improving the accuracy of the projection.

While the statistical model (Table 5) predicts a result of 283 million euros, which is also the mean of the PDFs (Figure 15), the realized result was 278 million euros, a median prediction for Córdoba.

Figure 15. Cumulative probability of economic output in relative terms for the two ex–ante projections (October and February) for a wet year (2007)



Source: own elaboration

Table 6. 5th and 25th percentiles of the production value (expressed in million €) for the years 2005 and 2009 and variations between the October and February projections

	2005				2006				2007				2008				2009			
Provincia	p05	Var(%)	p25	Var(%)	p05	Var(%)	p25	Var(%)	p05	Var(%)	p25	Var(%)	p05	Var(%)	p25	Var(%)	p05	Var(%)	p25	Var(%)
Córdoba	256.50	0.36	274.81	-1.18	250.60	0.62	268.91	-0.97	258.13	3.00	276.44	1.29	269.61	0.58	287.91	-0.91	279.19	1.21	297.49	-0.27
Jaén	354.22	0.54	446.27	0.42	404.36	0.43	496.41	0.34	451.13	-0.02	543.19	-0.02	458.19	0.38	550.24	0.30	487.85	0.24	579.90	0.20
Sevilla	707.46	1.44	853.48	-3.54	620.78	2.64	766.80	-3.13	652.95	11.90	798.97	4.67	622.79	2.63	768.81	-3.13	635.77	5.40	781.79	-0.78
Albacete	363.94	0.02	397.20	0.02	367.12	0.01	400.39	0.01	404.68	0.01	437.94	0.01	416.06	0.01	449.33	0.00	434.86	0.03	468.12	0.02
Castellón	139.97	0.26	173.93	0.29	134.21	0.14	168.17	0.20	127.00	0.14	160.97	0.20	118.47	0.04	152.43	0.12	110.66	0.45	144.62	0.44
Valencia	596.50	0.68	655.91	0.52	605.62	0.46	665.02	0.32	571.96	0.48	631.37	0.33	531.55	0.35	590.95	0.20	528.63	0.93	588.04	0.73
Huesca	524.38	1.75	589.51	-2.03	430.98	14.83	496.12	8.61	495.33	9.09	560.46	4.26	544.96	-4.47	610.09	-7.46	611.74	-11.95	676.87	-13.93
Lleida	575.96	-0.14	622.41	-1.37	526.32	6.36	572.76	4.50	519.29	4.18	565.73	2.46	511.37	-4.27	557.81	-5.30	546.99	-9.58	593.43	-10.13
Navarra	307.83	-0.18	314.96	-0.30	314.68	0.76	321.82	0.63	316.67	0.43	323.80	0.31	315.06	-0.75	322.19	-0.85	325.50	-1.53	332.63	-1.61
Zaragoza	544.23	0.56	617.89	-2.43	487.49	11.51	561.15	6.79	570.07	6.64	643.74	3.07	642.79	-4.59	716.45	-6.64	722.47	-10.63	796.13	-11.92
Murcia	1084.13	0.06	1171.33	0.09	1039.95	-0.05	1127.14	-0.02	967.80	-0.03	1055.00	0.01	890.44	-0.10	977.64	-0.07	891.05	-0.06	978.24	-0.02
Badajoz	762.49	-1.61	859.29	-2.38	777.29	-1.76	874.09	-2.49	777.79	2.48	874.59	1.28	704.20	-1.87	801.00	-2.66	703.78	1.30	800.58	0.13
C. Real	405.71	0.05	456.82	0.06	436.02	0.05	487.13	0.06	458.41	-0.04	509.52	-0.03	509.81	0.05	560.92	0.06	533.46	-0.01	584.57	0.00
León	209.02	0.46	221.46	-1.27	203.84	2.57	216.29	0.68	206.34	5.36	218.79	3.33	216.86	-2.12	229.31	-3.65	211.49	-0.34	223.93	-2.01
Palencia	122.04	-1.17	133.64	-1.67	130.99	1.40	142.60	0.73	130.12	4.82	141.73	3.86	144.23	-3.94	155.84	-4.16	142.80	-1.91	154.41	-2.28
Valladolid	228.59	0.29	239.27	0.37	236.21	-0.04	246.89	0.04	244.45	-0.47	255.13	-0.37	258.17	0.65	268.85	0.70	265.66	0.37	276.34	0.43

Source: own elaboration

To present all of the provinces and analyzed years in a snapshot, Table 6 reports the 5th and 25th percentiles of the projected economic results (in million euros) for 2005 through 2009. The right column beside each percentile (denoted by Var(%)) is the variation of the percentiles between October and May and between February and May. A negative change of Var(%) is associated with fattening of the left tail of the PDF. The gray shading denotes the cases where the variation exceeds 3%. A general inspection of both 5th and 25th percentiles shows that the left tail does not vary significantly between October to May and February to May. This means that the expectation of extreme results (left tail) does not change during this period.

The largest variations are found in the Ebro basin (the provinces of Huesca, Lleida and Zaragoza), and the largest shift is in Huesca's 2006 results, where the 5th percentile increased by 14.83%. In Seville, the 5th percentile increased by 11.9% between October and February in 2007. From a risk perspective, it is relevant to note that in some provinces (Seville, Huesca, León, among others), the sign of Var(%) is different between the 5th percentile and the 25th percentile, with the former being positive and the latter negative. This means that the risk profile changes, shifting some probability mass from the extreme left tail to the middle left tail and reducing the chances of the worst possible outcome.

While the changes in the percentiles are relatively small, a 5% increase or decrease of the 8-billion-euro output of Spanish irrigated agriculture (totaling the 25th percentiles for 2009) is equivalent to ±400 million euros. This is equivalent to the output of an average Spanish province. Thus, these results reinforce the value of this simulation method in that it allows us to monitor economic results and anticipate possible profits and losses for the agricultural sector, which in many cases are significant.

4.3 Linking agricultural productivity with water availability and water demand in a risk context: An application for managing hydrological risks at a local level[8]

The importance of water scarcity in irrigated agriculture in Spain provides the rationale for this section, which analyses and evaluates the risk of water scarcity on the economic result of this kind of agriculture. Water scarcity is understood here as the deficiency between water supply and demand. This risk may be monitored on a real-time basis, which makes the procedure very useful for water users. For this aim, as in the first part of the chapter, a number of regression models was estimated to explain irrigated agricultural productivity based on crop price indices, a time trend and water availability, but this section is performed at a local level. These models, which correct for auto-correlation, yield good explanatory power. In the second part ex-ante simulations of agricultural productivity using fitted distribution functions of water balance are carried out. The risk model framework provides the basis for a real time drought management system through a variety of distribution functions of expected economic results, which are influenced by both supply and demand risk. The revisions prior to the irrigation season are made on a more precise time lap, so that they can be revised on a monthly basis. The results of the simulation show how this kind of risk model can be used to anticipate the effects of droughts and complement the hydrological models used to manage interchangeably water storage or water demand in years of scarcity. Different risk profiles are identified to confirm and contrast results of previous section in a more detailed way. For example, in Genil-Cabra (located in Córdoba) we found that the resilience of the system after a drought period is very high, whereas in La Plana de Castellón the risk of irrigation area abandonment is increasing year by year. In Genil-Cabra the estimated losses were 60 million euros in 2007. The models were applied to some of the most agriculturally relevant irrigation districts in Spain.

The aims of this section are twofold. First, the econometric model is estimated to explain the variability in the economic performance of irrigated agriculture of small areas, using, among other explanatory variables, water availability in the irrigation

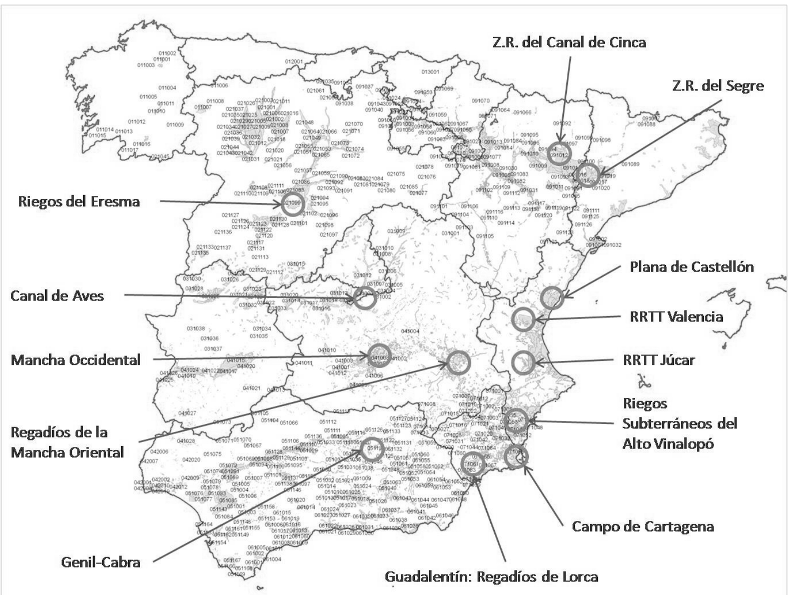
[8] This section has been published in Gil, M. A. Garrido and A. Gómez-Ramos. "How to link agricultural productivity, water availability and water demand in a risk context?" *Spanish Journal of Agricultural Research* 8(S2): 207-220, 2010

districts (the water level in the corresponding reservoirs before the start of the irrigation season). And, the second part develops a methodology to obtain the ex-ante probability distribution functions of the monthly value of agricultural production before the irrigation season starts considering both risk of supply and demand. A Monte-Carlo simulation model is proposed in which the stochastic balance of water – supply less demand – provides the basis for a real-time drought management system. By breaking up the period between the end of one irrigation season (October) and the beginning of the next (spring) into sub-periods (months), the risk analysis model provides a variety of distribution functions for the expected economic results, which can be revised before the beginning of the irrigation season. With this approach, possible drought impacts and early warning systems can be anticipated. This methodology was applied to a representative sample of irrigation districts in various Iberian basins in Spain.

4.3.1 Study areas: the irrigation districts

Map 5 shows the locations of the irrigation districts included in the study. They represent the diversity of the Spanish basins that are prone to periods of water scarcity and drought. In general, the southern and southeastern basins are more water-scarce than the ones in the north, but, finally the vulnerability to droughts depends not only on the reliability on water sources of each basin but also on the demand.

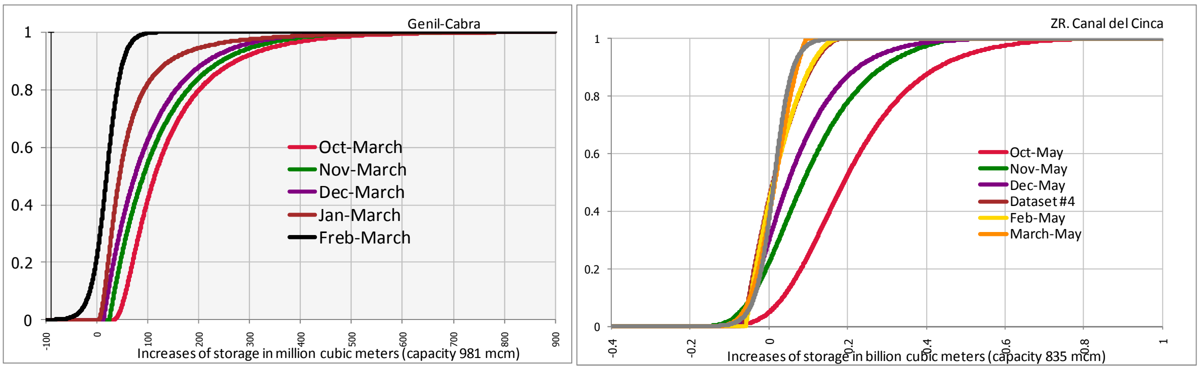
Map 5. Locations of the Spanish irrigation districts considered. RRTT: Riegos Tradicionales



Source: Own elaboration

To provide an idea of the monthly changes in supply availability and the importance of drought-risk analyses, cumulative probability distribution functions are shown below for two districts, Genil-Cabra in the Guadalquivir basin in Andalusia and Zona Regable del Canal de Cinca in the Ebro basin in Aragón (Figure 16). The graphs depict the different risk profiles of both districts and show the potential to perform risk analyses on a monthly basis. The fact that the cumulative distribution functions (CDFs) move from right to left as time goes by permits the same approach to be used to track the ex-ante risk analysis of the economic performance for each district.

Figure 16. CDFs of stock increases in the reservoirs serving Genil-Cabra and Zona Regable del Cinca (see Table 8). mcm: million cubic meters



Source: Own elaboration

4.3.2 Methods: water supply and water demand economic risks

First, an adaptation of the previous general model shown on Part II's introduction was made in an attempt to explain the variation in the irrigated production value in the irrigation districts. Then the risk perspective is introduced through the variability of water inflows into each storage system. This was matched with the variations in the water demands of crops in order to estimate the possible deficit of water available for the irrigation district. Taking into account the econometric model, the economic drought risk in light of the uncertainty in irrigation water supply sources was then simulated. The risk analysis considers the crops' changing water demands during the growing season, to facilitate monthly revisions of the ex-ante analysis of drought impacts.

4.3.2.1 *Econometric model at the irrigation district level*

The econometric model explains the variation in the economic value of agricultural production with three explanatory variables: the water availability, the time trend and the crop prices received by farmers in each geographical unit of analysis. This is the general model in which the variable to be explained is again the Ipv_{it} (irrigated production value), which we estimated at a local level (index *i* for each district) and for each year (index *t*). The model is defined for each unit *i* as follows:

$$Ipv_{it} = a_i + b_i T_t + c_i WA_{it} + d_i P_{it} + u_{it} \tag{8}$$

Where $u_{it} = \varepsilon_{it} + \rho_i \varepsilon_{it-1}$; $E(\varepsilon_t) = 0$ and $\sigma^2_{\varepsilon i} = \sigma^2_i$,

WA_{it} is the water availability variable that in this section will be treated as the specific water resources available for each irrigation district (measured in their corresponding reservoir storages) and it corresponds to the total volume of water used during the entire irrigation season. T_t is the time trend between 1996 and 2005, and P_{it} is the price index for each unit *i* and each year *t*.

The production value (Ipv_{it}) was calculated from the area irrigated and the yield of each crop along with its annual price as in previous section (Eq. 2) as well as the price index (P_{it}) that was obtained at a local level following also Eq. 3 from previous section.

The error term is estimated by the Prais-Winsten method for time series. The Durbin-Watson statistic was evaluated, correcting the effect of the errors' serial correlation.

4.3.2.2 *Methodological framework to analyze the economic risk of water scarcity at a local level*

The proposed methodology is meant to evaluate the economic risk of water shortage for the irrigators. The stochastic variable, water availability ($\widetilde{WA}_{it}$), is supposed to be partially responsive to the variations in the irrigated agriculture production values. It is, therefore, part of the instrument that connects the variability in water availability to the variability in the economic performance of the farming sector. The other source of variation related to water is the demand made by the irrigators. Both supply and demand are closely related and the risk of undergoing water scarcity cannot be thought without any of them. In the following sections, how WA_{it} was transformed to capture both demand and supply risk is described.

The water risk framework is presenter below: water demand and supply variability are modelized to generate water balances in terms of risk.

4.3.2.3 Estimates of water demand variation

The aim of this part of the methodology is to evaluate variations in water demand based on the observed cropping patterns in each district between 1996 and 2005, for this aim two estimation procedures have been carried out. Both of them estimate the blue water (crop´s necessary water from irrigation sources) that is assumed to be the water demand from planted crops. In Dem1 (see Table 7), the 'blue water' demand was estimated taking into account the actual precipitation and the potential evapotranspiration (PET) calculated using the Penman Monteith equation (Garrido et al. 2010). In Dem2, the 'blue water' was estimated following the method proposed by FAO (Allen 2003).

Table 7 allows for comparison on the estimations, Dem2 is almost always lower and its calculation procedure is more reliable. Variation coefficients are greater in Dem2, which may indicate both changes in crop patterns and changes in water demand management during the analyzed period. Dem1 is calculated between 1996 and 2005, while Dem 2 is calculated between 2001 and 2009, the latest represent more recent demand situation with more updated crop patterns.

Therefore, the water demand variable Dem2, which provides the most accurate estimate of the demand, has been used to the analysis in all districts. Hence, it will be generally called $\widetilde{D}_i$ (it is the stochastic demand variable from Dem2) and it has been fitted with alternative distribution functions (DFs) chosen among those that yield the best fit according to Chi-square test. These DFs subsequently provided the demand side in the analyses of the stochastic water balances. Among the DFs with the best fit, we selected truncated normal distributions, a discrete distribution (based on 10 percentiles) and uniform distributions. As the statistics reported in Table 7 attest, the coefficients of variations are in the range of 0.15-0.25, except for the Canal de Aves district, which has a coefficient of variation of 0.39.

Table 7. Estimations of the irrigation water demand (in millions of m^3) with two procedures

District	VARIABLE	Mean	st. dev.	v.c.	p5	p25	p50	N	Years
Eresma	Dem1	$8.74\cdot10^{7}$	$1.46\cdot10^{7}$	0.17	$6.37\cdot10^{7}$	$7.89\cdot10^{7}$	$8.85\cdot10^{7}$	10	(1996-2005)
	Dem2	$6.69\cdot10^{7}$	$1.32\cdot10^{7}$	0.20	$4.63\cdot10^{7}$	$5.66\cdot10^{7}$	$7.08\cdot10^{7}$	9	(2001-2009)
C. Aves	Dem1	$9.29\cdot10^{7}$	$1.55\cdot10^{7}$	0.17	$5.69\cdot10^{7}$	$8.65\cdot10^{7}$	$9.51\cdot10^{7}$	10	(1996-2005)
	Dem2	$4.82\cdot10^{7}$	$1.90\cdot10^{7}$	0.39	$2.45\cdot10^{7}$	$3.25\cdot10^{7}$	$4.72\cdot10^{7}$	10	(2000-2009)
M. Occidental	Dem1	$6.67\cdot10^{8}$	$1.14\cdot10^{8}$	0.17	$5.18\cdot10^{8}$	$5.60\cdot10^{8}$	$6.88\cdot10^{8}$	10	(1996-2005)
	Dem2	$5.78\cdot10^{8}$	$8.69\cdot10^{7}$	0.15	$4.58\cdot10^{8}$	$5.03\cdot10^{8}$	$5.84\cdot10^{8}$	10	(2000-2009)
Genil	Dem1	$2.67\cdot10^{8}$	$2.88\cdot10^{7}$	0.11	$2.17\cdot10^{8}$	$2.47\cdot10^{8}$	$2.69\cdot10^{8}$	10	(1996-2005)
	Dem2	$2.35\cdot10^{8}$	$3.37\cdot10^{7}$	0.14	$1.87\cdot10^{8}$	$2.23\cdot10^{8}$	$2.31\cdot10^{8}$	9	(2001-2009)
C. Carta	Dem1	$2.64\cdot10^{8}$	$1.62\cdot10^{7}$	0.06	$2.32\cdot10^{8}$	$2.52\cdot10^{8}$	$2.66\cdot10^{8}$	10	(1996-2005)
	Dem2	$2.69\cdot10^{8}$	$3.77\cdot10^{7}$	0.14	$1.96\cdot10^{8}$	$2.42\cdot10^{8}$	$2.71\cdot10^{8}$	10	(2000-2009)
Lorca	Dem1	$1.03\cdot10^{8}$	7,244,676	0.07	$8.93\cdot10^{7}$	$9.97\cdot10^{7}$	$1.02\cdot10^{8}$	10	(1996-2005)
	Dem2	$1.01\cdot10^{8}$	$1.25\cdot10^{7}$	0.12	$8.72\cdot10^{7}$	$8.99\cdot10^{7}$	$9.93\cdot10^{7}$	10	(2000-2009)
Plana	Dem1	$1.07\cdot10^{8}$	$1.96\cdot10^{7}$	0.18	$6.91\cdot10^{7}$	$9.48\cdot10^{7}$	$1.12\cdot10^{8}$	10	(1996-2005)
	Dem2	$7.98\cdot10^{7}$	$2.06\cdot10^{7}$	0.26	$5.24\cdot10^{7}$	$6.67\cdot10^{7}$	$7.66\cdot10^{7}$	10	(2000-2009)
RRTT[1] Valencia	Dem1	$1.05\cdot10^{8}$	$1.50\cdot10^{7}$	0.14	$7.25\cdot10^{7}$	$9.98\cdot10^{7}$	$1.07\cdot10^{8}$	10	(1996-2005)
	Dem2	$7.78\cdot10^{7}$	$1.95\cdot10^{7}$	0.25	$4.33\cdot10^{7}$	$6.81\cdot10^{7}$	$7.12\cdot10^{7}$	10	(2000-2009)
M. Oriental	Dem1	$5.52\cdot10^{8}$	$1.08\cdot10^{8}$	0.20	$4.41\cdot10^{8}$	$4.73\cdot10^{8}$	$5.35\cdot10^{8}$	10	(1996-2005)
	Dem2	$4.27\cdot10^{8}$	$8.12\cdot10^{7}$	0.19	$3.05\cdot10^{8}$	$3.60\cdot10^{8}$	$4.34\cdot10^{8}$	10	(2000-2009)
RRTT[3] Júcar	Dem1	$3.00\cdot10^{8}$	$3.82\cdot10^{7}$	0.13	$2.20\cdot10^{8}$	$2.70\cdot10^{8}$	$3.17\cdot10^{8}$	10	(1996-2005)
	Dem2	$2.26\cdot10^{8}$	$5.00\cdot10^{7}$	0.22	$1.49\cdot10^{8}$	$1.93\cdot10^{8}$	$2.21\cdot10^{8}$	10	(2000-2009)
Vinalopó	Dem1	$7.53\cdot10^{7}$	8,788,780	0.12	$5.98\cdot10^{7}$	$7.23\cdot10^{7}$	$7.61\cdot10^{7}$	10	(1996-2005)
	Dem2	$7.54\cdot10^{7}$	$1.46\cdot10^{7}$	0.19	$5.55\cdot10^{7}$	$6.67\cdot10^{7}$	$7.24\cdot10^{7}$	10	(2000-2009)
Cinca	Dem1	$3.90\cdot10^{8}$	$8.16\cdot10^{7}$	0.21	$2.57\cdot10^{8}$	$2.95\cdot10^{8}$	$4.30\cdot10^{8}$	10	(1996-2005)
	Dem2	$2.82\cdot10^{8}$	$3.16\cdot10^{7}$	0.11	$2.42\cdot10^{8}$	$2.43\cdot10^{8}$	$2.95\cdot10^{8}$	6	(2004-2010)
Segre	Dem1	$2.05\cdot10^{8}$	$1.40\cdot10^{7}$	0.07	$1.89\cdot10^{8}$	1.92·108	$2.02\cdot10^{8}$	10	(1996-2005)
	Dem2	$1.50\cdot10^{8}$	$2.84\cdot10^{7}$	0.19	$1.17\cdot10^{8}$	1.32·108	$1.38\cdot10^{8}$	10	(2000-2009)

Source: Own elaboration
[1]RRTT: Riegos Tradicionales

The hydrological year is divided into two periods: the first period goes from October 1st, the beginning of the hydrological year, until the beginning of the irrigation season, which varies significantly between zones. The second period goes from the beginning of the irrigation season until September 30th. It is divided into these two groups because there are significant differences in terms of water demand due to crops.

In the first period, the ex-ante water shortage risk was evaluated. The water demand ($\widetilde{D}_{i,t+1}$) was calculated to fulfill the entire crops' water needs for the whole season. During the second period, the expected crop demand is re-evaluated on a monthly basis to include only the demand for the remaining months of the season ($\Delta\widetilde{D}^{j}_{i,t+1}$).

4.3.2.4 Estimates of water supply variation

The variation in water supply results from the monthly changes in the reservoirs that service each irrigation district. The analysis was based on the records of the reservoirs' monthly stocks between 1989 and 2007. All reservoirs servicing each unit were included in the analysis, but their specific allocations have been ignored except for the minimum storage levels, which were assumed to be equal for each month to the minimum levels observed from the records. October 1st is assumed to be the beginning date of the hydrological year, although actual water application does not begin until February or March of the following year. The start of the irrigation season varies significantly from north to south within Spain, but usually it begins earlier in the southern districts. As it was said, the analysis is divided into two different periods, the first of which goes from October until the beginning of water application and the second covers the duration of these applications.

In the first period, the stochastic availability of water in a given reservoir, for month h before the irrigation season starts, is given by:

$$\tilde{R}^{h}_{i,t+1} = \bar{R}^{h}_{i,t} + \Delta\tilde{R}^{h}_{i,t+1} \tag{9}$$

Where $\tilde{R}^{h}_{i,t+1}$ is the random variable representing the available resources stored in a reservoir when season *t+1* begins. This variable results from the sum of the known storage *h* months before the actual irrigation application begins, $\bar{R}^{h}_{i,t}$ (the actual storage when the projection is made) and the stochastic increase, $\Delta\tilde{R}^{h}_{i,t+1}$, which is the random variable that defines the uncertain increase of stock during the months between *h* and the beginning of the season. $\Delta\tilde{R}^{h}_{i,t+1}$ can be represented by a distribution function specific for the reservoir and for the month *h*. This variable has been estimated using the records of time on the reservoir stock and provides the probability of having enough water for covering the demands for the whole season before the season begins. It allows us to perform ex-ante supply risk projections on a monthly basis. Table 8 reports the probability distribution functions (PDFs) for the districts for which results are offered in the following sections.

Table 8. Estimated probability distribution functions (PDFs) of the supply increases (in millions of m^3) of five districts and statistical values (Standard Deviation, 5th and 25th percentiles)

District		**Average**	**SD**	**p5**	**p25**	**Fitted PDF**[1]
Genil-Cabra	Δ oct_mar	146.27	104.75	49.72	76.85	Invgauss
	Δ nov_mar	120.92	95.87	29.79	52.44	Exponential
	Δ dec_mar	102.38	89.89	17.81	31.84	Exponential
	Δ jan_mar	70.74	86.92	11.57	25.92	Loglogistic
	Δ feb_mar	19.52	27.15	-24.56	3.07	Loglogistic
La Plana de Castellón	Δ oct_feb	18.96	14.51	0.04	8.73	Extvalue
	Δ nov_feb	17.37	10.94	-0.69	9.98	Norma
	Δ dec_feb	13.42	11.96	-2.1	5.68	Loglogistic
	Δ jan_feb	7.35	8.3	-3.46	1.52	Extvalue
RR TT[2] Valencia	Δ oct_feb	25.29	20.48	4.81	11.3	Invgauss
	Δ nov_feb	20.9	14.53	-2.95	12.05	Loglogistic
	Δ dec_feb	28.42	22.23	-0.64	9.58	Triangular
	Δ jan_feb	9.6	12.18	-2.02	0.87	Exponential
Cinca	Δ oct_may	215	158.23	0.85	100.81	Extvalue
	Δ nov_may	105.36	128.29	-73.87	9.22	Pearson5
	Δ dec_may	74.19	111.92	-56.77	-10.78	Weibul
	Δ jan_may	20.35	59.67	-57.61	-30.1	Triangular
	Δ feb_may	21.39	56.87	-53.01	-26.7	Triangular
	Δ mar_may	12.89	45.03	-65.85	-18.2	Invgauss
	Δ apr_may	12.51	41.44	-55.26	-12.62	Logistic

Source: MARM (various years).
[1]Results of the estimation are available from the author upon request, including the exact parameters of each PDF. [2] RRTT: Riegos Tradicionales

4.3.2.5 Estimates of the water balance equation

The water balance was divided into the same two analysis periods as the water supply and demand. Different assumptions were made for each stage. In the first period, we assumed that storage varies from month to month but stochastic irrigation demand does not. In the second period, we assumed that storage does not depend on future increases as water is consumed, but the demand varies from month to month as the season approaches its end.

— Stochastic water balance before the start of the irrigation season

The difference between supply and demand yields the stochastic water balance available for irrigation. Let $\bar{S}_i$ be the minimum storage reservoir that must be maintained in all circumstances, either because environmental services must be met or because operational restrictions apply. The stochastic water balance is thus defined as:

$$\tilde{B}_{i,t+1}^{h} = \tilde{R}_{i,t+1}^{h} - \widetilde{D}_{i,t+1} - \bar{S}_i \tag{10}$$

$\tilde{B}_{i,t+1}^{h}$ is the stochastic volume of water available from the reservoir for the upcoming irrigation season *t+1*, evaluated h months before the irrigation season begins. Note that in Eq. 10, monthly revisions are based only on the revisions of $\tilde{R}_{i,t+1}^{h}$, which, according to Eq. 9, originates from the monthly stock increases $\Delta\tilde{R}_{i,t+1}^{h}$. $\widetilde{D}_{i,t+1}$ is the water demand distribution function for the entire upcoming irrigation season.

— Stochastic water balance once the irrigation has started

When the irrigation season has already started, in month *j* (*j>h*), the stochastic water balance is defined by:

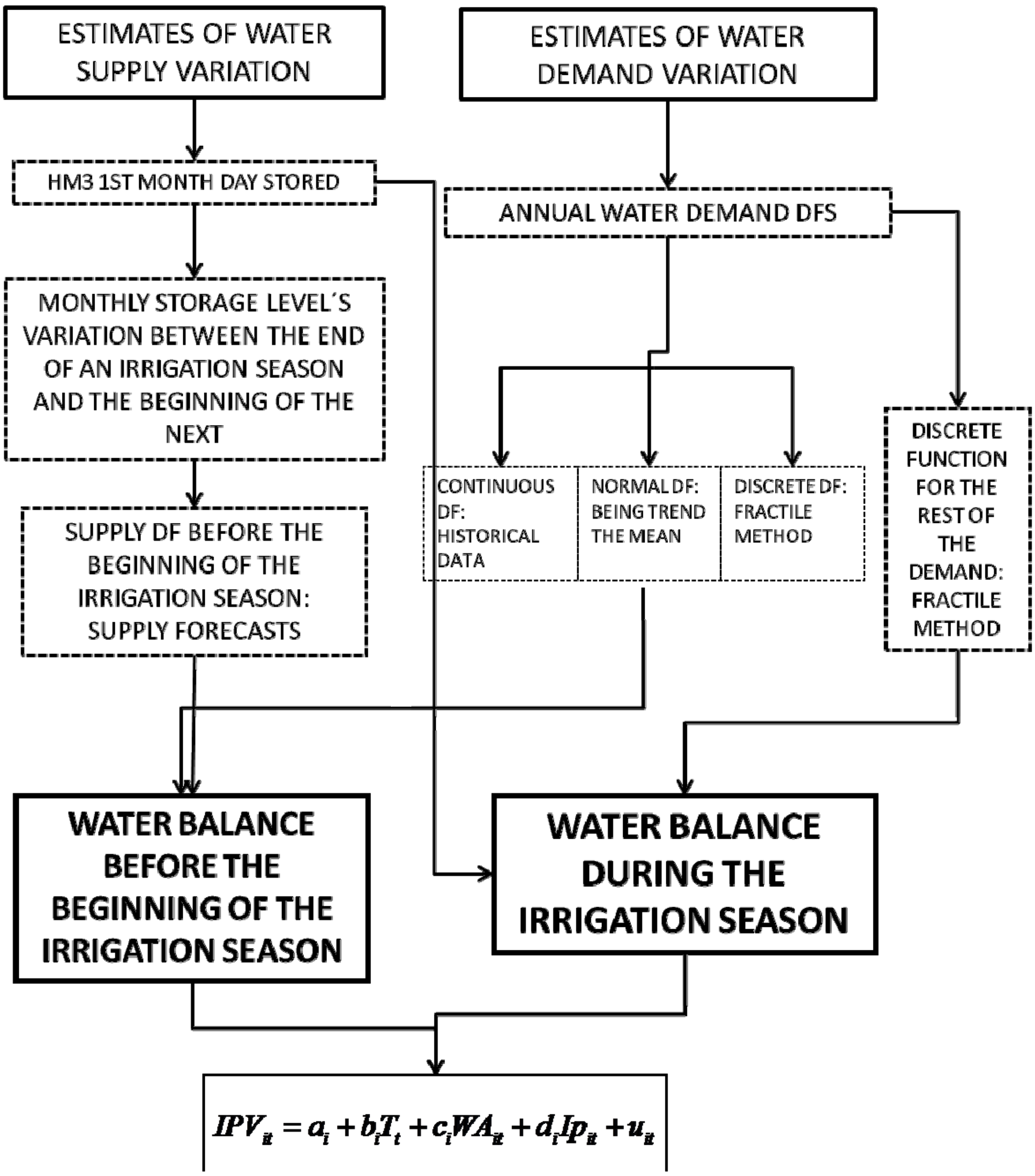
$$\tilde{B}_{i,t+1}^{h} = \bar{R}_{i,t}^{h} - \bar{S}_i - \Delta\widetilde{D}_{i,t+1}^{j} \qquad j>h \tag{11}$$

Where $\bar{R}_{i,t}^{h} - \bar{S}_i$ is the deterministic stock available at the beginning of month h, and $\Delta\widetilde{D}_{i,t+1}^{j}$ is the stochastic remaining water demand from month j until the end of the season.

4.3.3 Risk analysis of the economic performance of the irrigation districts

Econometric models were used to transform hydrological results into economic values. Establishing relations between the water and economic results for each district, a range of values in euros was obtained as a result of water availability (see Figure 17). Those values are ex-ante economic predictions made before the irrigation season had begun and during it. Based on the past economic performance of each irrigation district, a differentiation can be made between the districts that have experienced changes in irrigated acreage and those whose irrigated acreage has remained stable.

Figure 17. Scheme of the risk analyses. DF: distribution function



Source: Own elaboration

— Districts with stable irrigated acreage

Based on Eqs. 10 and 11, it may be the case that $\tilde{B}^{h}_{i,t+1}$ includes only positive numbers or negative and positive numbers. If it is positive with probability p=1, which means that the stock available will always meet the demand, the stochastic economic value is assumed to be:

$$\widetilde{Ipv}^{h}_{i,t+1} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i p75(\tilde{B}^{h}_{i,t+1}) + \hat{d}_i \bar{P}_{it} + \tilde{u}_{it}$$

$$\text{With } \tilde{u}_{it} = \tilde{\varepsilon}_{it} - \hat{\rho}\tilde{\varepsilon}_{i,t-1} \quad (12)$$

Where $p75(\tilde{B}^{h}_{i,t+1})$ is the 75th percentile of $\tilde{B}^{h}_{i,t+1}$, $\bar{P}_{it}$ is the moving average of the price indices considering t-1 and t-2 and $\hat{\rho}$ is the estimated serial autocorrelation.

If $\tilde{B}^{h}_{i,t+1}$is negative for p>0, then:

$$\widetilde{Ipv}^{h}_{i,t+1} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i(\tilde{R}^{h}_{i,t+1} - \bar{S}_i) + \hat{d}_i \bar{P}_{it} + \tilde{u}_{it} \quad (13)$$

— Districts without stable irrigated acreage

For districts that have experienced changes in the irrigated acreage, a two-stage procedure was applied. First, the following quadratic model was fitted:

$$Suf_{it} = a_i + b_i T_t + c_i WA_{it} + d_i WA^2_{it} + \varepsilon_{it} \quad (14)$$

$$\text{with } E(\varepsilon) = 0 \text{ and } \sigma^2 = \sigma^2$$

Then, Eq. 12 was used to simulate the irrigated surface as follows:

$$\widetilde{Suf}^{h}_{i,t+1} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i(\tilde{B}^{h}_{i,t+1}) + d_i(\tilde{B}^{h}_{i,t+1})^2 + \hat{\varepsilon}_{it} \quad (15)$$

where $\widetilde{Suf}^{h}_{i,t+1}$ is the stochastic irrigated surface dependent on the water balance (Eq. 14). In the second stage, the following model was fitted and subsequently used for the stochastic simulation:

$$Ipv_{it} = a_i + b_i Suf_{it} + \varepsilon_{it} \quad \Longrightarrow \quad \widetilde{Ipv}_{i,t+1}^{h} = \hat{a}_i + \hat{b}_i \overline{Suf}_{it} + \tilde{\varepsilon}_{it} \qquad (16)$$

4.3.3.1 *Stochastic simulation*

The main objective posed here is to translate the stochastic nature of the water stock changes into economic evaluations in the form of probability distributions. The modeling strategy presented above involves two sources of stochasticity. One originated from the hydrological processes, which include the water supply and demand, and the resulting water balance, $\tilde{B}_{i,t+1}^{h}$. The other stochastic factor is generated as a result from the variability of the econometric model. Since a monthly approach has been developed, each district has several specific stochastic supply variables (as many as the number of months preceding the irrigation season) and several stochastic demand variables (one for the period prior to the beginning of irrigation and the others corresponding to the remaining months during the irrigation period). In addition, since the connection between the hydrological variables and the economic performance is not deterministic, there are modeled errors involved in the causation effects that must also be taken into account. In sum, the Monte-Carlo simulations include both hydrological random variables and error terms.

As a hypothesis, one could expect that the crops' water demand is dependent on the cropping patterns and that the water storage before the planting season influences the choice of crops. That is, if storage before the season begins is low, irrigators would tend to plant less water demanding crops and to reduce the area in which more water demanding crops were grown. This hypothesis was tested and found that observed district's water demand was not explained by the water storage before the irrigation season began. We compared the stock levels in October, November and December with the calculated water demand for each upcoming season in those months. The variations in the supply and demand variables were not correlated. This check supports the assumption that water demand variation and water supply variation are independent variables, at least before the irrigation season begins.

4.3.4 Irrigation District Results

This section presents first the results of the econometric models, reporting the regression models fitted for each irrigation district. And then the simulation results are reported for the value of production for various years in a selection of four distinct cases.

4.3.4.1 Results of the econometric models for the irrigation districts

The dependence of the value of irrigation production in the selected districts on water availability was measured via the econometric model (Eq. 8). This model takes into account that the irrigated area changed over the years of study (a factor that is captured by the trend) and that commodity prices also influence the value of production (a factor that is captured by the price index). Using aggregate data, Eq. 8 provides an ex post analysis that quantifies the economic damage directly related to the lack of irrigation water, isolating the effect of crop value losses attributable to falling prices.

Table 9. Econometric estimations of economic results with two water demands (based on Eq. 8)

	Dem1					Dem2				
District	Ad-R^2	N	Year	Dem1	Price index	Ad-R^2	N	Year	Dem2	Price index
Genil-Cabra	0.92	10	6,063.85*	-83.64	635.79	0.92	10	6,138.49	-161.42	657.83
Vinalopó	0.60	10	1,041.94	47.49	628.86	0.63	10	1,146.49	209.35	577.96
RR TT Júcar	0.84	10	-11,908.86**	-95.91	297.04	0.90	10	-12,010.36**	-173.32	398.54
RR TT Valencia	0.99	10	-1,838.85	62.53	917.33	0.92	9	-1,811.17*	116.03	908.18**
Plana Castellón	0.81	10	-9,665.85*	-230.05	1,000.18	0.82	10	-8,297.04	-135.09	1,143.57
M. Oriental	0.87	9	32,334.74*	-110.06	-3,203.15	0.81	10	27,334.14*	62.31	1,259.89
C. Cartagena	0.46	10	8,128.28	14.01	416.68	0.44	10	7,720.24	331.90	1,044.94
R. de Lorca	0.28	10	-6,905.45	-309.52	3,044.12	0.26	10	-6,860.48	553.70	3,312.99
ZR[1] del Segre	0.97	10	-2,785.48	-582.36	1,286.54*	0.94	10	-2,710.87	-383.18	942.59
M. Occidental	0.97	10	9,292.59	949.048*	-5045.56	0.92	10	27,089.41 (*)	-15.66	958.25
Eresma	0.86	10	-361.69	214.97	312.19	0.68	10	-1,736.00	514.75	554.24
Canal de Aves	0.83	10	-1,287.99	518.37**	58.34	0.82	10	-1,146.84	367.84*	-62.39

*p< 0.05; ** p<0.01

[1] ZR: Zona Regable

Table 9 shows the results of the regressions corresponding to the 13 districts. The coefficients of determination (adjusted R^2), together with the level of significance of the explanatory variable, Dem1 or Dem2, provide generally good but somewhat ambiguous results. The majority of the models show high values of R^2, being them above 0.60.

The results of the econometric analysis vary between districts. For the irrigation districts directly relying on surface water storage, the analysis yielded very good explanatory power. In these areas, the effects of low water availability can be isolated from other factors of *Ipv* variability. However, for the districts in which groundwater supplies are important, the goodness of fit was worse. Alternative equations including aquifer levels were estimated, but the results were no better.

The trend (year) turns out to be very important for reproducing the changes experienced by the agricultural sector in the past decade. Some districts exhibited increases in irrigated acreage, while others showed strong decreases. This trend is a crucial factor for modeling economic drought risks because it captures the structural changes occurring in districts due to water and land competition from other non-farm sectors and the adoption of irrigation technologies.

4.3.4.2 Results of the risk economic performance of water balances

To make clear the need of risk analysis, Table 10 reports the probabilities of not meeting the water demand of an entire irrigation season for a selection of four irrigation districts: one in the north, Zona Regable Cinca (in Aragón, Ebro river basin), one in the south, Genil-Cabra (in Andalusia, Guadalquivir river basin) and two more in the eastern Mediterranean regions, Riegos Tradicionales de Valencia (in Valencia, Júcar river basin) and Plana de Castellón (in Valencia, Júcar river basin). The table includes the monthly probability revisions, marked in grey in the cases in which the season's prospect improved and marked in dark (and white text) in the cases in which the season's prospect worsened. The estimated probabilities changed significantly from month to month, offering room for preparation and planning before the season began.

Table 10. Probabilities of not meeting the stochastic irrigation water demand

Irrigation season	Genil-Cabra (Andalusia, Guadalquivir)							RR TT Valencia (Valencia, Júcar)						
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
2001	0.75	0.76	0.76	0.69	0.28	0	0	0.91	0.81	0.59	0.69	0.54	0.15	0
2002	0	0	0	0	0	0	0	0.58	0.55	0.39	0.53	0.54	0.54	0.3
2003	0	0	0	0	0	0	0	0.07	0.06	0.06	0.02	0	0	0
2004	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2006	0.37	0.42	0.42	0.46	0.58	0.62	0.18	0	0	0	0	0	0	0
2007	0.67	0.73	0.75	0.85	0.98	1	0.98	0.43	0.53	0.34	0.57	0.54	0.54	0.3
	Plana de Castellón (Júcar, Valencia)							Canal del Cinca (Ebro, Aragón)						
2001	0.99	0.59	0.5	0.51	0.3	0.3	0.3	0.47	0.59	0.25	0	0	0	0
2002	0.73	0.69	0.65	0.67	0.64	0.64	0.42	0.12	0.11	0.15	0.28	0.29	0.25	0.15
2003	0.24	0.29	0.37	0.39	0.3	0.15	0	0.57	0.54	0.33	0.03	0	0.01	0
2004	0.34	0.34	0.37	0.35	0.3	0.15	0.15	0.15	0.02	0	0	0	0	0
2005	0.36	0.37	0.42	0.38	0.3	0.3	0.3	0.33	0.42	0.5	0.66	0.7	0.77	0.85
2006	0.81	0.84	0.72	0.69	0.64	0.64	0.73	0.8	0.65	0.69	0.8	0.79	0.76	0.42
2007	0.91	0.94	0.93	0.96	0.96	0.92	0.73	0.36	0.14	0	0	0	0	0

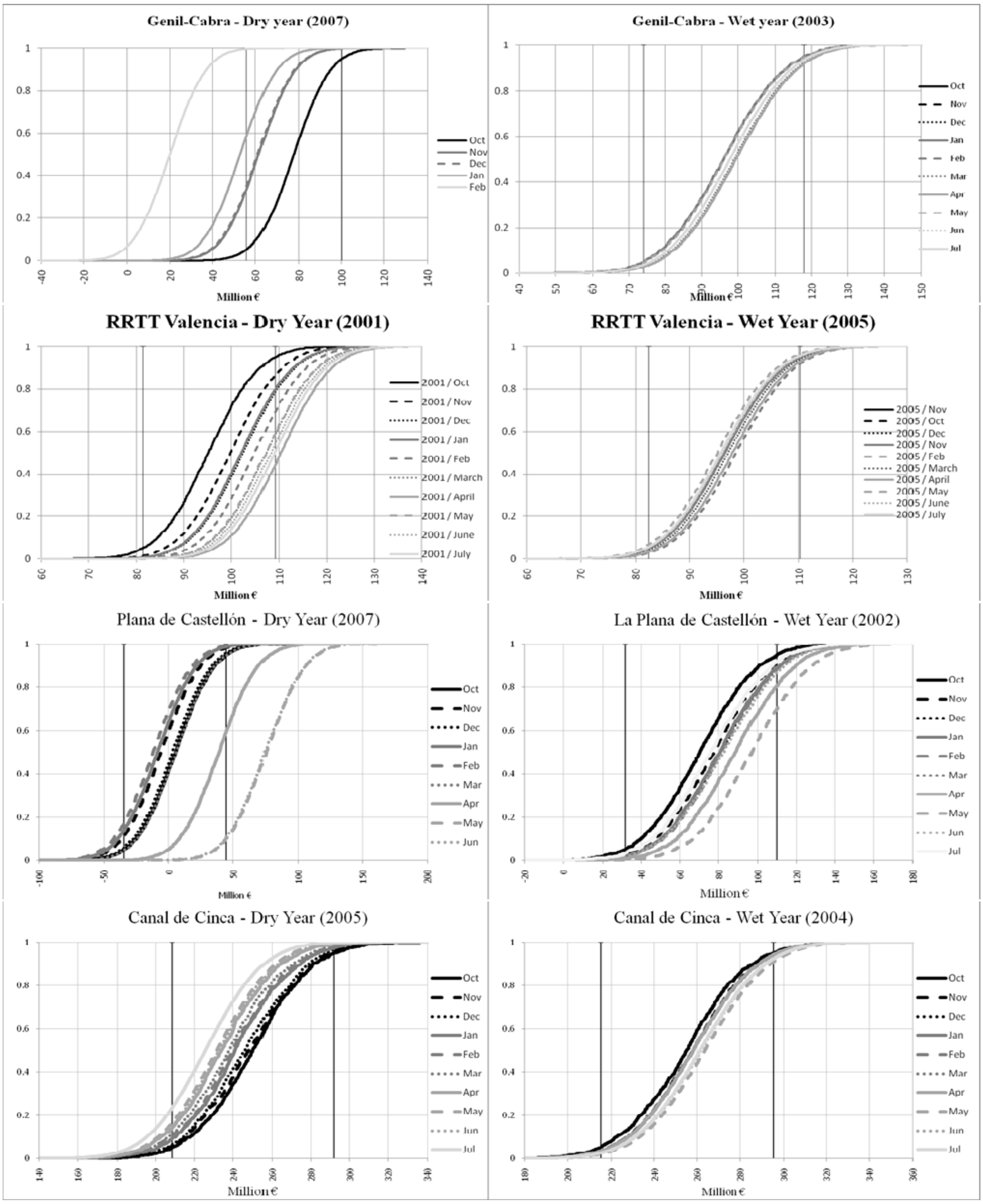
Source: Own elaboration

Between 2002 and 2005 in Genil-Cabra water demand should have been fully met, according to our probability calculations (Table 10). In contrast, García-Vila et al. (2008) estimated that supply did not reach 70% of the demand for the same years. This discrepancy is due to the standpoint from which the crops' water demand is estimated. While our work the demand was based on the observed cropping patterns, which may have already included less-demanding crops, García Vila et al. (2008) optimized the land and water potentials and compared those with the observed water application levels. During 1991 and 2005, their evaluation of the ARIS (Annual Relative Irrigation Supply) ratio of the 'Annual volume of irrigation water flow' and the 'Annual volume of crop irrigation demand' was always below 0.7. This is about 30% less than the crops demanded in theory, but it represents a standard behavior over the entire period studied of the district. García-Vila et al. (2008) suggested that farmers in Genil-Cabra may be risk averse, misguided by the Common Agricultural Policy subsidized crops and perhaps too old to recognize options that might increase profits. We believe that other factors must be constraining their decisions to explain the continuous poor performance over the 16-year period, and we assume that the presumably suboptimal application rates can be taken as normal.

Based on the districts represented in Figure 17, this section presents the economic results for each district represented in probabilistic terms. Figure 18 shows a plot of the CDFs of the economic results for the selected districts. Two seasons are plotted for each irrigation district (one dry and another wet, selected among the seasons in which probability of expected shortage increased or decreased respectively). The curves represent the CDF of the value of production in each district evaluated in million euros.

The greatest changes are apparent in the upper part of Figure 18, especially in Genil-Cabra and Plana de Castellón. In the first case, in a dry year for this district like 2007, the CDF shifts leftwards month after month, covering an "economic distance" (from the mean in October, in black, to the mean in February, in pale grey) of almost 60 million euros. The reason the curves shift month after month is due to the probability of experiencing sufficient precipitation to build up the storage diminishing as the beginning of the irrigation season approached. In February, the stochastic variation in the economic output for the district is no longer dependent on the water availability but on other sources of variation, like output prices or variability in yields.

Figure 18. Cumulative distribution function (CDF) of the economic results (in millions of €) for four irrigation districts in a wet year (left) and in a dry year (right)

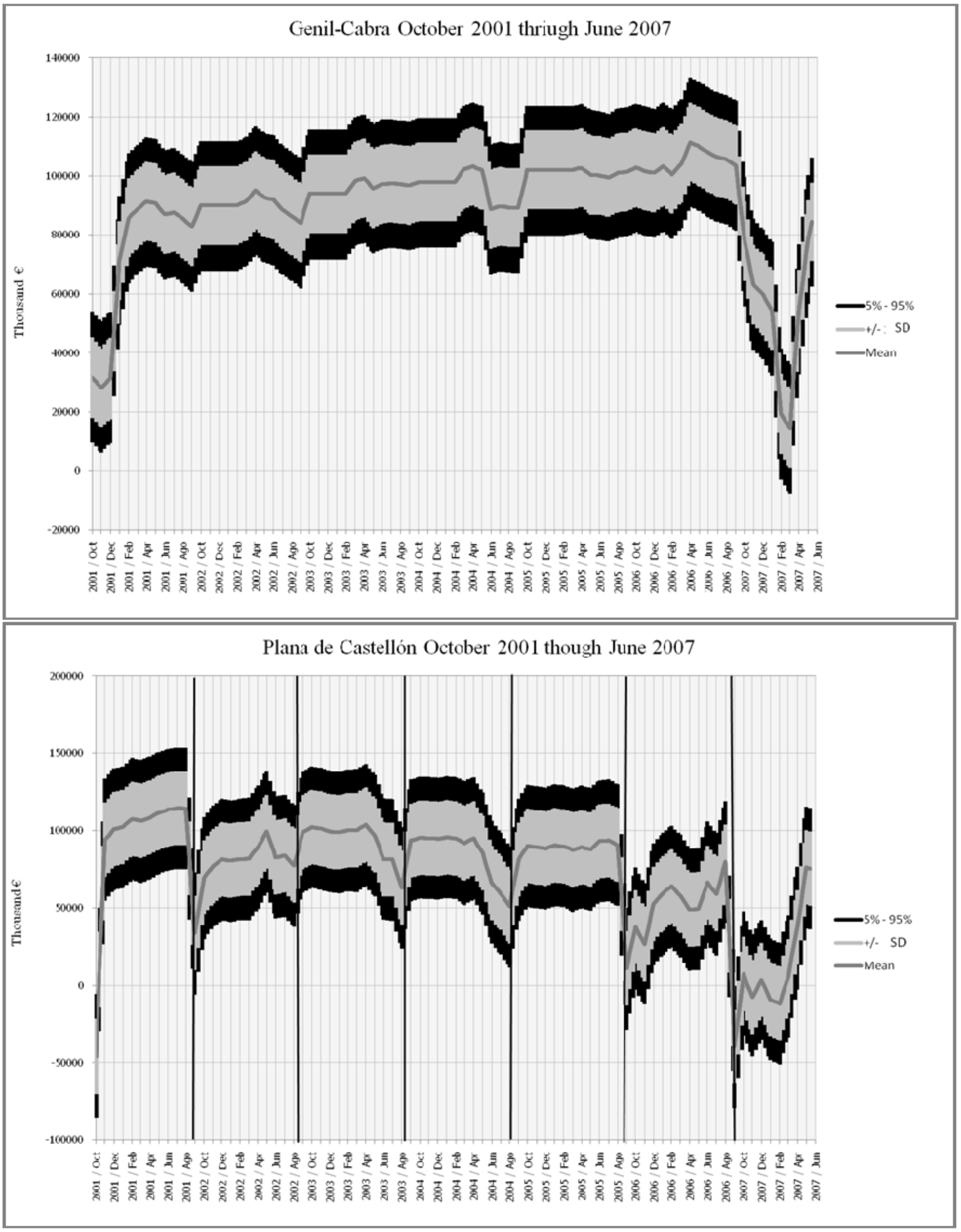


* The Y axis shows probability
Source: Own elaboration

The upper part of Figure 19 shows a plot of the entire set of economic forecasts for Genil-Cabra. The risk profile shows very little variation during the study period, except for the first and last seasons. Water shortages seem to occur only when severe droughts occur; in between, the economic variability is low and somewhat predictable. Note, however, that storage increases can also allow rapid recovery from severe situations (see the 2001 season).

In the case of Plana de Castellón in 2007, which had a wet winter, shown in the third panel on the left of Figure 18, the opposite movement of the CDFs of the economic output of the district can be seen. In this case, the forecast in October for the next upcoming irrigation season predicted a negative economic output. Until about March, the forecasts did not improve significantly, but, in a wide shift, the forecasts in May and June indicated a monthly improvement of about 40 million euros. This proves the suitability of the monthly revisions in a lower geographical level, where accurate data of supply for irrigation is available. The lower part of Figure 19 shows a plot of the entire set of economic forecasts for this district. The plot exhibits a downward trend that was captured by the regression model formulated by Eq. 8 and was taken into account in the simulation models described by Eqs. 9 through 11. Nonetheless, each season differs from the others in its risk profile.

Figure 19. Economic forecasts for Genil-Cabra and Plana de Castellón



Source: Own elaboration

4.4 Final remarks

Spanish irrigated agriculture is subject to water scarcity risk and the impact of droughts. The importance and frequency of drought periods make economic risk analyses based on sound attribution models of drought effects especially useful. To the extent that drought impact models establish a statistically significant relationship between water availability and irrigated farm productivity, they can be incorporated into reservoir management models. Such an approach can assist water managers in running reservoirs and storage facilities and agricultural stakeholders in preparing for water scarcity.

The method proposed at two different geographical levels gives a global and also complementary view of drought risk. By presenting the risk of water supply variability at a wider domain a general risk profile is settled, and with the local analysis the water demand side is introduced to further represent the reality. Water variables can be used to monitor hydrological and operational droughts and they are robust to support complementary economic risk analyses. Both provincial and local analyses are performed with reservoir levels as water indicators which are the main data input for official drought indices. It shows then that the drought index used by Spanish suitable for monitoring the risk.

The variation in the production value of irrigated surfaces can be explained by a time variable, a representative price index of the crops grown in each unit and a hydrological variable fundamentally based on the storage levels of the representative reservoirs (and on groundwater sources where necessary). Using this approach, the economic effects of water scarcity are isolated from other causes of reduced economic output (a downward trend due to structural factors such as reductions of farmland and price volatility unrelated to water availability). Differences in crop value variability across regions that can be attributed to hydrological variables are found.

Regression models provided here have sufficient explanatory power to be used in the risk analyses and to perform ex-ante projections of the economic results of the irrigation sector measured in probability terms. However, in the case of the irrigation districts some of the causation models are not sufficiently robust to assure confidence in the stochastic simulation.

In the case of provincial analysis, areas that rely on groundwater and secure supply sources are more exposed to price volatility than other provinces where the economic output is more dependent on surface water scarcity. Risk projections clearly show this behavior by providing stable profiles.

By looking at a vast array of hydrological, agronomical and geographical features, represented by the 16 provinces and the 13 irrigation districts included in the study, different drought risk profiles were identified. Multiple drought profiles were identified in both provinces and irrigation districts that were uniformly distributed around the Spanish irrigation area. Differences between northern and southern catchments, as differences between Mediterranean and Atlantic basins are reported. For the areas that rely on surface sources and water storage systems, robust ex-ante risk characterizations were performed with clear potential for real-time monitoring. Managers can generate production value ranges for the next irrigation season at the end of the previous season.

At the irrigation district level the water balance provides a risk dimension that can be monitored on a monthly basis. And, in the provincial analysis the hydrological variable (storage levels) can be also traced weekly on almost a real-time basis (using the MARM database). By inserting stochastic changes in either the storage levels or the water demand needs on a monthly basis into the regression models, risk models are developed here to connect the hydrological variability with the resulting economic variability. Just as the hydrological state is subject to stochastic processes, the economic performance of the sector that depends on hydrological variables is also stochastically connected to them. An accurate drought attribution model must single out other sources of production variability, especially crop prices.

The probability distribution functions for economic output can be revised simply by updating the storage information that is recorded electronically. The left tail of a production PDF can change significantly in a matter of months. Managers can simulate ex-ante the economic effects of any strategic response to either favorable or unfavorable hydrological conditions. A PDF of the economic impact of augmented environmental flows (in terms of foregone agricultural benefits) can also be generated if such flows are required to secure wildlife and habitat conservation at the expense of the irrigation water supply.

In contrast, the intra-annual risk predictions have lesser potential for the areas that rely primarily on groundwater resources. Water tables vary less than surface storage levels, and the effects of drought manifest for longer periods (see Llamas and Custodio, 2003). In the short term, price volatility is a much larger source of revenue instability for farmers, especially if they grow fruits and vegetables, as evidenced by the results of Murcia (in southeastern Spain). Drought indices based on reservoir levels are obviously poor indicators for users relying on groundwater.

Drought risk analysis can vary depending primarily on the water supply and secondarily on weather characteristics. It can be concluded that the revisions of ex-ante projections are the key for having accurate information and a proper awareness system to prevent drought negative impacts. The ease of these calculations has been emphasized and their potential for ex-ante drought management in all areas analyzed.

5 DIRECT AND INDIRECT ECONOMIC IMPACTS OF DROUGHT IN THE AGRI-FOOD SECTOR IN THE EBRO RIVER BASIN (SPAIN)

5.1 Introduction

The aim of this chapter is to evaluate the economic impacts on the agricultural sector and measure the extent to which they are transmitted from primary production to industrial output and related employment. Econometric models are fitted to determine the magnitude of the economic loss attributable to water scarcity. Both the direct impacts of drought on agricultural productivity (irrigation and rainfed) and the indirect impacts of drought on agricultural employment and the Agri-food industry are evaluated. A direct attribution model is proposed to measure the direct losses and, based on this, an indirect attribution model is also proposed to measure the indirect relations. The transmission of water scarcity effects from agricultural productions to macroeconomic variables are measured through concatenated elasticities.

Irrigated agriculture is the main water user in Spain, using up to 90% of available water resources in the case of the Ebro river basin (CHE-SDMP 2007). This dependency on available water resources makes irrigated agriculture vulnerable to drought risks. Rainfed agriculture is more vulnerable to drought risk, but has lower exposure, because of lower land productivity in comparison with irrigated agriculture. Both irrigated and rainfed agriculture provides the primary inputs for the Agri-food industry.

Droughts originate from a deficiency in precipitation that results in water shortages for human consumption, economic activities or environmental requirements (Wilhite and Glantz 1985). The special characteristics of droughts make impacts difficult to assess (Wilhite 1993). Among the special features of drought, the main difference with other natural hazards is its slow temporal onset and uncertain spatial propagation. The slow onset of this natural hazard requires different and innovative methodologies to evaluate the economic impact and scope of drought (Wipfler et al. 2009). Some of the methodologies employed to measure the scope of the impacts of drought are revised here. Econometric models used by Garrido et al. (2010) Gil et al. (2011) are adapted here to measure the amount of impact and its scope across different economic sectors.

Water-dependent activities like agriculture, Agri-food processing industry and agricultural employment are severely impacted by the lack of available water. Wilhite et al. (2007) and Iglesias et al. (2007a) highlighted the complexity of drought impacts which over time spread through many sectors. Therefore, it is essential to have methodologies that allow for the measurement of losses directly and indirectly related to water shortages and also to describe how these losses are related to each other.

The goal of an accurate measurement of the economic impacts of drought is to enable a better management of water as a scarce natural resource. The Xerochore project (2010) emphasized the need of improving the quality and reliability of drought impact assessments to inform mitigation and risk management policies. Basin-wide studies that integrate economic and hydrologic optimization models have been commonly developed to assess different policy alternatives in order to minimize the impacts. Drought related losses must be taken into account in order to develop mitigation strategies that help to minimize costs. According to Ding et al. (2011), most drought impact studies are developed ad-hoc for a specific drought event, and that contributes to the improvement in the assessment for policy makers. However, a greater emphasis has to be put into the real scope and spread of the damages produced by drought from primary to industrial sectors and isolate its effects from other sources of economic performance variations (such as price variations).

5.2 Evaluation methods of economic direct and indirect drought impacts

The economic impact of reduced water availability is determined by many factors. An accurate estimation of this effect would allow us to discriminate the impacts of drought from other influencing factors and therefore would lead to an improved policy-assessment. This can be accomplished by including relevant explanatory variables of the event and by using econometric models to measure the causal relation and the attribution effect between variables (Martínez-Cachá 2004). The use of econometric models as a tool to evaluate the negative impacts at different levels would have the advantage of its potential discriminatory effects (distinguishing drought effects from others). Furthermore, it allows us to obtain production elasticities with respect to water availability, and related effects across sectors (from primary sector to Agri-food industry and agricultural employment).

Water is an important input for the agricultural production function, and variations in the amount of water affect agricultural production levels, although the variation is not necessarily proportional. The elasticity between these two factors determines the amount of impact that will occur and, in turn, the relationship between these variations and the macroeconomic impact is also determined by the existent elasticity between agricultural productions and related macroeconomic variables, including employment and Agri-food Gross Value Added.

Most of the analyses concerning the elasticity of water as production input evaluate the price elasticity of water demand. Schoengold et al. (2006) measure the direct effects of water pricing on water demand, and the indirect effects on changes in crop choices or irrigation technology, using the concept of elasticity. However, regardless of variations in water prices, water use variations also generate different indirect impacts that can be evaluated. In this section, the direct and indirect economic effects of water supply on agriculture are evaluated.

While Decaluwe et al. (1999) conclude that introducing water price elasticity in analytical models is adequate to evaluate policy alternatives considering welfare criteria and water conservation objectives, there are other relevant elasticities related to water. Moore and Negri (1992) show how a reduction of 10% in water supply leads to increases in crop prices. The result is an overall decrease in the value of agricultural production. The elasticity of production with respect to water availability can also be used to calculate how these decreases are transmitted from variables directly affected by water to indirectly affected variables.

The evaluation of the economic impacts of drought and its spreading and repercussions throughout the economy of a region occurs through economic links between the markets of primary products, whose production relies on water availability, and the economic activities that process them. A number of studies analyzing the economic impact of droughts use mathematical programming models to simulate economic impact (Calatrava and Garrido 2005, Salami et al. 2009, Peck and Adams 2010). Others use econometric models fitted at the macroeconomic level (Alcalá Agulló and Sancho

Portero 2002, Martínez-Cachá 2004) or at the level of the irrigation district (Lorite et al. 2007), the irrigated farm (Rubio Calvo et al. 2006) or single crops (Quiroga and Iglesias 2009). Other authors have used computable general equilibrium models (Goodman 2000, Gómez et al. 2004, Berrittella et al. 2007). Finally, input-output models have also been used to study the regional effects of water scarcity (Pérez y Pérez and Barreiro-Hurlé 2009).

Evaluations of direct and indirect impacts of drought have often been made through Input-Output (IO) models, but they tend to overestimate the magnitude of losses attributable to drought. IO models use the direct impact as the starting point of analysis to derive the indirect impacts through forward and backward economic linkages. This approach assumes that negative effects provoked by changes in final demand will transfer a multiplying effect to production and employment in the economic structure of the region (Leontief 1986). Therefore, if the effect in production is incorrectly measured none of the other relations would be precise.

IO tables are highly specific for the economy of a particular geographical area. In Spain Pérez y Pérez and Barreiro-Hurlé (2009) and Chóliz et al. (2009) use this approach to evaluate the economy of the Ebro river basin in the Aragón Autonomous Community which is also a part of the Ebro basin, the geographic focus of this work. The specificity is clearly represented in Chóliz et al. (2009) who modeled the economic importance of water within the economy of Aragón by using the Social Accounting Matrix and Environmental Accounts (SAMEA). Although Morrilla et al. (2007) justify its use as a means of measuring the efficiency of industrial water uses, he also denotes the multiplier effect that it has. This effect increases the estimation of impacts as they are transmitted. Therefore, IO analysis are useful as a means to understanding the general functioning of various sectors in a specific period of time, but do not necessarily accurately assess the economic impacts of a specific drought situation.

Computable General Equilibrium models have also been used to evaluate drought impacts. It is a method derived from Input-Output models that gives higher importance to price adjustments. Gómez et al. (2004) used it in the Balearic Islands to evaluate water use efficiency gains through water trading between agricultural and urban water uses. They also assess the economic impacts of various water allocation criteria in the Balearic Islands using the National Agricultural Accounting Network and the IO tables for 1997 for future scenarios. The problem of overestimation becomes less significant here, because the alternatives are used for comparison between scenarios. Berrittella et al. (2007) simulate a Global Trade Analysis (GTA) using CGE for restricted water supply, also with data from 1997. It may be useful as an assessment for management solutions or options. The potential to productively inform actual management criteria for scarce resources diminishes as the lapse between the reference year used for model calibration and the projection period expands. It is also worth noting that Computable general equilibrium models (CGE) serve as an analytical tool for the description of the economy of a region, but most of the parameters, such as elasticities and the coefficients of production functions, soon become outdated.

Those IO and CGE methodologies are similar and both try to capture the relationships and causation chains that result in the indirect impacts of drought. However, their objectives and inference potential differ. For instance, CGE models will reveal price changes and income of firms and consumers, whereas IO models do not provide market price impacts and has a rather sectoral approach. Conceptually, the relevance of the indirect impacts is always related to the direct impacts, but the multiplier effects will likely change with technology and other external sources. Impacts on the Agri-food industry are dependent on drought impacts on agriculture, and it is assumed that impacts tend to be attenuated in sectors not directly related or dependent on primary sector. This hypothesis is one of the main considerations of this study. Chóliz et al. (2009) also point to the close relation between agricultural water use and the use of inputs from agriculture by the Agri-food industry, but in order to be relevant for our purposes the relation must be directly attributable to drought. Berrittella et al. (2007) describe water as mobile between agricultural economic sectors. This mobility can be measured through the transmission of economic impacts or, as it will be shown in this section, through concatenated elasticities.

Labor utilization is also considered an indicator of the indirect impacts of drought, as both self-employment and hired employment are presumed to be related on water availability and, therefore will be impacted by water scarcity. Garrido et al. (2010) and Schuh (1962) measured variations in hired labor through econometric models, and both find no significant relationship between water availability and agricultural employment. These findings are inconsistent with evaluations of drought impacts through IO and CGE models (see for example Pérez y Pérez and Barreiro 2009). The fact that agricultural employment is apparently not severely impacted by droughts indicates that other important variables affecting changes in employment, including time trends and technical innovation, may blur the effect of water scarcity in the agricultural labor markets.

In this chapter we address two sets of questions. Concerning the direct impacts of drought, we evaluate the magnitude of the effects of drought on the value of agricultural production, trying to discriminate the effects of the lack of water from other variables that may be influencing the final output. Secondly, the study also evaluates the effect of direct impacts on Agro-industrial production, as an example of indirect impacts.

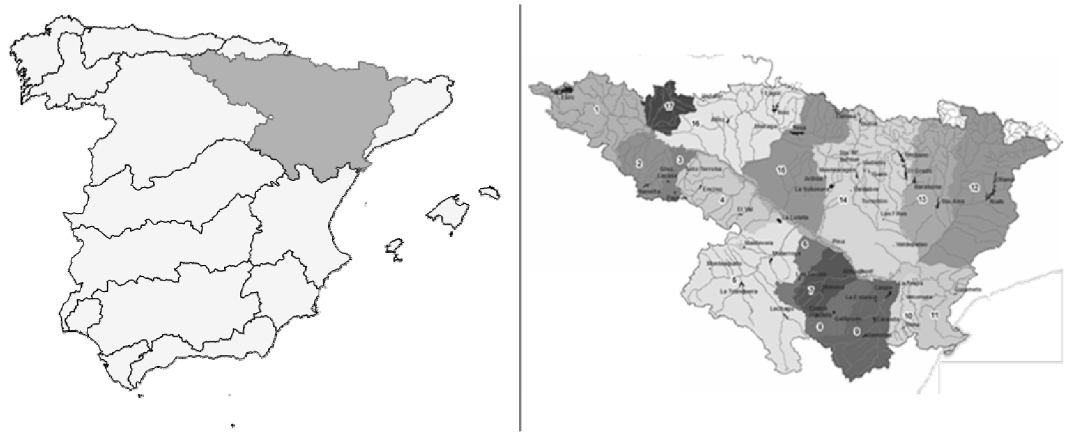
The main contribution of this section to the existing literature is to create a common methodology based on econometric models that explain the relations between directly and indirectly affected sectors and to calculate concatenated elasticities in order to analyze how impacts are spread between sectors. Models include a number of important explanatory variables obtained from general statistics, and so it makes it replicable in other catchments or even countries.

5.3 Context and focus of the study

The methodology proposed here builts on general econometric models developed by Gil-Sevilla et al. (2010), Garrido et al. (2010) and Gil et al. (2011) to measure drought impacts using impact attribution models. This work focuses geographically on the Ebro river basin (in northeastern Spain) and considers 15 years of data (1995-2009). Map 6 represents the Ebro river basin and the Management Areas in which it is divided for management purposes according to the Confederación Hidrográfica del Ebro (2011). The analysis provided here is performed at different geographical levels, but the unit of analysis is the river basin. Data collected at different geographical scales has been processed and adapted to match the study´s objectives.

The river basin dimension is appropriate for the analysis of drought impacts, because of two main reasons: (i) it is the adequate boundary from the management perspective (Estrela and Vargas 2012) and (ii) from the impact assessment perspective it is the basic unit of interrelations between direct and indirect impacts (Chóliz et al. 2009, Pérez y Pérez and Barreiro-Hurlé 2009).

Map 6. Case study: the Ebro river basin and its Management Areas



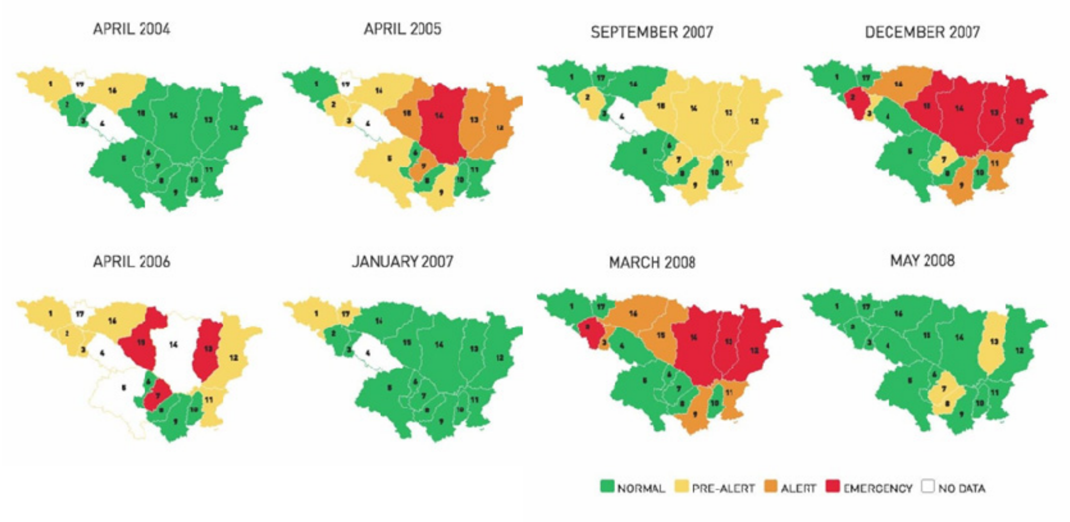
Source: (CHE (Confederación Hidrográfica del Ebro) 2011) (Available at: http://www.chebro.es/contenido.visualizar.do?idContenido=12011&idMenu=2224 accessed: January 27, 2012)

The Ebro river basin, with a total storage capacity of 7,500 Mm^3 (MAGRAMA 2009) and an average annual precipitation of 478 mm/year (AEMET 2009), suffers drought periods approximately every ten years, although the rate in short-term droughts has increased slightly since 1950s (CEDEX 2011). These trends seem to also be supported by regional studies like Valencia Delfa et al. (2010), who found that in the Ebro basin the precipitation regime is now more homogeneous than thirty years ago, although the rate of droughts has augmented. Vicente-Serrano and Cuadrat-Prats (2007) also demonstrated that from 1951 to 2000 there has been an increase in the severity of droughts in the Middle Ebro Valley, although with wide spatial variability.

Iglesias et al. (2007a) produced a set of guidelines to develop adequate drought management plans in Mediterranean countries. They emphasize the need for a robust system of indicators that can provide information for early detection of drought episodes and promote preparedness activities. Drought indicators in Spain were designed and evaluated starting in 2008 in an attempt to anticipate the risk (Estrela and Vargas 2012). Map 7 shows the evolution of these indicators (some of them were calculated after designing the indices). Drought indices consider both the availability and the demand of water (to set up the thresholds). From the water availability point of view, indices are often simplified and refer to the availability of the predominant source of water in each Management Area (generally reservoir levels) instead of considering all alternative sources of water used in the management area.

During the period of analysis (1995-2009), the Ebro river basin experienced two major drought events: one between 1995 and 1996 and another between Spring of 2005 through Spring of 2008. Both drought events affected most river basins in Spain. Map 7 illustrates the evolution of the drought in the Ebro basin through the evolution of drought indices.

Map 7. Monthly evolution of drought regulated indices between 2004 and 2008 in the Management Areas of the Ebro river basin



Source: Own elaboration with data from CHE

5.4 Methodology

Econometric models are used to evaluate the socio-economic impacts of drought. We first fit direct attribution models (linear models based on general approach of Part II) and then, using the fitted variables as explanatory variables, we fit another set of linear attribution models to evaluate indirect impacts. The direct damages of drought are here measured for both irrigated and rainfed agricultural production using economic productivity measurements as dependant variables. The indirect damages are measured in terms of agricultural employment and Gross Value Added (GVA) index of the Agri-food industrial sector.

For the indirect impacts an alternative inference procedure using related elasticities is formulated. Previous linear models are fitted in logarithms in order to estimate how impacts are spread through different sectors. This part of the methodology provides an alternative vision of how water shortages generate different amounts of impacts across the economy.

5.4.1 Direct attribution model

The direct attribution model has been adapted from previous models (Gil et al. 2009, Garrido et al. 2010, Gil-Sevilla et al. 2010), where the value of production is the variable to be explained when direct damages are considered. It captures the variations in the value of agricultural production between 1995 and 2009, a period that includes two basin-wide drought periods. A water availability indicator is required as explanatory variable to measure the impact of drought on crops' growth and harvests. For this purpose, we selected the drought indices defined by the Ebro River Basin Authority (RBA) for each management area in the basin between 1995 and 2009 (CHE 2011) and the accumulated precipitation from January to June (AEMET 1995-2009). This period was selected because precipitation patterns during these months impact crops' growth (Quiroga Gomez et al. 2010). Drought indices are used for the irrigated agriculture model and accumulated precipitation for rainfed agriculture. Each model is fitted separately. Those variables provide the most objective and transparent indicators of farmers' water availability. There are other variables that influence the economic results of both irrigated and rainfed agriculture, but they are not related to drought.

A general econometric model is proposed for both irrigated and rainfed agriculture to explain the variation in the economic value of harvests. The variable to be explained (production value Pv_{it}) is a function of a time trend, the water availability and a crops' price index, as formulated in the following equation for each province (i) of the Ebro river basin.

$$Pv_{it} = a_i + b_i T_t + c_i Wa_{it} + d_i P_{it} + u_{it} \quad (1)$$

$$\text{With } u_i = \varepsilon_{it} + \rho_i \varepsilon_{it-1}, \; E(\varepsilon_{it}) = 0 \text{ and } \sigma_{\varepsilon i}^2 = \sigma_i^2$$

where T_t is the time variable expressed in years (from 1995 until 2009), Wa_{it} is the hydrological variable (Water Availability) expressed as a drought index value (for the irrigation model) and expressed in mm of accumulated precipitation during the growing season (for the rainfed model) and P_{it} is a crop's price index for each province and each model (one for irrigation, another for rainfed).

The dependent variable Pv_{it} is the production value of rainfed and irrigated agriculture calculated using data on surface, yields and prices of both types of agriculture to obtain an annual and provincial value in thousand of nominal euros separately. The model (Eq.1) is fitted using the Prais-Winsten method for time series data. The Durbin-Watson statistic was calculated and the effect of serial correlation errors was corrected. Multicollinearity between Wa_{it}, P_{it} and T_t was tested measuring the Variance Inflation Factor (VIF) which is around 1.43 for irrigation regressions, and 1.51 for rainfed.

The fitted model is used to measure the impact attributable to the shortage of water for both irrigated and rainfed agriculture. The fitted model allows for comparing an economic "normal" or "average" result with a drought-year "bad" result. This requires defining what a "normal" situation is in each type of agriculture. It is calculated with the fitted model by introducing on it an average value of the water variable ($\overline{W_{a_\iota}}$) to obtain the Pv_{it} that would result from a normal water availability and without altering the other conditions of year *t* and province *i*.

For irrigated agriculture the "normal" water availability variable is the Drought Index of normal conditions (when the drought index falls between 0.5 and 1 the water supply is enough to satisfy all demands). Taking into account the available drought index historical series it can be shown that it has not risen above 0.75 (CHE 2011). According to the Ebro RBA Special Drought Management Plan, no drought management measures are implemented until the index falls below 0.3. Therefore, 0.5 has been selected as the value above which the water availability variable is considered "normal". In the case of rainfed agriculture the "normal" water availability is calculated with the moving average of rainfall from the previous 3 years (Eq. 2), where R_{it} is the accumulated rainfall of each province and each year.

$$\overline{R_{\iota t}} = \frac{\sum_{i-3}^{i-1} R_{it}}{3} \qquad (2)$$

Those "normal" variables are introduced into each fitted model to obtain the average Production Value of each year in order to compare this value with the one obtained with the model each year (Eq. 3).

$$\overline{Pv}_{it} = \hat{a}_i + \hat{b}_i T + \hat{c}_i \overline{Wa}_{it} + \hat{d}_i P_{it} + u_{it} \tag{3}$$

Where $\overline{Pv}_{it}$ is the "normal" production value, $\overline{Wa}_{it}$ is the normal water availability, that is, the "normal" drought index for irrigated agriculture's model, or the accumulated average rainfall for the rainfed agriculture one. The normal Production value ($\overline{Pv}_{it}$) provides the values that would have been obtained in each province if a sufficient amount of water had been available. It can be also expressed in a range of values if we consider also the error term (u_i) of the model. The result ($\overline{Pv}_{it}$) can be compared with the result obtained with less water (lower drought index or less precipitation) $\left(\widehat{Pv}_{it}\right)$ for each year (fitted Eq. 1). The comparison of both values leads to an estimation of the economic impact due to lower drought index or lower precipitation, which means lower water availability in both cases. Therefore, Direct impacts (Di_{it}) for a specific year t are the following for each province *i*:

$$Di_{it} = \widehat{Pv}_{it} - \overline{Pv}_{it} \tag{4}$$

5.4.2 Indirect attribution model: two step model

The second component of the methodological approach is also based on econometric models. The objective of the methodology is to clearly identify which variables are directly related to the lack of water and also to identify how these variables affect other sectors indirectly.

To evaluate the economic variations of indirectly affected variables an indirect attribution model (two-step model) is proposed. The aim of this part of the methodology is to explain the evolution of Agri-food industrial Gross Value Added (GVA) and agricultural employment through models fitted in two steps. The first step measures the direct relations and the second step measures the indirect relations. The explanatory variables are the fitted variables obtained from the models developed to estimate irrigated agriculture and dryland agriculture production values (Eq. 1).

Indirectly affected variables (indirect variables hereafter) are modeled in an attempt to obtain better estimations of drought losses. The model proposed in step two estimates indirect variables depending on fitted Irrigated Production Value and fitted Rainfed Production Value (from step one, Eq. 1) as Eq. 5 indicates:

$$Iv_{it} = a_i + b_i I\hat{p}v_{it} + c_i R\hat{p}v_{it} + \varepsilon_{it} \quad (5)$$

$$\text{with } E(\varepsilon) = 0 \text{ and } \sigma^2 = \sigma^2$$

where Iv_{it} (indirect economic variable) refers to Agri-food industrial GVA (INE 1995-2007) or Agricultural employment (Social Security 1999-2007), but both are estimated separately. $I\hat{p}v_{it}$ is the fitted Irrigation Production Value and $R\hat{p}v_{it}$ the fitted Rainfed Production Value. These two are estimated from the models formulated by equation 1.

Although the trend has been omitted as an explanatory variable, it is included as the time trend for both fitted Irrigation Production Value (*Ipv*) and Rainfed Production Value (*Rpv*). Different alternatives have been tested to eliminate the trend and isolate the variances on indirect variables from strong trends over time. But, as will be shown in the results section, one of the most significant factors influencing indirect variables are the trends in agricultural production, thus it cannot be omitted. Multicollinearity between explanatory variables has also been tested with the VIF statistic, and results show that there are not mulcollinearity problems, the values range between 1.71 (for Agri-food industrial GVA) and 1.78 (for employment).

Additionally, linear simple regressions between Iv_{it} and actual or fitted Irrigation Production Value and separately regressions between Iv_{it} and actual or fitted Rainfed Production Value have been done. Results prove the main hypothesis of this study, that is that the relation between direct affected variables and indirect sectors is important (some of them can be seen in Figure 22).

5.4.3 Spread of impacts: concatenated elasticities

To measure the spreading of the actual impact on indirect variables affected by the Ebro drought (2005-08), the methodology proposed is based on inference procedures. By calculating different elasticities the spread of impacts from directly affected variables to indirectly affected ones, can be estimated. We consider a model from which elasticities can be extracted from an adaptation of the econometric models formulated in previous sections. Equations 1 and 5 are transformed into logarithmic form and reflected in the following production functions:

$$\left.\begin{aligned} Rpv &= e^{\theta_i+\lambda_i T} {Wa_2}^{\mu_i} P^{\xi_i} && (6)\\ Ipv &= e^{\delta_i+\varepsilon_i T} {Wa_1}^{\zeta_i} P^{\eta_i} && (7)\\ Iv &= e^{\alpha_i} I\hat{p}v^{\beta_i} R\hat{p}v^{\gamma_i} && (8)\end{aligned}\right\}$$

The elasticities found in this equation system (Eqs. 6, 7 and 8) are divided into two groups: some dependant on water availability (water for irrigation or precipitation in the case of rainfed agriculture) and others dependant on irrigation or rainfed productions. The elasticities are the following:

$$\beta_i = \frac{\partial \log Iv}{\partial \log Ipv};\ \gamma_i = \frac{\partial \log Iv}{\partial \log Rpv} \text{ and } \zeta_i = \frac{\partial \log Ipv}{\partial \log Wa_1};\ \mu_i = \frac{\partial \log Rpv}{\partial \log Wa_2} \qquad (9)$$

None of them measure the elasticity between water availability and indirect variables. However, variations on either irrigation water availability (Wa_1) and/or rainfed water availability (Wa_2) must have an impact on indirect variables. Since there is a relation between indirectly and directly affected variables, and moreover directly affected variables are related to water availability, a combination of elasticities would lead us to obtain how the impacts are transmitted. By substituting Eqs. 6 and 7 into Eq. 8, the following expression is obtained:

$$Iv_{it} = e^{\alpha_i}\left(e^{\delta_i+\varepsilon_i T} {Wa_1}^{\zeta_i} P^{\eta_i}\right)^{\beta_i}\left(e^{\theta_i+\lambda_i T} {Wa_2}^{\mu_i} P^{\xi_i}\right)^{\gamma_i} \qquad (10)$$

$$Iv_{it} = e^{\alpha_i}\left((e^{\delta_i+\varepsilon_i T})^{\beta_i}\left({Wa_1}^{\zeta_i\beta_i}\right)(P^{\eta_i\beta_i})\right) \times \left((e^{\theta_i+\lambda_i T})^{\gamma_i}({Wa_2}^{\mu_i\gamma_i})(P^{\xi_i\gamma_i})\right) \qquad (11)$$

No contemporaneous relation between accumulated precipitation for rainfed crops (*Wa2*, spanning only 5 months) and drought indices that use reservoir storage values as primary indicators (*Wa1*)[9] is assumed. The partial derivate of indirect variable by *Wa1* would be $\zeta_i\beta_i$ (Elasticity of Indirect variables in relation to irrigation water) and the partial derivate of indirect variable by *Wa2* is $\mu_i\gamma_i$ (Elasticity of Indirect variables in relation to rainfed water) form Eq (11).

[9] R^2 resulting from an OLS regression between drought indices and accumulated precipitation is 0.04 and the p-value is not significant (0.133). Both variables are certainly related in a longer term period (interannual).

5.5 Data sources

The main variables measured in this study, and used as independent variables on the econometric models, are: (i) Economic Production Value (distinguishing irrigated agriculture and rainfed agriculture), (ii) Gross Value Added of the Agri-food industry, (iii) Agricultural Employment (both self and hired labor, collected from Spanish Social Security data for the period 1999-2009).

Each production value (Ipv_{it} and Rpv_{it}) is calculated as follows:

$$Pv_{it} = \sum_{j=1}^{94} S_{ji} \times Y_{ji} \times p_{jt} \quad (12)$$

where S_{jt} is whether the irrigated surface or the rainfed surface in province i, year t, and crop j ($j=1,\ldots,94$), Y_{jt} denotes the yield of each crop (differentiating irrigated or rainfed) in province i and year t, and p_{jt} is the national price for each crop in year t evaluated at the farm gate.

Agricultural GVA is collected from the National Statistics Institute for a time series that spans between 1995 and 2010 at a regional level (Autonomous Community) and is measured at a nominal Euro rate. Employment is also collected from official data at the Social Security from 1999 until 2009 in the number of self-employed and hired workers per province.

Additionally, as the economic impact is being calculated, a weighted price index for each geographical unit and each type of agriculture (denoted by P_{it}) has been built to capture the variations in product value due to crop price variations. This index takes into account the importance of each group of crops (twelve groups: cereals, fruits, industrial crops, etc.) within each unit and is calculated using the following formula:

$$P_{it} = \frac{\sum_{k=1}^{12} Pvt_{ikt} \times P_{kt}}{Pv_{it}} \quad (13)$$

where Pvt_{ikt} is the total value of crop group k (k=1,..,12), which is representative of the crops grown in each province. All 94 crops were included in these 12 groups so that each group has a specific price index, P_{kt}, which is published by the official statistical source (MAGRAMA 1995-2009).

Elasticity values obtained from $\zeta_i\beta_i$ and $\mu_i\gamma_i$ are used to measure the impacts on Agri-food industrial Gross Value Added (GVA) attributable to water availability, as is indicated in Eq. 13. To calculate the drought impact on GVA at an Autonomous Community level from provincial-level elasticities of water availability, percentages of production importance in the corresponding Autonomous Community must be calculated and applied.

$$\Delta GVA(\%) = \zeta_i\beta_i * \Delta Wa_1(\%)\;;\; \Delta GVA(\%) = \mu_i\gamma_i * \Delta Wa_2(\%) \qquad (14)$$

The impact produced in a drought year is calculated with reference to the average water availability for each case, which can be the average drought index (0.5) or the average rainfall (Eq. 2).

5.6 Results: Goodness of fit and estimated elasticities

Table 11 reports the results from the direct attribution econometric models (Eqs. 1 and 5). The left part corresponds to the results from the irrigated agriculture models and the right part to the rainfed agriculture models. The majority of the coefficients of determination (R^2) are above 0.60 and almost 50% of them are above 0.70. This means that the variations on the dependent variables are moderately well explained by the used explanatory variables. Water variables that better explain the production value are the ones from the rainfed model, thus rainfall variation is a very good explanatory variable for the value of rainfed agricultural production (most of them are significant or very significant, $p<0.05$). However, irrigated production models (left panel) offer a less accurate explanation of the evolution of agricultural production values as a result of variations in water availability expressed through drought indexes), with prices being more important than in rainfed values and the trend (T) being the most significant explanatory variable. The value of rainfed agricultural production is less impacted by price variations than the irrigated agriculture, where outputs have higher price levels and higher market risks. Despite that, the coefficients of price indexes are negative in a few provinces, which may capture the cases when agricultural production output is low, supply decreases and, therefore prices increase.

Table 11. Regression results from Direct Attribution models. Correlation coefficients and significance of explanatory variables

Provinces	IRRIGATED PRODUCTION VALUE				RAINFED PRODUCTION VALUE			
	R^2	T	Wa_1	P	R^2	**T**	Wa_2	P
Alava	0.19	-146.52	17371.33	318.16	0.84	-504.48	69.52*	-175.99***
Huesca	0.64	16381.63***	114071.70***	-2767.12*	0.57	932.01	250.88***	442.60
Lleida	0.92	6232.80**	74747.75	2095.821	0.83	-4475.29***	148.12**	542.17
La Rioja	0.42	5055.99**	-9284.28	625.82	0.17	512.24	34.44	-96.44
Navarre	0.98	11359.90***	20953.68	462.58	0.72	1996.65**	134.83*	-958.46
Teruel	0.62	-785.91	-10925.92	1491.99**	0.69	-241.24	206.82**	666.05
Zaragoza	0.92	32127.00***	124000.80**	-7548.45***	0.63	1782.61	264.59	2222.89

***$p<0.01$; **$p<0.05$; *$p<0.1$, (n=14 observations)

Table 12 reports the results from the econometric models of indirect variables, in the left side results for the GVA of the Agri-food industry (at the level of Autonomous Community) are presented, and on the right side the results from the employment models (divided into two types: family and hired labor) are shown. Overall results suggest that the proposed methodology is consistent, because high levels of R^2 and coefficients of statistical significance are reported.

A more detailed vision of the results shows how irrigated agricultural production is the main explanatory variable for Agri-food GVA in almost all cases. Irrigated productions are the main input for the economic activity of the Agri-food industry and, furthermore the strong trend followed by the irrigation sector was accompanied by the variation of the total GVA of the industry related to agricultural products. Regarding employment, a negative sign is predominant for both rainfed and irrigation, which may indicate that employment variation is not so much dependent from water and production variations. In this case, a strong negative trend as a consequence of both modernization and migration from the agricultural sector to other productive sectors makes it difficult to accurately measure the impacts attributable to water scarcity.

Table 12. Regression results of two step models for indirect impacts of drought: Agri-food industrial GVA (regional level) and Employment (provincial level). Correlation coefficients and significance of explanatory variables

INDIRECT IMPACTS										
GVA Agri-food industry					Family labor			Hired labor		
Autonomous Communities	R^2	$R\hat{p}v$	$I\hat{p}v$	Provinces	R^2	$R\hat{p}v$	$I\hat{p}v$	R^2	$R\hat{p}v$	$I\hat{p}v$
B. Country[1]	0.30	-12.80	55.71**	Alava	0.62	-0.01	-0.04**	0.56	0.039	0.095**
Navarre	0.95	8.38	8.98***	Navarre	0.97	-0.02	-0.02***	0.67	-0.05	0.03**
				Zaragoza	0.68	0.0007	-0.008**	0.1	-0.005	0.001
Aragon	0.77	0.71	1.71***	Huesca	0.34	0.03	-0.02	0.004	0.0008	0.00005
				Teruel	0.65	-0.02	-0.13*	0.09	-0.0002	0.01
La Rioja	0.72	-4.98	12.08***	La Rioja	0.86	-0.05**	-0.01*	0.65	0.03	0.06*
Catalonia	0.91	-89.49***	45.08***	Lleida	0.89	0.07***	-0.02**	0.81	-0.03**	0.02**

1 Basque Country

***p<0.01; **p<0.05; *p<0.1

Elasticities calculated to identify the transmission of drought impacts to Agri-food industry GVA are summarized in Table 13. The significance obtained from the fits is also reported. Elasticities between GVA and Water availability show no significance, because they are obtained by multiplying the other estimated elasticities. Elasticity between irrigation production and water availability (ζ_i) ranges between 0.10 and 0.20 when it is significant, and so rainfed elasticity (μ_i) varies in a much higher dimension between 0.23 and 0.57 if significant. Rainfed productions are more easily affected by variations in its water availability (precipitations) than irrigation productions that usually have a higher supply guarantee.

The left part of Table 13 reports the estimated direct elasticities and the right part the indirect effects. All of them allow the estimation of the amount of impacts transmitted through the elasticity factors. ζ_i and μ_i represent the effect that changes in water availability have in production values. These effects are the first to appear as the result of drought, and are transmitted to the macro-economic variable through to β_i and γ_i. On the other hand, the left part of Table 13 measures the same transmissions directly, that is, the factors reported there measure how changes in water availability produce changes in the macro-economic variable.

Table 13. Economic variables elasticity in relation to water availability

		Direct elasticities								Indirect Effects	
Province	Autonomous community	β_i[1]	Conf Interv	γ_i[2]	Conf Interv	ζ_i[3]	Conf Interv	μ_i[4]	Conf Interv	$\zeta_i\beta_i$[5]	$\gamma_i\mu_i$[6]
Alava	B. Country	0.79	(-0.25 1.83)	-0.18	(-0.47 0.10)	0.03	(-0.26 0.32)	0.35	(-0.24 0.95)	0.02	-0.06
Navarre	Navarre	1.04***	(0.66 1.42)	0.64*	(-0.10 1.39)	0.02	(-0.03 0.07)	0.29	(-0.08 0.66)	0.02	0.19
Lleida	Catalonia	1.47***	(0.64 2.30)	-0.51***	(-0.77 -0.26)	0.01	(-0.06 0.08)	0.23*	(0.00 0.46)	0.01	-0.12
La Rioja	La Rioja	1.83***	(0.97 2.68)	-0.27	(-2.70 2.15)	-0.02	(-0.14 0.09)	0.01	(-0.29 0.31)	-0.04	0.00
Huesca						0.10*	(0.01 0.19)	0.57***	(0.24 0.91)	0.09	0.08
Zaragoza	Aragon	0.86***	(0.42 1.30)	0.14	(-0.23 0.51)	0.20***	(0.09 0.31)	0.28	(-0.22 0.77)	0.17	0.04
Teruel						-0.04	(-0.11 0.02)	0.49**	(0.10 0.89)	-0.04	0.07

***p<0.01; **p<0.05; *p<0.1

1 *Elasticity of GVA with respect to Irrigation productions*

2 *Elasticity of GVA with respect to rainfed productions*

3 *Elasticity of Irrigation productions with respect to water availability for irrigation*

4 *Elasticity of Rainfed productions with respect to water availability for rainfed*

5 *Elasticity of GVA with respect to availability for irrigation*

6 *Elasticity of GVA with respect to availability for rainfed*

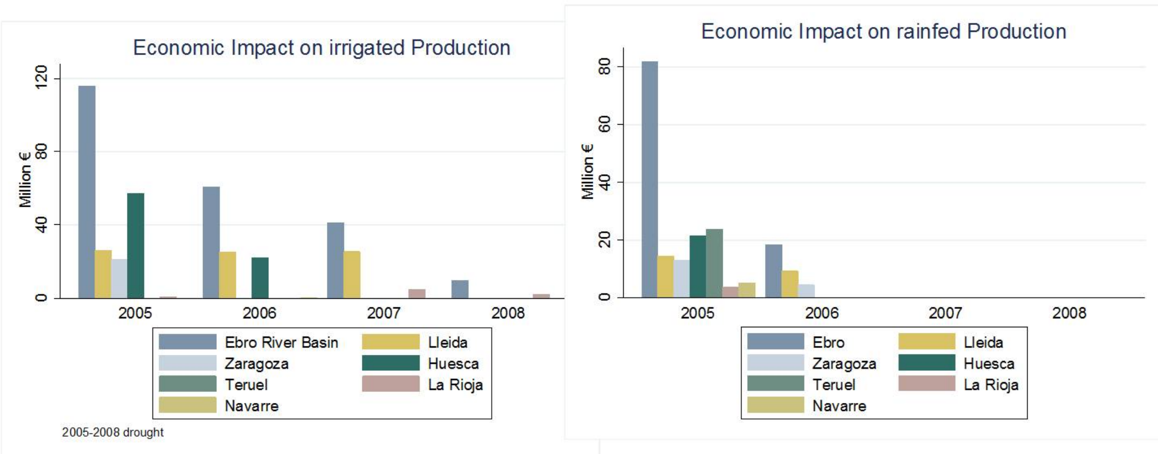
The elasticities are empirically applied to either measure actual losses or potential losses in hypothetical water scarcity scenarios. This gives a perspective of the vulnerability and the risk of each geographical unit. For example in Zaragoza where ζ_i is 0.20 (with $p<0.001$) a decrease of f 1% in water availability would be reflected in a decrease of 0.20% of the irrigated production value, and this decrease (0.20%) is transmitted to the Agri-food GVA as a decrease of 0.17% in value (the indirect effect of $\zeta_i\beta_i$). In a scenario of water scarcity (for the same province) where the hypothetical reduction of water reaches 50%, the value of agricultural production would decrease by up to 10%, and the reduction in Agri-food GVA to 8.5%.

In the case of rainfed agricultural production in Huesca, where μ_i is 0.57 ($p<0.001$), the same hypothetical decrease of 50% in water availability, would result in a negative impact in rainfed production of 28.5% (double the impact than the one recorded for irrigated productions in Zaragoza), and a decrease of only 4% in Agri-food GVA values (measured through $\gamma_i\mu_i$).

5.7 Discussion: the economic impacts of drought

Impacts of the 2005-2008 drought in the Ebro river basin are concentrated in the tributaries of the left margin and in the 2004/05 hydrologic year (see Map 7). Figure 20 shows the economic impacts of the drought on irrigated (on the left side) and rainfed agriculture (on the right side), in the different provinces and for the whole catchment. Sixty five percent of total losses were concentrated in 2005, reaching almost 200 million euros. The impact subsided during the following years, but remained significant until 2008 for irrigation. Irrigated agriculture in the province of Huesca was particularly affected in 2005 and 2006. On the other hand, impacts on rainfed agriculture were more uniformly distributed throughout the basins. Pérez y Pérez and Barreiro-Hurlé (2009) estimate the total loss of agricultural production in 482 million euros for 2005, while the model proposed here estimates a total loss of 286.33 million euros (calculated as the sum of impacts from both types of agriculture). This difference may indicate the degree of overestimation that input-output models generally assume.

Figure 20. Economic impacts of the 2005-2008 drought on irrigated and rainfed agriculture (million €) at the Ebro Basin and provincial levels

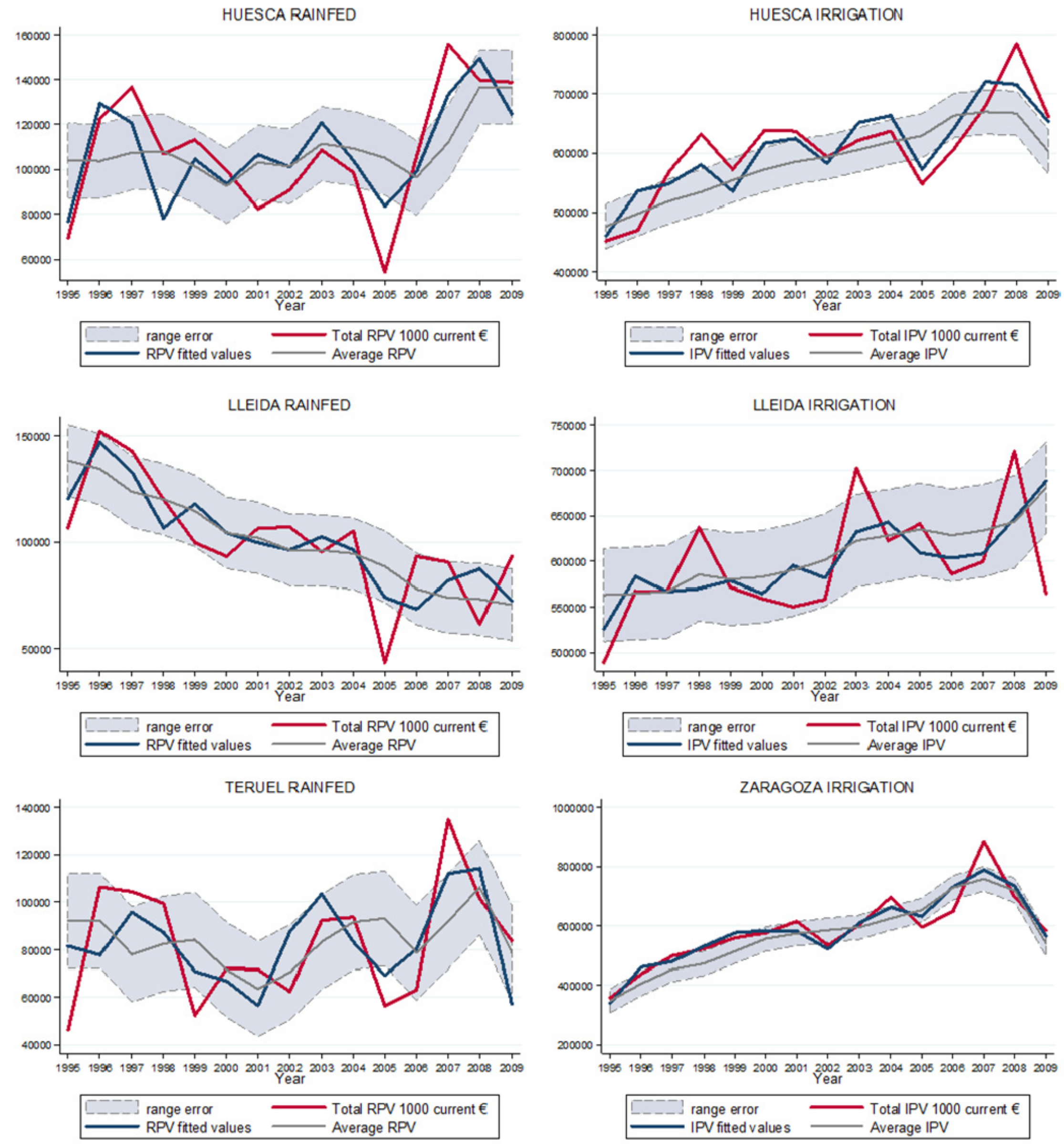


Source: Own elaboration

The measurement of the direct impacts is performed by comparing a "normal situation" (that is, the result of the model with normal water availability) and what the model predicts for a dry year (Eq. 4). Figure 21 shows the comparison between a normal situation, the model´s predicted values, and the actual values of both irrigated and rainfed production values in the provinces of Huesca, Lleida, Zaragoza and Teruel, that were the most affected in the Ebro river basin (see Map 6, Map 7 and Figure 20). Total production value in current euros is represented in red, whereas the blue line defines the value predicted by the model, and the grey line is the normal production value along with the range delimited by dashed lines that include the models confident intervals of the error terms. Total losses will be defined in a drought year by the distance between the grey and blue lines. This means that the difference between those two modeled values is attributable to the difference in water availability, and therefore the economic impact attributable to water scarcity. Losses that exceed the range of error represented a strong economic impact in the analyzed provinces.

All provinces represented in Figure 21 show an important decrease in production values in 2005, and, furthermore the real decrease (red line) is always greater than what the model predicts (green line), except for the case of Lleida. However, the entire decrease in agricultural output cannot be attributed to water shortages. The model used here provides a discriminatory method to establish the percentage of the variance only caused by changes in water availability, from the sources of variation captured by the time trend or by the changes in prices. To isolate the water scarcity effect we measure the difference between production value predicted with the model (in years where water availability is lower than normal) and the "normal" production value (with "normal" water availability included in its calculation). In all cases the real decrease of the economic value was below the decrease due to drought. If the models' goodness-of-fit is good, then we can assume that there are other sources of losses that cannot be imputable always to drought. In these figures we also represent by a dashed line the standard deviation of the error term and, hence there are a range of values among which the production value may naturally vary.

Figure 21. Production values of rainfed and irrigated agriculture (thousand of current €) in the provinces of Huesca, Lleida and Teruel (1995-2009). Observed data, predicted value, average values and confident intervals



Source: Own elaboration

Table 14 summarizes all direct impacts calculated for the 2005-2008 drought on the Ebro river basin. The percentage of the total reduction in the value of production that is attributable to water scarcity is also indicated. The percentage is calculated with reference to the total decrease of production value that is the difference between the actual production value and the trend, in the cases where an impact is identified. The impacts are calculated by the difference between models, and therefore it is possible to see the case where the models predict an impact but the actual result of the sector does not. In those cases there is no percentage of the decrease to be represented and maybe a case of losses compensation is being shown (years where shortages occur but prices and other sources of revenue result in no impact for production value). That is, the model predicts an impact due to water scarcity, but the final output was above the trend. Table 14 shows these percentages of decrease marked in gray where appropriated.

Table 14. 2005-2008 Direct impacts, percentage of the total decrease in the value of production attributable to water scarcity

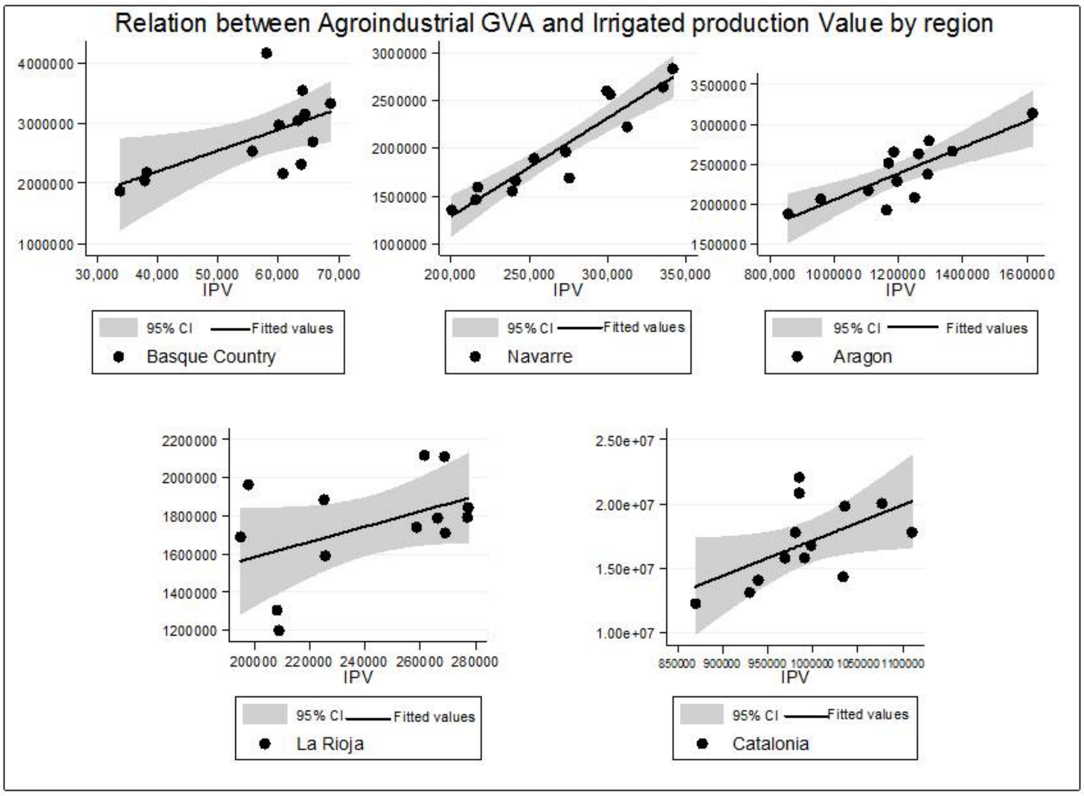
Year	Province	Autonomous community	*Impact on irrigation (million €)*	*%of irrigation losses from total loses*	*Impact on rainfed (million €)*	*%of rainfed losses from total losses*	*total yearly irrigation loss (million €)*	*total yearly rainfed loss (million €)*
2005	Alava	Basque country	0.00	0.00	0.09	0.00	104.78	81.7
	Navarre	Navarre	0.00	0.00	5.15	0.00		
	Lleida	Catalonia	25.94	0.00	14.38	32.80		
	La Rioja	La Rioja	0.70	0.00	3.73	0.00		
	Huesca	Aragon	57.04	58.36	21.57	35.38		
	Zaragoza		21.10	36.88	13.00	28.84		
	Teruel		0.00	0.00	23.78	80.48		
2006	Alava	Basque country	2.70	0.00	4.67	0.00	49.6	18.45
	Navarre	Navarre	0.11	0.37	0.00	0.00		
	Lleida	Catalonia	25.11	63.54	9.26	0.00		
	La Rioja	La Rioja	0.00	0.00	0.00	0.00		
	Huesca	Aragon	21.68	41.41	0.00	0.00		
	Zaragoza		0.00	0.00	4.52	12.85		
	Teruel		0.00	0.00	0.00	0.00		
2007	Alava	Basque country	0.00	0.00	0.00	0.00	29.85	0.00
	Navarre	Navarre	0.00	0.00	0.00	0.00		
	Lleida	Catalonia	25.21	76.59	0.00	0.00		
	La Rioja	La Rioja	4.64	0.00	0.00	0.00		
	Huesca	Aragon	0.00	0.00	0.00	0.00		
	Zaragoza		0.00	0.00	0.00	0.00		
	Teruel		0.00	0.00	0.00	0.00		
2008	Alava	Basque country	0.00	0.00	0.00	0.00	1.96	0.00
	Navarre	Navarre	0.00	0.00	0.00	0.00		
	Lleida	Catalonia	0.00	0.00	0.00	0.00		
	La Rioja	La Rioja	1.96	22.46	0.00	0.00		
	Huesca	Aragon	0.00	0.00	0.00	0.00		
	Zaragoza		0.00	0.00	0.00	0.00		
	Teruel		0.00	0.00	0.00	0.00		

Source: Own elaboration

Indirect impacts appear to be closely related to irrigation and rainfed production values and are thus related to the water used for those productions. The evolution of Agri-Food industry GVA shows this behavior, but employment is more disengaged from water availability (see). The negative signs obtained (see Table 12) especially in hired labor show how employment is following a decreasing trend instead of being affected by water variability. This is the main reason for not calculating the precise impacts for labor. The same situation happens for rainfed productions in Lleida, the strong negative trend prevents us from relating it with droughts and, thus from calculating the impact of it on GVA.

Agri-food industrial GVA is not directly related to water scarcity, but it suffers the impacts of drought through impacts on the main direct variables affected. The irrigation production value is the most significant explanatory variable on the indirect models (see Table 12), Figure 22 depicts the relation between the GVA and irrigated production value by a quadratic fit with the 95% of Confidence Interval.

Figure 22. Relation between observed irrigated production value (IPV, on x axis) and Agri-food industrial output (GVA, on y axis)



Source: Own elaboration

The proposed inference method to measure the indirect impacts provides a variety of elasticities to measure the relation between water availability and GVA, and also between agricultural productions and GVA (see Table 13). The spread of the impacts through the value chain can be described through related elasticities. Thus, the calculated elasticities produce two types of impacts on Agri-food industry GVA, one due to drought impacts on rainfed productions and the other due to drought impacts on irrigation. The addition of both types of impacts is the impact produced on GVA and attributable to both types of water scarcity.

Table 15 contains those calculations for the worst years of the drought period (2005 and 2006). The first two columns of each part of the table show the variation on each type of water availability with respect to the average expressed in percentage terms. The considered average value for water availability for irrigation is the 0.5 value of drought index, and the considered average for rainfed is the previous 3 years moving average of rainfall. The following columns the percentages of direct and indirect impacts transmitted through elasticities are shown, and the amount of GVA impact in million euros.

The case of Huesca in 2005 is a clear example of how the impacts on irrigation are transmitted to GVA: variations of 97% in water availability produce a 9.83% impact on irrigation production, which translates in a 3.99% impact on GVA, which is equivalent to 107.8 million euros.

Table 15. 2005-2006 Spread of impacts: percentages of reduction in Water availability (either drought indices or precipitations), percentage changes of impact transmitted through elasticity on Production values and on GVA. Final indirect impacts (million €) on Agri-industry GVA: impacts produced by irrigation water scarcity and impacts produced by rainfed water scarcity

			Irrigation effects				Rainfed effects			
Provinces	Autonomous community	year	ΔWa1 (%)[1]	IMPACT ON IPV (%)[2]	IMPACT GVA Wa_1 (%)[3]	IMPACT GVA Wa1 (MILLION €)	ΔWa2 (%)[4]	IMPACT ON RPV (%)[5]	IMPACT GVA Wa_2 (%)[6]	IMPACT GVA Wa2 (MILLION €)
Alava	B. Country	2005	-	-	-	-	0.32	0.11	-	-
Lleida	Catalonia		69.42	0.53	0.50	100.37	53.88	12.34	-	-
La Rioja	La Rioja		-	0.35	0.63	12.45	45.65	0.33	-	-
Navarre	Navarre		-	-	-	-	13.34	3.85	2.47	58.70
Huesca	Aragon		97.73	9.83	3.93	107.79	42.04	24.01	0.84	23.03
Teruel			71.06	-	-	-	51.42	25.36	0.92	25.24
Zaragoza			34.03	6.71	2.91	79.87	24.60	6.80	0.47	12.94
Total						300.48				119.91
Alava	B. Country	2006	31.07	0.94	0.50	17.46	18.73	6.59	-	-
Lleida	Catalonia		67.20	0.51	0.48	99.09	51.57	11.81	-	-
La Rioja	La Rioja		3.71	-	-	-	-	-	0.03	0.57
Navarre	Navarre		1.02	0.02	0.02	0.42	-	-	-	-
Huesca	Aragon		38.02	3.82	1.55	43.83	-	-	-	-
Teruel			64.20	-	-	-	-	-	-	-
Zaragoza			-	-	-	-	10.05	2.78	0.16	4.65
Total						160.8				5.22

1 *% of water availability decrease in comparison to 0.5 average drought index*

2 *Direct impact on Irrigation production value produced by* ζ_i

3 *Indirect impact on Agri-food industry GVA produced by* $\zeta_i\beta_i$

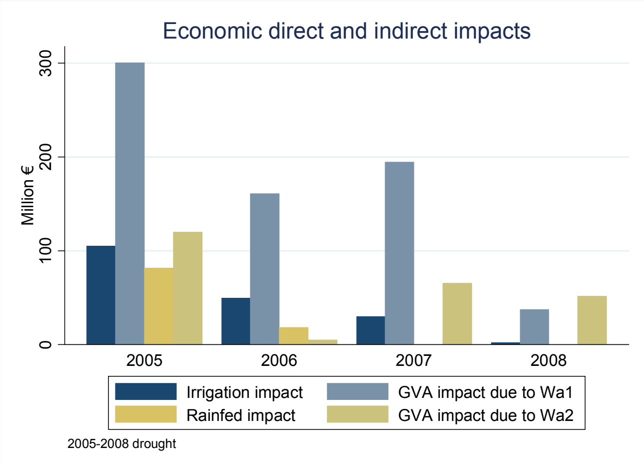
4 *% of water availability decrease in comparison to 3 year precipitation moving average*

5 *Direct impact on Rainfed production produced by* μ_i

6 *Indirect impact on Agri-food industry GVA produced by* $\gamma_i\mu_i^6$

Results from Pérez y Pérez and Barreiro-Hurlé (2009) for the indirect impacts are smaller than the results calculated with the elasticities. They report a total impact on GVA of 202 million euros for the whole Ebro river basin in 2005, while the elasticities here indicate that it may be twice that amount. IO procedure calculates the direct impact without a direct relation between water and the economic result, thus the indirect impact would be also randomly obtained with no drought-dependency.

Figure 23. Comparison of the amount of direct and indirect impacts of the 2004-2008 drought on the Ebro river basin (million €)



Source: Own elaboration

The changes in the macroeconomic variable Agri-food industry GVA also depend on other factors unrelated to the inputs and to water availability. Thus, to generalize the procedure for all provinces there is no validity without a thorough review before being implemented. For Catalonia at least, it was not correct for rainfed.

The other variable affected indirectly by drought, and analyzed here, is agricultural employment. It has especial characteristics in regard to the other variables, because it is the only variable not analyzed on economic terms. Therefore, the impact will be measured on the number of jobs. (Pérez y Pérez and Barreiro-Hurlé 2009) estimate total employment loss due to drought of 11,275 jobs, and the losses directly related to agriculture, forestry and fisheries of 8,094 jobs. However, results from our econometric models of this study reveal that there were no significant impacts on employment. On the one hand, farm family employment shows a clear and long-sustained decreasing trend as a result of structural change. Table 12 shows the significance of irrigation with negative sign, which is a proxy variable for the trend followed. And, on the other hand, hired labor shows no pattern of evolution with erratic and small variations unrelated to water availability.

5.8 Final remarks

Drought is a natural hazard that affects many sectors, but as agriculture is one of the main water uses (around 90% in the Ebro river basin) it has an important impact on it. Therefore, the analysis of these impacts is particularly important when defining efficient and sustainable drought management and mitigation strategies.

An accurate assessment of the damages along with a simple methodology capable of being replicable in other river basins may be a useful innovation in order to better harmonize agricultural water use in the context of the economy of a region.

The econometric models formulated here are robust enough to measure the impacts and they have the advantage that they can discriminate between losses produced by water scarcity and economic losses produced by other factors, including farm prices or simply a downward trend.

Unlike other studies, our analysis develops a complete framework by considering direct and indirect impacts. As indirect impacts have been considered, some assertions can be made: (i) indirect impacts are more related to direct results of drought impacts than to water scarcity, indeed they result from impact transmission processes, (ii) indirect impacts can be compensated in the macro level by market fluctuations or trends, therefore all of the losses must be analyzed in detail, and drought impacts are diluted in the indirect variables affected, (iii) Agri-food industry is closely related to the results of irrigation, and probably to commodity price shocks; and (iv) agricultural employment has negligible impact related to water scarcity.

Elasticities can measure the existent relation between water scarcity and the economic output in different sectors, especially if the sector is directly dependent on agricultural inputs. This procedure allows for having a vision of how much reduction in water availability causes a certain amount of impact in the macro level. Elasticities also reveal the importance of drought impacts according to the total economic importance of each measured variable. This importance diminishes as we approach the macroeconomic indicators from those directly dependent on water abstractions and precipitation.

This methodology can be applicable to other regions by proposing the same econometric models, but the specific reality of each region must be taken into account to elucidate if the impacts are attributable to water scarcity, because there might be other trends acting independently of drought periods.

The importance of having accurate information is relevant for policy makers and water users. These results suggest that more open agricultural markets, and wider and more flexible procurement strategies of the Agri-food industry reduce the socio-economic exposure to drought cycles.

6 ECONOMIC IMPACT OF AGRICULTURAL DROUGHTS FOR IRRIGATED AGRICULTURE IN CHILE

The direct economic impact of drought on irrigated agriculture turns out to be very different when either the water management or the policy scenario changes. An increasing number of nations have begun developing drought policies over the last decades. Moreover, increased importance has also been placed on provincial and local drought policy and planning, emphasizing self-reliance and drought resilience. Spain has a strongly State guided drought policy, while other countries' policy framework involve less public intervention and, thus, drought impacts will greatly vary. This section analyzes the drought impact on Chilean irrigated agriculture characterized by the liberalization of markets and the implementation of water use rights markets as a temporary and permanent water use right reallocation mechanism.

The section starts with a brief introduction providing the context of the main issues and reviews the related literature, followed by a description of the impact assessment method and of the employed data. Finally, the drought impact assessment results are discussed and the main conclusions are presented.

6.1 Chilean context

6.1.1 What kind of drought affects Chilean agriculture and why?

Drought is a recurring phenomenon that has affected agriculture throughout history. Chile, that presents a Mediterranean climate in most of its intensive agricultural production areas, has experienced severe droughts in recent years and throughout its history. The American Meteorological Society (AMS Council 1997) groups drought definitions and types into four categories: meteorological or climatological, agricultural, hydrological, and socioeconomic. A meteorological drought is defined by the lack of precipitation from the normal and the extension of the duration of the drought period. While agricultural drought refers to situations in which the water availability is not sufficient to meet the needs of the crops growing in the area. Focus is placed on precipitation shortages, reduced water flows for irrigation (which are the main source of water for Chilean irrigated agriculture), and differences between actual and potential evapotranspiration, among others. On the other hand, a hydrological drought associates the effect of periods of precipitation shortfalls on surface or subsurface water supply. And finally, socioeconomic drought refers to the situation that occurs when water shortages affects society. It associates economic impacts with the elements of meteorological, agricultural, or hydrological drought.

Water shortages are thus the main indicator of drought. However, the relationship between the different types of droughts is complex and its characteristics vary significantly between geographical areas. Geographical characteristics of Chile makes agriculture mainly rely on river flows as its water source. Chile North-South axis is 4200 Km long and has an average width of 177 Km, with the Andes Mountains towards the east and the Pacific Ocean to the west. Two primary mountain ranges, the Andes and the Coastal Mountains span the length of central Chile and provide the limits to the coastal plain and the central valley.

The rainy season is in winter, June to September months, and much of the precipitation is stored in the snowpack in the Andes mountain range. Water flows in most basins have a mixed origin, since its waters come from winter precipitations and summer snow melt, presenting highest flows in summer (November-February) due to snow melt and pronounced reductions in winter (April-June).

There exist significant regional differences with respect to the available water resources. From Santiago to the north, arid conditions prevail with average water availability below 800 m^3/person year. South of Santiago, on the other hand water availability is significantly higher reaching over 10,000 m^3/person year (World Bank 2011). Consumptive water use in Chile is dominated by irrigation with 73% of consumptive water extraction.

In the northern Chilean desert, approximately between 17° and 26° south latitude, the limited water resources sustain a few coastal cities, some specialized agriculture, and large mining operations; this is the main copper mining area in Chile. In north central Chile, between 26° and 33° south latitude, there is an adequate supply of water in a few river valleys for canal irrigation. Water storage reservoirs have been constructed to support these irrigation systems, especially in the Limarí Valley where three reservoirs have a storage capacity of 990 million m^3. Central Chile, between 33° and 39° south latitude, contains the nation's major urban and industrial areas, including: Santiago with a population of 5,700,000. Irrigated crops include fruits, vineyards, basic grains, forage, and vegetables. Industrial products include processed food, pulp and paper, chemicals, plastics, and petroleum products. Also central Chile remains the region with the greatest hydroelectric generation capacity, especially in the Maule and Bío-Bío basins. Southern Chile, south of 39° south latitude, is humid, forested and scarcely populated. There is little irrigation in the area, which produces forest products, cereals, dairy and livestock, potatoes, and sugar beets. Because of its cool water, clear lakes, and coastal fjords, this area contains Chile's large aquaculture industry. In 2008 there were an estimated 493 marine and 185 freshwater intensive salmon and trout farms in the region.

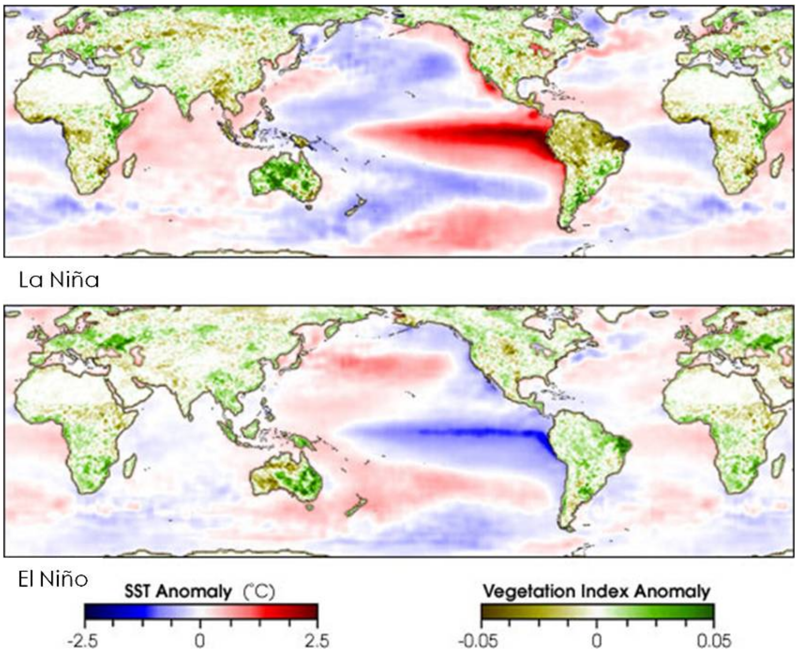
Thus, under these conditions, the objective to be analyzed in this section are the impacts of agricultural droughts, and they must be considered as a natural hazard that must be characterized by both climatological and hydrological parameters (Mishra and Singh 2010), as well as agronomic parameters.

Additionally, it is also important to note that agricultural drought vulnerability has increased worldwide for various reasons. An important driver of increased agricultural droughts is population growth, which depends on a limited natural resource such as water (Wilhite 1993, Wilhite 2000). Climate change is a second important driver. Several authors such as Lehner et al. (2006), Le Houérou (1996), and Quereda Sala et al. (2005) point to an escalation in the frequency and intensity of droughts even under the less pessimistic scenarios of climate change.

6.1.2 ENSO Southern oscillation in the case study

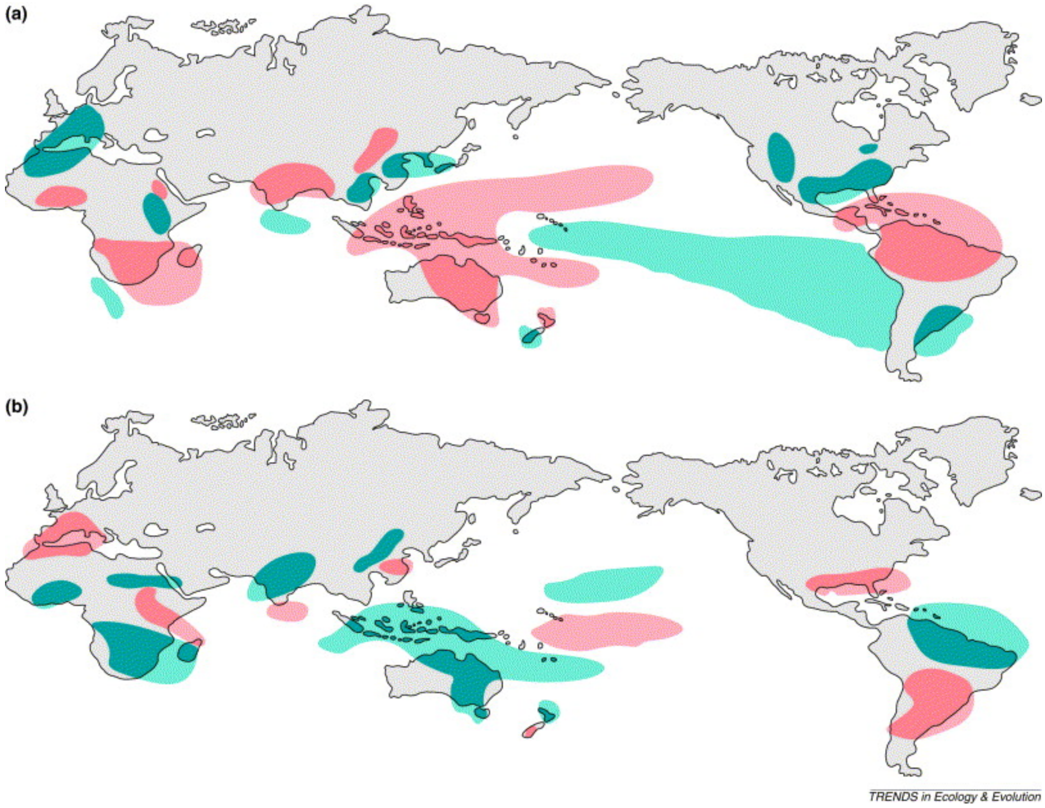
El Niño Southern Oscillation (ENSO) is a climatic pattern characterized by two opposite events (El Niño and La Niña) that occurs across the Pacific Ocean roughly every five years. It seriously affects rainfalls, resulting in significant reductions or increases in water flows. El Niño refers to the increases in temperature of the ocean surface and has generally meteorological droughts associated to its occurrence (Potgieter et al. 2010), whereas la Niña normally brings an increase of the precipitations in central and Southern America due to decreases in ocean surface temperature. Map 8 represents the average variations in ocean temperature and on vegetation index during both events for two representative years (1983 on the upper part and 1989 on the lower part of the map). However, the variations on precipitation parameters are mixed along the continent. While droughts are very intense during El Niño in Central America and the northern part of South America, the precipitations usually experiment increases in northern and central Chile (Jaksic 2009, Dirección Meteorológica de Chile 2012).

Map 8. Average El Niño and la Niña events



Source: NASA (2012) (http://earthobservatory.nasa.gov/Features/SSTNDVI/sst_ndvi4.php)

Map 9. Regions showing increased precipitation (blue) and drier conditions (orange) during El Niño (a) and La Niña (b) phases of the ENSO phenomenon

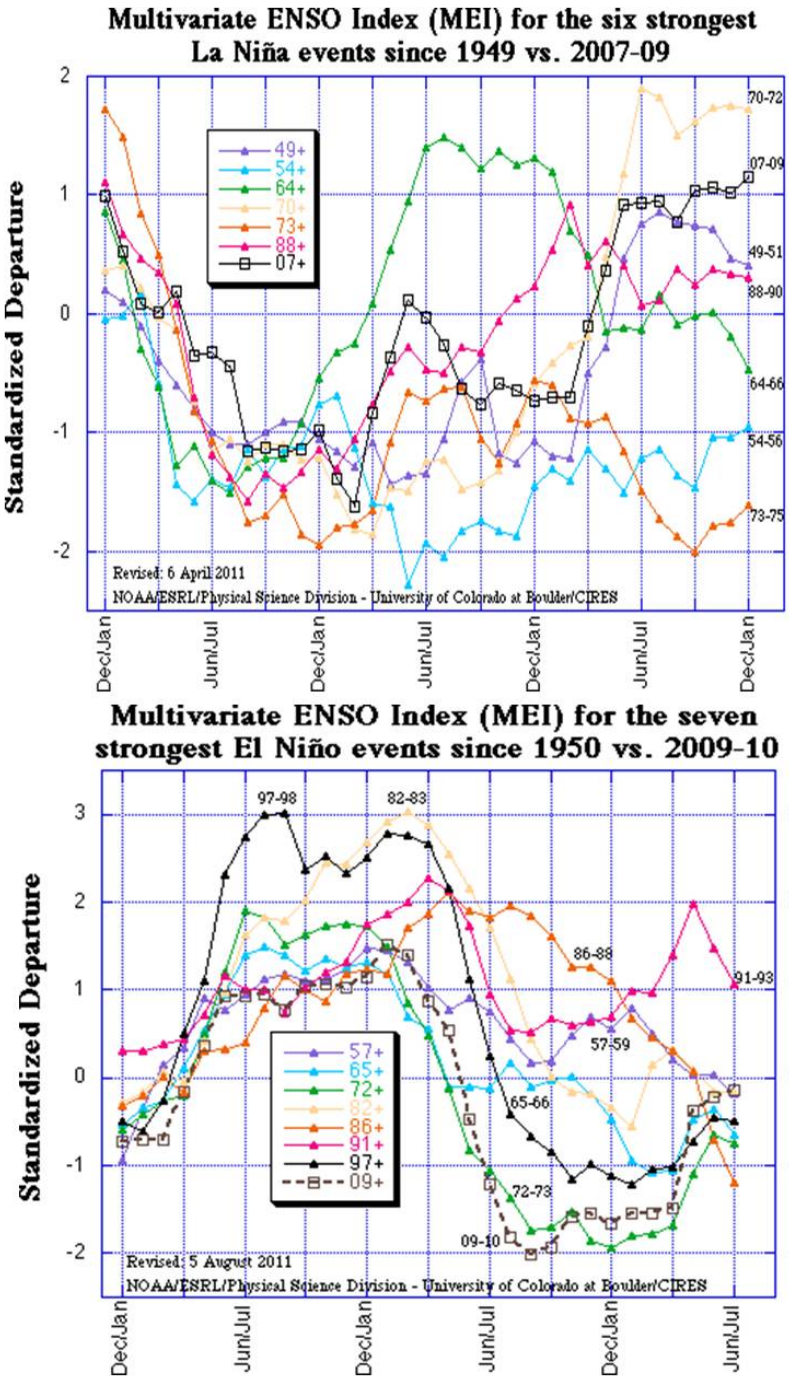


Source: Holmgren et al. (2001)

Map 9 shows the regional consequences of El Niño and La Niña. It can be seen how in Chile El Niño normally increases the rainfall and la Niña usually produces droughts. Therefore, in the Chilean context one must also take into account that due to the country's geographical position, its agriculture has been hit by the El Niño-Southern Oscillation (ENSO) several times. It is therefore important to understand the relationship between drought, climatic factors, and local ocean temperatures to address agricultural drought vulnerabilities (Mishra and Singh 2010).

This section deals with the impact of agricultural droughts in Chile (as water flows are the main source for irrigation in the country) and pays special attention to the ENSO phenomenon. Figure 24 shows the recent important ENSO events since 1994. Data collected for the present research includes two representative years of this figure (1997 and 2007). El Niño event of 1997 was one of the less severe, however the rainfall patterns were affected in Chile showing values above the average (Jaksic 1998). While in 2007 the country was hit by La Niña event (See Figure 24) which decreased rainfall leading to agricultural drought conditions in a vast area of the country. This phenomenon must be managed along with drought effects posing a preventive management to mitigate the impacts (Kogan 2011).

Figure 24. Multivariate ENSO index for the most important El Niño and La Niña events since 1949



Source: NOAA (2012) http://www.esrl.noaa.gov/psd/enso/mei/#ElNino

Chileans have gotten used to hearing about La Niña, as the climatic phenomenon that brings unusually hot, dry weather to South America's Pacific Coast, reducing rainfall from southern Chile to northern Colombia. La Niña has struck again in 2010, however, the drought has been less severe than the previous one in 2007-2008. Recent agricultural drought events in Chile and the magnitude of drought losses may indicate the continuing vulnerability of Chilean agriculture to drought. Many farmers partially mitigate drought impacts through crop selection, irrigation, and tillage practices. However, impacts show that the emphasis of disaster management has been largely on response and recovery from drought, with little or no attention to mitigation, preparedness, prediction and monitoring. Thus, Chilean agriculture remains highly vulnerable to droughts, and the scarcity of both water infrastructure and risk based management plans increases drought risk exposure.

6.1.3 Economic impact of drought in Chile: consequences of water and drought management

This section presents an estimation of agricultural drought vulnerability in Chile through the assessment of its economic impacts. This research primarily assesses the economic loss of irrigated agriculture due to the lack of water flows to satisfy irrigation water demands at the sub-basin level for several rivers of Chile. Precipitations are also considered as they are related to annual water flows and crop needs. Thus, we focus on the economic impact caused by productivity loss due to agricultural droughts. Other researchers have focused on non-productive economic impacts, such as the lack of water flows to insure instream flows to protect critical habitat requirements (Ward and Booker 2006).

Water flows are of great importance when managing water resources in Chile. Water management is characterized by the significant participation of the private sector, an operation guided by market forces and incentives. Since 1981 with the approval of the Water Code framed by a neoliberal institutional reform process, a market-based policy was implemented for the distribution and use of water. State participation is aimed at ensuring the proper performance of the parties (Código de Aguas de Chile 1981). This leads to a growing competency for the use of water that faces a limited supply and a quite inelastic demand, especially because water use rights do not increase in the short-term. Market related factors, such as price variations must be taken into account for the assessment of drought losses.

The intrinsic characteristics of agricultural droughts and its fuzzy boundaries impose difficulties for the precise estimation of its impacts. It is precisely these characteristics that make this natural phenomenon difficult to clearly identify in time and space. This research contemplates the dynamic nature of agriculture, by explicitly considering the important crop distribution changes over time. Bahamondes (2003) points out that the Region of Coquimbo (IV Region) presents a significant increase in irrigated surface between 1991 and 1999, primarily due to an increased access to agricultural credit. In order to account for this dynamism, the bases of our analysis are the agricultural census of 1987, 1997, and 2007.

Molina (2000) points out that the drought occurred in the 90´s decade severely affected Chile for an extended period of time. In the event of a prolonged drought, optimal water management should focus on long-term adaptability (Harou et al. 2010), in order to mitigate its impacts. Adaptability to droughts in the Chilean case is focused on the efficient functioning of water use rights markets and the efficient exchange of water use rights in times of scarcity. The Chilean water code bases water allocation on tradable private water use rights (Water Code of Chile 1981).

However, Bakker (2000) documented the difficulty of managing droughts with private water use rights. Similarly, Bauer (1998) found limitations to water management and the implementation of environmental policies under a market context of private water use rights. The main factor that generated an obstacle was the institutional dependence of the transfer of water use rights, which explained the lack of effectiveness as a response to droughts.

In general, Chile´s water use right markets have received wide attention (Rosegrant and Gazmuri 1995, Hearne and Donoso 2005, Donoso 2006, Alevy et al. 2012). One of the key conclusions of these studies is that water use right markets are driven by demand from relatively high-valued water uses and facilitated by low transactions costs in those valleys where water user associations and infrastructure present assist the transfer of water. In the absence of these conditions trading has been rare and water markets have not become institutionalized in most valleys (Hearne and Donoso 2005). Although market transactions are still rare they are becoming more frequent in areas subject to economic growth and increased water scarcity. Another lesson of these studies is that the operation of the water use right markets is variable across the country, and they depend significantly on the relative scarcity of water resources, the distribution infrastructure and water storage capacity, and the proper functioning of water user associations. It should be noted that during the 2000s, the market was more active than in the previous two decades, 1980's and 1990's. This is largely due to a slow maturation in the public's knowledge concerning the new legislation. In a sense, the 80s represented a preparatory stage in bringing the new Code into full operation, in social, political and economic terms.

The design of public policies and vulnerability assessment strategies for drought requires local analysis of impacts (Dono and Mazzapicchio 2010). A local approach allows for the understanding of particular characteristics of each area which determine the appropriate drought management. In this section local economic impacts of agricultural droughts are evaluated at the sub-basin level of several rivers that are representative of different climatic zones of the country.

Additionally, inefficient water management and poor drought response are less shown when the level of management or/and the level of analysis are reduced. Thus, in small watersheds, where transaction costs are low, water use rights trading has been successful in Chile to mitigate negative impacts in drought periods, (Hearne and Donoso 2005, World Bank 2011).

To move towards efficient drought management, many factors are involved. The assessment of drought impacts is essential to obtain a clear view of the scope of the damage of an agricultural drought. Impacts can be measured in different ways, but a correct measurement of the economic impact is of paramount importance for the management and planning of freshwater (Mishra and Singh 2010). These measurements should be used to provide information to water users and thus give rise to a correct response to droughts, mainly proactive based on preparedness. Drought management must focus on risk reduction, due to drought´s high uncertainty, and the several factors involved on its onset and consequences (Thurow and Taylor Jr 1999).

6.1.4 Agricultural drought impact assessments

There are different ways of estimating the impact of droughts on agriculture. The initial economic consequences of droughts occur at the farm level, generating impacts at the macro level due to its effects throughout the production chain. The impact of droughts at the macro level is dampened due to the diverse impacts on other sectors than agriculture. There are studies that estimate drought impacts at the macro level through the Agricultural Gross Value Added (Garrido et al. 2010) and by assessing losses in net farm income and gross domestic product (Klein and Kulshreshtha 1989, Horridge et al. 2003). Salami et al. (2009) employs a linear programming model to estimate the direct costs of droughts on agriculture and its macroeconomic effect.

Warren et al. (2010) estimate the long-term economic impacts caused by drought-induced climate change on USA agriculture, based on a methodology that converts changes in precipitation and water flows into changes in economic activity. These changes allowed the authors to conduct simulations of the economic impacts using a large-scale macroeconomic model of the USA economy. Other approaches suggest that droughts can cause changes in the financial position of households that depend directly on water flows (Edwards et al. 2009).

Bergh and Nijkamp (1998) suggest that the impacts of a drought or of another natural hazard should be modeled as long-term costs due to a major drought or climate change. Through a comprehensive review of drought economic impacts and the associated quantitative assessment methodologies, Ding et al. (2011) summarize the economic impact studies in both agricultural and non-agricultural sectors, with no regard to non-market impacts, but valuable, economic welfare losses. In this field, Carroll et al. (2009) does one of the most original but also controversial estimations. By matching rainfall data with individual life satisfaction for the case of Australia over the period 2001 to 2004, estimating high economic losses. The Life Satisfaction Approach (LSA) represents a new non-market valuation technique which builds on the recent development of subjective well-being research in economics which empirically approximates individual welfare based on measures of reported life satisfaction (Frey et al. 2009).

In Argentina, Hartmann et al. (2003) describes how unplanned alert measures managed to reduce economic losses for farmers due to droughts. However, they show that this approach does not take into account the full impacts of droughts and that these represent a risk that should be optimally managed. In contrast, Klein and Kulshreshtha (1989), employ an impact assessment model of agricultural drought that focuses primarily on assessing economic impacts of planned drought mitigation strategies. But, nevertheless according to Ding et al. (2011) drought-induced production losses cause negative supply shocks, but the amount of incurred economic impacts and distribution of losses depends on the market structure and interaction between the supply and demand of agricultural products.

In summary, it is important to note that by studying droughts and their impacts optimal adaptation strategies can be developed (Tagel et al. 2011). Furthermore, increasing probabilities of drought events highlights the importance of river basin analysis based on an integrated water management and economic models (Rosegrant et al. 2000). The appropriate unit of analysis to address the challenges facing water resources management is the basin or sub-basin level; modeling at this scale provides essential information for policymakers in their water management decisions and drought adaptation strategies. This coincides with Ding et al. (2011) who point out that impact assessments are basin specific, and their impacts could be very different between regions, and thus, not comparable. Therefore, given the geographical characteristics of Chile, where different basins are subject to different climates and are characterized by different agricultural production structures, agricultural drought impacts must be estimated at the basin or sub-basin level.

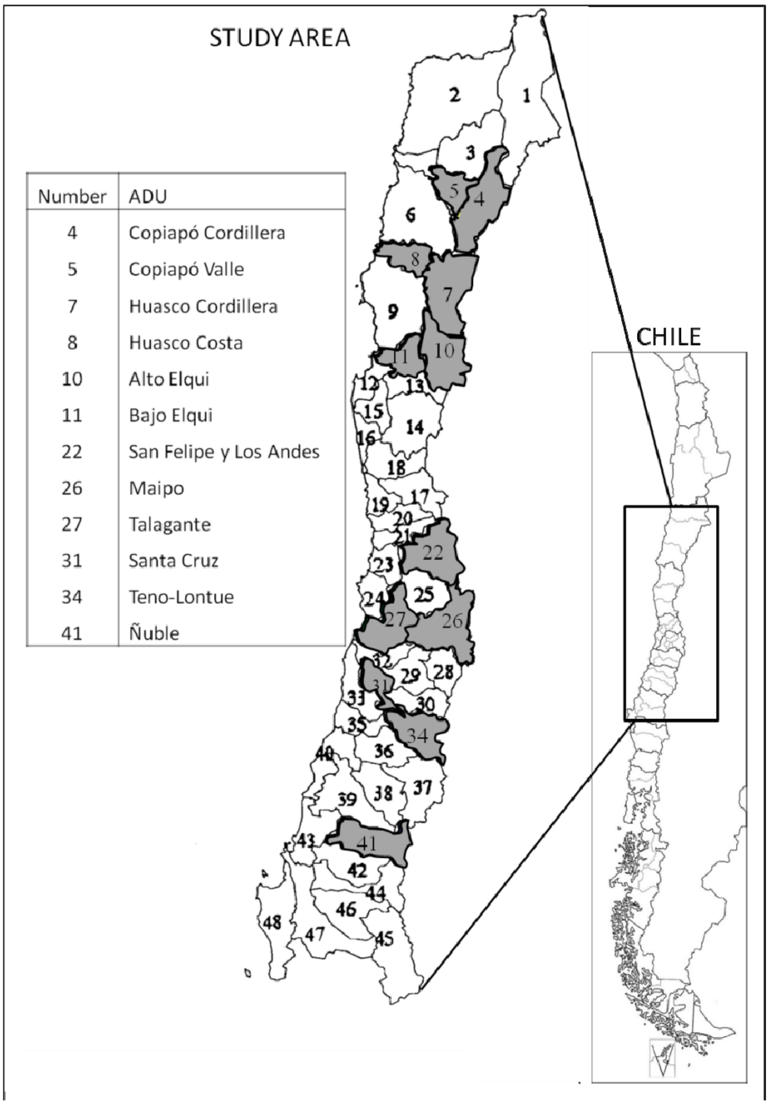
Econometric models can be used to estimate these economic impacts of droughts isolating the effects of water shortages from other sources of economic loss (Gil et al. 2011). The objective of this econometric model is to measure economic losses due to increased water scarcity situations, as well as to identify the main determinants of these economic losses, such as the influence of prices and water management strategies. Additionally, this model provides the necessary knowledge to assess drought vulnerability and drought management policies in Chile.

6.2 Material and methods: panel data analysis

As has been mentioned, an econometric model is proposed to measure the economic impact of agricultural droughts on irrigated agriculture in different agro-climatic areas of Chile. The model estimates the changes in the value of irrigated agricultural production at the sub-basin level. The econometric model also accounts for variables that may affect the value of irrigated agricultural production so as to discern which are the factors that motivate such changes.

The model is estimated at different water basins or sub-basins. The selection of these units of analysis is based on the characterization made by the General Water Directorate of the Ministry of Public Works (DGA, Dirección General de Aguas and PUC, Pontificia Universidad Católica de Chile 1997) with the aim of studying the economic impacts of hydrological droughts. According to this characterization, the area between the Region of Atacama and the Los Lagos Region (where most of the arable land is concentrated) was divided into 47 water basins and sub-basins. These units, governed by the same water hydrology and water management scheme, are denominated Agrarian Demand Units (ADU), following the model proposed in the study of Gil et al. (2011). In this study we have selected 12 ADUs of the 47 characterized by the DGA (1997), which constitute a representative sample of the drought-stricken agricultural reality in Chile. They are spread throughout the country from the Region of Atacama (III Region) to the Bio-Bio Region (VIII Region). Map 10 shows each of the chosen units, their names and their location.

Map 10. Chilean Agrarian Demand Units



Source: Own elaboration

In this context, the econometric model proposed to explain the value of agricultural output at the ADU level, at constant prices of 2007, is formulated as follows

$$IPV_{it} = \alpha_o + \beta Fm_{it} + \gamma Dem_{it} + \delta Pa_{it} + \varepsilon Pi_{it} + \sum_i \phi_i D_i + u_{it} \qquad (1)$$

where IPV_{it} represents the value of agricultural output (Irrigation Production Value) at the i^{th} ADU level for year *t*, Fm_{it} is the annual minimum water flow for i^{th} ADU for year *t* measured in m^3/sec., Dem_{it} is the i^{th} ADU's water demand for year *t* measured in m^3, Pa_{jt} represents the accumulated precipitation for year *t* at ADU *i* measured in mm, Pi_{it} is a Price index of the main 5 agricultural crops of i^{th} ADU for year *t* measured at constant prices of 2007, D_i is a binary variable that takes the value of 1 if the ADU corresponds to the i^th^ unit and 0 in any other case, α, β, γ,. δ, ε, and ϕ are parameters and u_{it} is the stochastic error term. The model combines three years with 12 geographic units.

The dependent variable is the value of irrigated production at constant prices of 2007 (IPV_{it}), deflated by the Wholesale Price Index of the National Statistics Institute (*Instituto Nacional de Estadística*, INE 2010). This variable was calculated as follows:

$$IPV_{it} = \sum_{j=1}^{84} Sur\_irrg_{jt} \times Yield_{jt} \times p_{jt} \quad (2)$$

where Sur_irrg_{jt} is the irrigated area of crop j (j = 1,…,84) at time t (hectares) at the i^{th} ADU obtained from agricultural census data of 1987, 1997 and 2007, $Yield_{jt}$ represents i^{th} crop yield at time t (kg/ha) from FAOSTAT (2010), p_{jt} are prices of crop j at time t (\$/kg) collected from the Office of Agricultural Studies and Policies (Oficina de Estudios y Políticas Agrarias, ODEPA 2010).

The model includes a hydrological and meteorological explanatory variable: Fm_{it}, and Pa_{jt}, respectively. The annual minimum flow (Fm_{it}) is measured in m^3/sec and has been obtained from the Hydrological Bulletins of the DGA (2010). The accumulated precipitation (Pa_{it}) is calculated as the sum of monthly rainfall in mm and was obtained from the Meteorological Directorate of Chile (*Dirección Meteorológica de Chile*). Both variables are key parameters to measure drought conditions in Chile.

The third hydrological explanatory variable is the ADU's agricultural water demand at time t (Dem_{it}). This variable, measured in m^3, is calculated following FAO's Irrigation and Drainage Paper Nº 33 as follows:

$$Dem_{it} = \sum_{\substack{j=1 \\ m=1}}^{\substack{j=84 \\ m=12}} 10 \times Sur\_irrg_{jit} \times (ETr_{jimt} - PP_{imt}) \quad (3)$$

where Dem_{it} is the demand for water in m^3 for each ADU i, for each year t. Sur_irrg_{jt} is the irrigated area of crop j at time t for each ADU i. ETr_{jmt} is the actual evapotranspiration for each crop *j* in each month *m* for each ADU *i,* for each year *t,* which , in turn, is calculated as:

$$ETr_{jmt} = Kc_{jm} \times ET_{0\,jmt} \tag{4}$$

where Kc_{jm} is the j[th] crop coefficient for month *m* at ADU *i* for each year *t* and ETo_{jmt} represents actual evapotranspiration for crop j and month m at ADU *i* for each year *t.* Data on Kc_{jm} and ETo_{jmt}, was obtained from the Natural Resource Information Center (*Centro de Información de Recursos Naturales*, CIREN 2010). Finally, the variable PP_{jmt} represents monthly precipitation of each year t for each unit i, measured in mm.

It is considered important to introduce in the model an explanatory variable related to the prices of the main crops grown in each ADU so as to control for their behavior in periods of drought that affect extended agricultural areas, such as those agricultural droughts that occur due to ENSO effects. This variable, Pi_{it}, also allows us to distinguish between market effects due to a geographically extended agricultural drought and the effects due to the local lack of water. Pi_{it} is a price index of the main 5 agricultural crops of i[th] ADU for year *t* measured at constant prices of 2007, which was calculated as follows

$$Pi_i = \frac{\sum_{k=1}^{5} Sur\_irrg_{ik} \times P_k}{Sur\_irrg_i} \tag{5}$$

The model is estimated with feasible generalized least squares for panel data, which corrects for heteroscedastic error terms with no autocorrelation. The panels are defined by i[th] ADU and year *t*. An advantage of feasible generalized least squares for panel data is that it allows for the correction of unobserved heterocedasticity and the estimation of fixed effects between ADUs, captured by ϕ_i. Finally, the stochastic error term u_{it} satisfies the following properties, $E(u_{it}) = 0$, $E(u^2{}_{it}) = \sigma^2$ and $E(u_i u_k) = \sigma_{ik} \;\; \forall i \neq k$.

6.3 Results from the econometric model

Estimation of Eq. 1 allows for the estimation of the economic impacts of agricultural droughts in each ADU for each year. Additionally, through the estimation of the econometric model one can distinguish between market effects due to a geographically extensive agricultural drought and the effects due to the local lack of water. Table 16 presents the general estimation results obtained from the estimation of the econometric model with panel data. In this section the adjustment statistics and the parameter estimates are presented with particular attention to their signs and their significance.

The model presents a significant Chi^2 and, thus, a high goodness of fit. It is important to note that twelve covariances were estimated and that the model does not present autocorrelation problems.

Parameter estimates and their significance are presented in table 17. The results indicate that all the explanatory variables besides the ADU dummies are significant.

Table 16. General Estimation Results

Estimated Covariances	12	Number of observations	36
Estimated Autocorrelations	0	Number of Groups	12
Estimated Coefficients	16	Time Periods	3
		Wald $Chi^2(15)$	103.31
		Prob > Chi^2	0.000

Source: Own Elaboration

Table 17. Estimated coefficients of the irrigated production value econometric model for each ADU and year t

Irrigated Production Value (Constant $ of 2007)	Estimated Coefficient	Standard Error	z-statistic	P>|z|	[95% confidence interval]
Annual minimum water flow	-854514.7	246145.3	-3.47	0.001	[-1336951, -372078.7]
Agricultural water demand	0.1315335	0.0230109	5.72	0.000	[0.0864329, 0.176634]
Accumulated precipitation	14500.37	3567.199	4.06	0.000	[7508.787, 21491.95]
Price index	8103.2	3953.998	2.05	0.04	[353.5059, 15852.89]
Copiapó Valle	506729.3	2353789	0.22	0.83	[-4106613, 5120072]
Huasco Cordillera	2631648	2458320	1.07	0.284	[-2186572, 7449867]
Huasco Costa	398835.3	3093354	0.13	0.897	[-5664026, 6461697]
Alto Elqui	2830602	2529351	1.12	0.263	[-2126835, 7788039]
Elqui Bajo	-2876492	3360797	-0.86	0.392	[-9463532, 3710549]
San Felipe y Los Andes	-1.67E+07	3902530	-4.28	0.000	[-24400000, -9073043]
Maipo	10500000	4627673	2.27	0.023	[1418462, 19600000]
Talagante	-6241199	6137249	-1.02	0.309	[-18300000, 5787588]
Santa Cruz	-2361911	5315076	-0.44	0.657	[-12800000, 8055446]
Teno-Lontue	-3893346	1.02E+07	-0.38	0.704	[-24000000, 16200000]
Ñuble	-8133586	3009595	-2.70	0.007	[-14000000, -2234888]
Constante	-5378350	2371230	-2.27	0.023	[-10000000, -730823.5]

Ource: Own Elaboration

The parameter estimates of agricultural water demand at time *t* (Dem_{it}) and accumulated rainfall (Pa_{jt}) are positive and significant at the 1 percent level of significance. The price index (Pi_{it}) is also positive but significant only at a 5% level of significance. These three parameters present the expected signs.

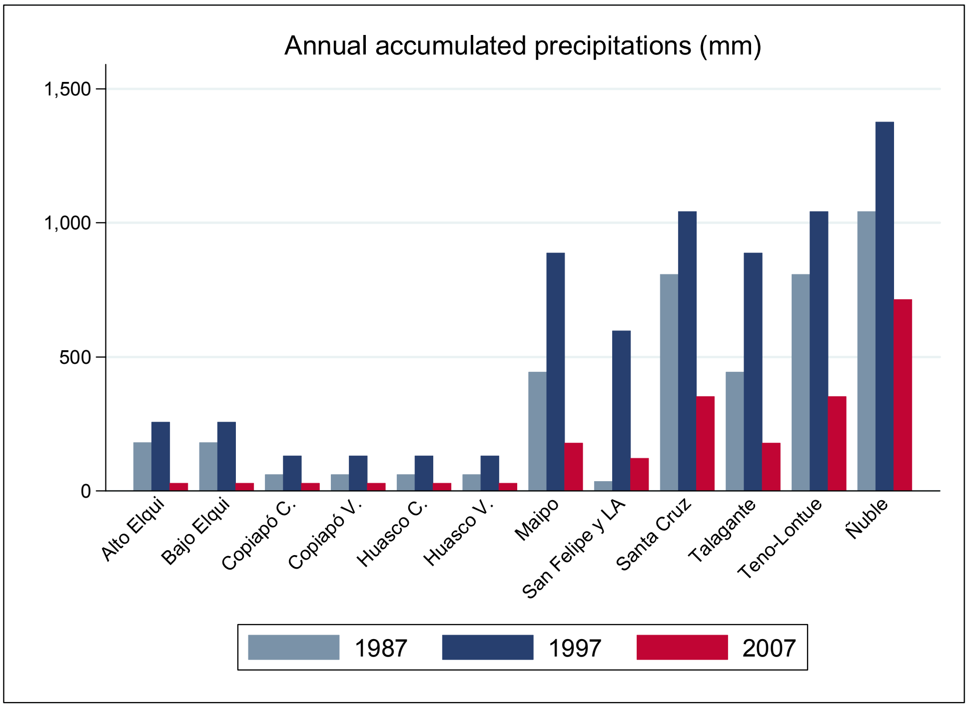
However, the parameter estimate of annual minimum water flow (Fm_{it}) presents a counterintuitive sign. Fm_{it} presents a negative and significant parameter at the 1% level of significance. This result is counterintuitive since as the ADU counts with a greater annual minimum water flow, there is a lower probability of agricultural drought and, thus, irrigated production value should increase. This result will be analyzed in greater detail in the following section.

Of the ADU dummies, only three are significant: *'San Felipe y Los Andes'* in the Valparaiso Region, *'Maipo'* in the Metropolitan Region, and *'Ñuble'* in the Maule Region. All the other ADU dummy parameter estimates are not significant, and thus there are no significant differences in the irrigated production value function for these ADUs.

6.4 Discussion: impacts of agricultural droughts

In order to anlayize the existence of drought conditions in the data base, accumulated precipitations and water flows were analyed. As shown in Figure 24 Chile was hit by El Niño in 1997 and by La Niña in 2007. Precipitation patterns are represented in Figure 25 that clearly shows the increase of precipitations during 1997 and the decrease during 2007. Water shortages of 2007 were very severe all over the country. Differences in rainfal water availability are pronounced between the north and the south. But, agricultural drought conditions are not only given by precipitations but also by water flows. As they are very correlated with rainfalls, especially in a country where river lengths are mainly short, we had selected the minimum water flow (instead of the average) to control by critical situations, and to correctly estimate Eq. 1.

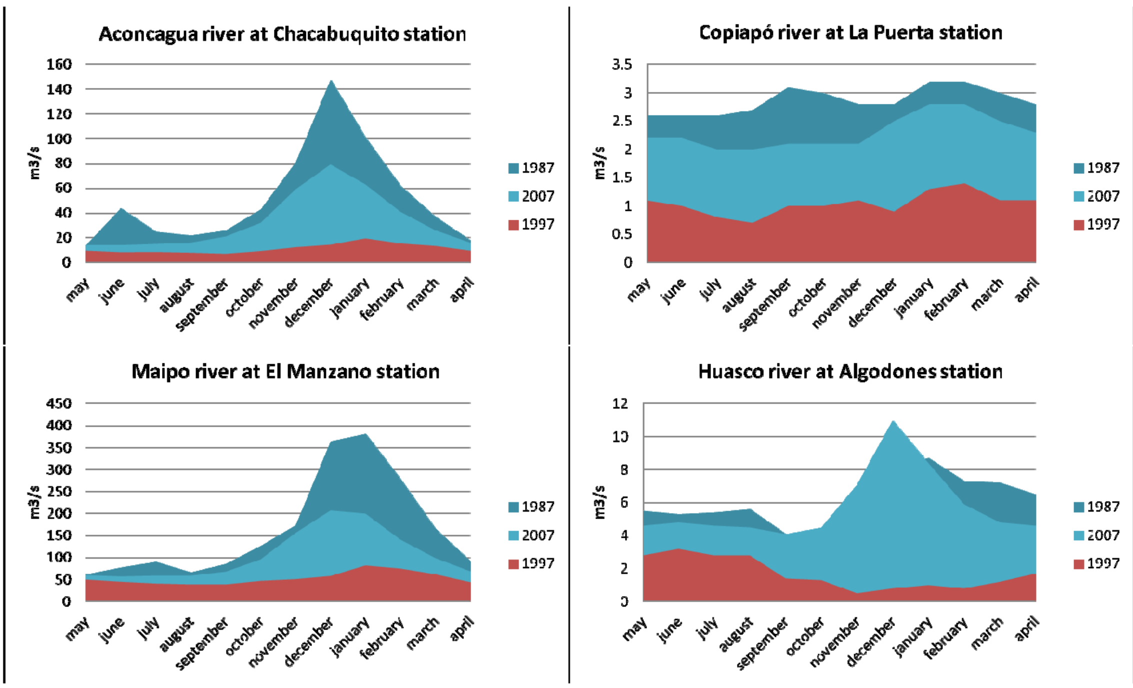
Figure 25. Annual accumulated precipitations (mm) for the analyzed Agricultural Demand Units



Source: Own elaboration with data from the Meteorological Directorate of Chile

Therefore water flow data for each ADU at time *t* was analyzed. Figure 26 presents monthly average water flow in m^3/s for each of the years 1987, 1997, and 2007, for some of the most important river basins that supply water to the ADUs. Red color represents the monthly average water flow of 1997, which corresponds to an El Niño year. It can be seen that the monthly average water flow during 1997 in all ADUs is significantly lower than the water flows in the other years included in the study. Water flows are correlated to the previous year hydrologic conditions, and especially the minimum values may indicate high variability during El Niño event. La Niña event (drought) appears to have lower water flows than 1987 (normal year) which combined with precipitation patterns results in a drought situation. The worst cases of agricultural drought during 2007 occur in the river basins of the Aconcagua and Maipo (Valparaiso Region), where the normal increase in water flows during the spring months due to snow melt (October to January) is significantly reduced. This situation exposes farmers to higher agricultural drought risk, whose magnitude depends on the agricultural surface and the agricultural demand for irrigation water.

Figure 26. Monthly average water flow (m^3/s) between May year t-1 and April year t



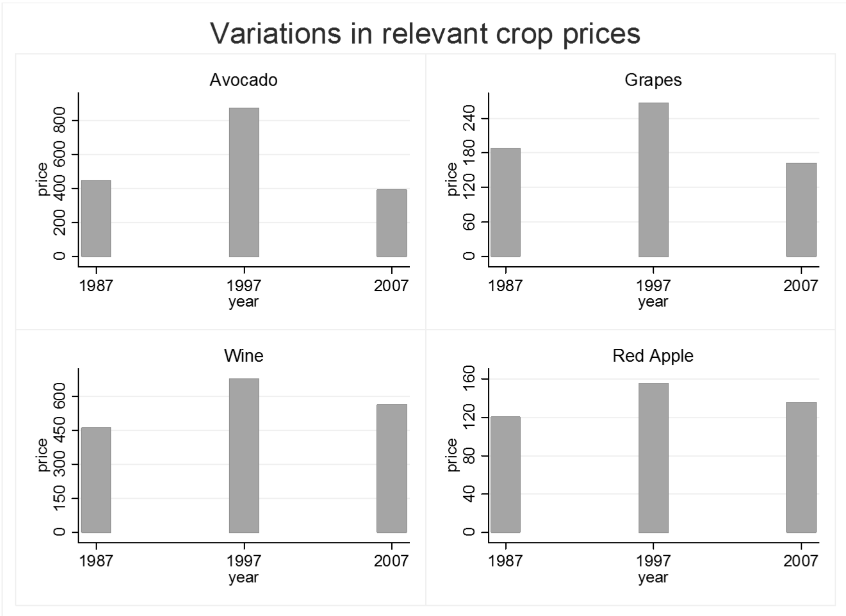
Source: Own elaboration from Hydrological Bulletins Dirección General de Aguas (DGA)

The estimated parameter of the annual minimum water flow (Fm_{it}) is negative, which, as previously pointed out, is counterintuitive since it apparently implies that when farmers face an agricultural drought, irrigated production value increases. This result can, however, be explained by the positive relationship between agricultural prices and extended agricultural droughts produced by El Niño in many other parts of the world; many crop prices respond to water scarcity because reduced harvests increase crop prices and vice versa, when the agricultural drought covers an extended geographical area (Westhoff 2008).

While a local community might experience significant losses due to a localized and short agricultural drought, at a regional or national scale there are farmers who benefit from increased commodity prices, due to agricultural supply reductions produced by extended agricultural droughts (Kunkel et al. 1999). Brunner (2002) studied the historical effects of the El Niño-Southern Oscillation (ENSO) cycle on world prices and concludes that ENSO has important and statistically significant effects on world real commodity prices. For example, ENSO accounts for approximately 20% of commodity price inflation movements over the past several years (Brunner 2002).

There is evidence that ENSO has important and statistically significant effects on agricultural prices in Chile and in the ADUs, specifically. Figure 27 shows selected agricultural prices (in constant pesos of 2007) of some of the country’s most important crops for 1987, 1997, and 2007. In all products, there is a significant increase in prices during 1997, which corresponds with and ENSO Cycle. Increases of international prices are transmitted to national markets, especially when dealing with exports. Figure 27 gathers the main exportable agricultural products. Prices were significantly affected, being avocado 100% higher, and grapes, wine, or red apples around 40% higher, in comparison to the 20 year data. This suggests, that the more flexible and efficiency the crop markets are the larger the compensating effect on irrigators’ total revenue (Garrido et al. 2010).

Figure 27. Prices of Selected Agricultural Products in constant CLP of 2007



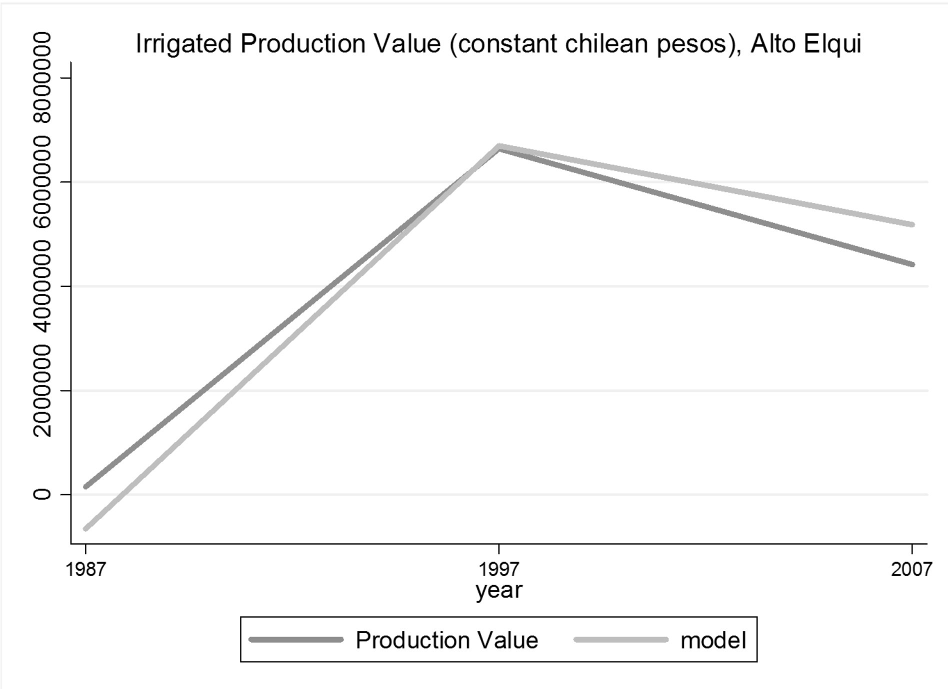
Source: Agricultural product prices, Oficina de Estudios y Políticas Agrarias, ODEPA

The combination of ENSO incidence and the management scenario of Chile intensify the price rise in comparison with other countries like Spain where most price-vulnerable products are subsidized. Institutional management in Chile is manly based on a liberal model, where market forces play an important role while there is reduced State intervention. And so, agricultural management is not supported by price subsidies, and market forces normally guide growers' decisions. Furthermore, preventive management strategies for drought are not common, and the impacts produced are generally compensated by economic transactions for farmers affected. This also increases the risk of suffering high prices when external shocks occur, because not much prevention is put in place to deal with natural hazards.

On the other hand, the year 2007 is representative for a drought year. Figure 25 (Precipitations) and Figure 26 (water flows) demonstrate the hydrological situation that year. Minimum water flow was low (at least lower than 1987 normal year), and moreover the accumulated precipitations where also very low. The model (Eq. 1) estimates the value of agricultural production in the years studied and in each of the ADUs. The agricultural drought suffered that year had consequences for the agricultural sector that are analyzed below along with some of the most relevant results are presented.

Figure 28 represents the model's prediction for the ADU *'Alto Elqui'*, in the Coquimbo Region (north part of Chile). Output value for the years 1987, 1997 and 2007, in constant pesos of 2007, are depicted by the dark gray line. The light gray line represents the fitted values of the model. The accuracy of the prediction appears to be high, and thus the predicted agricultural output value approaches the actual values. This ADU is representative for the two meteorological events identified in this research. La Niña produced a decrease in the agricultural value of irrigated productions by causing a disruption of the previous followed trend of the sector. The growth of the sector in the analyzed period is clearly shown between 1987 and 1997, but, the agricultural drought associated to the decrease in precipitations and water flows had an associated economic cost. El Niño event is also appreciable in 1997 with high agricultural output due to high rainfall availability and the spike in agricultural prices.

Figure 28. Predicted and Actual Output Value in ADU Alto Elqui (Millions of constant CLP of 2007)



Source: Own elaboration

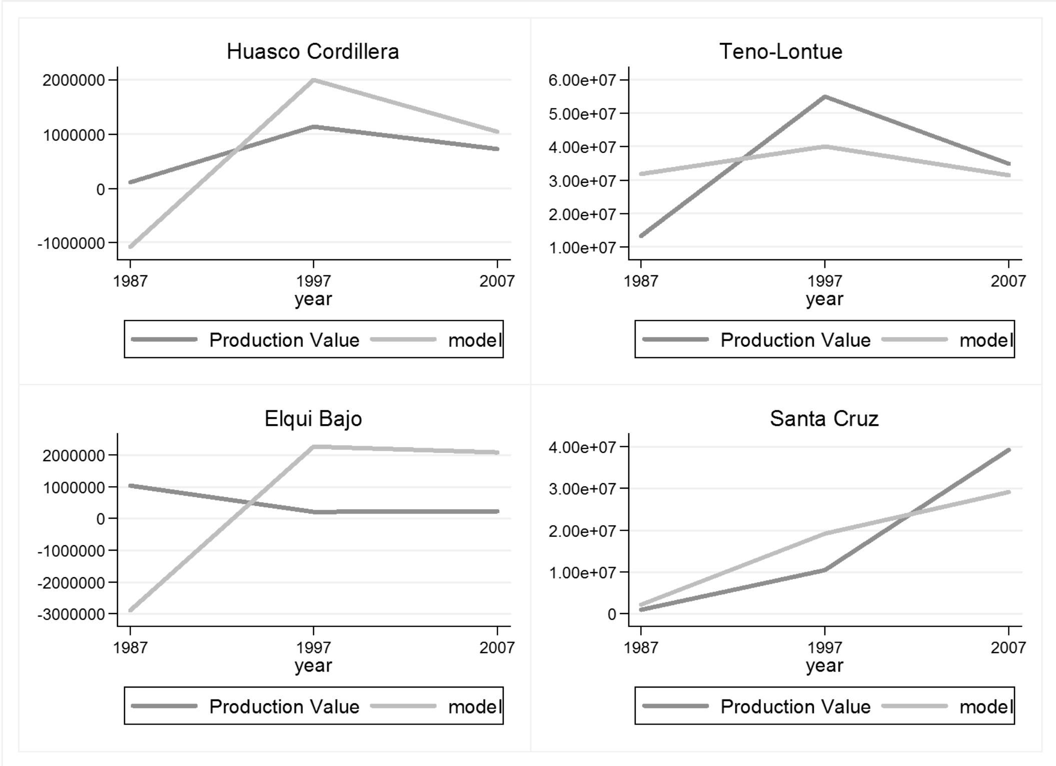
Elqui River basin is located at the north of the arable land of the country, where water scarcity is a common problem for farmers in the area. Water markets are here more developed than in the south, as shown by Donoso (2006) and Alevy et al. (2012) , but event then there are drought impacts. Young et al. (2010) evaluates the vulnerability of an irrigated-dependent community of the Elqui river basin and highlights that the community remains vulnerable especially to changing conditions of water availability and accessibility among the physical, economic and political context of the area. Therefore, water markets are able to mitigate part of drought impacts, but there is a need for managing other factors that are making the area vulnerable.

Figure 29 presents actual and predicted agricultural output value for 4 ADUs in which the model's accuracy is not as high as in the previous case. But, all of them draw the upward trend followed by the irrigation productions. In the case of *'Huasco Cordillera'* (Coquimbo Region), the model tends to over predict; for 1987 it under predicts, over predicting for 1997 and 2007. This reduced goodness of fit indicates that for this ADU other explanatory factors not included in the model are important. The opposite occurs in the ADU *'Teno-Lontué'* where the model under predicts the value of production obtained in 1997 and 2007, over predicting only in 1987. Therefore, the rise in the actual agricultural output value is not only due to factors such as water supply and prices. But, both ADUs show a decrease of agricultural production during the 2007 drought that may indicate the damage suffered.

The lower part of Figure 29 presents two units with no rise in prices during 1997 El Niño event, but with different effects in 2007 as a result of the agricultural drought. *'Elqui Bajo'* presents a very low goodness of fit; in this case, the model predicts negative agricultural values when facing a water scarcity year, but the actual outputs depict no growth between 1997 and 2007. This may be explained by the negative impact produced by the lack of water, which equals ten year separated values. Moreover the prices of some of the main products in this area suffer a small slowdown in their growth trend (like lettuce, celery, and table grapes). Again the vulnerability of Elqui river basin is proven in these results.

In the case of the *'Santa Cruz'* ADU, the actual value of agricultural production increases for all years. The model also presents the same behavior. However the predicted agricultural value grows at a faster rate than the actual agricultural value, with a reversion in the last year. This ADU is located at one of the most productive area of the country, where high value crops have been implanted along the last decades. This is a clear example of the experimented growth of the sector.

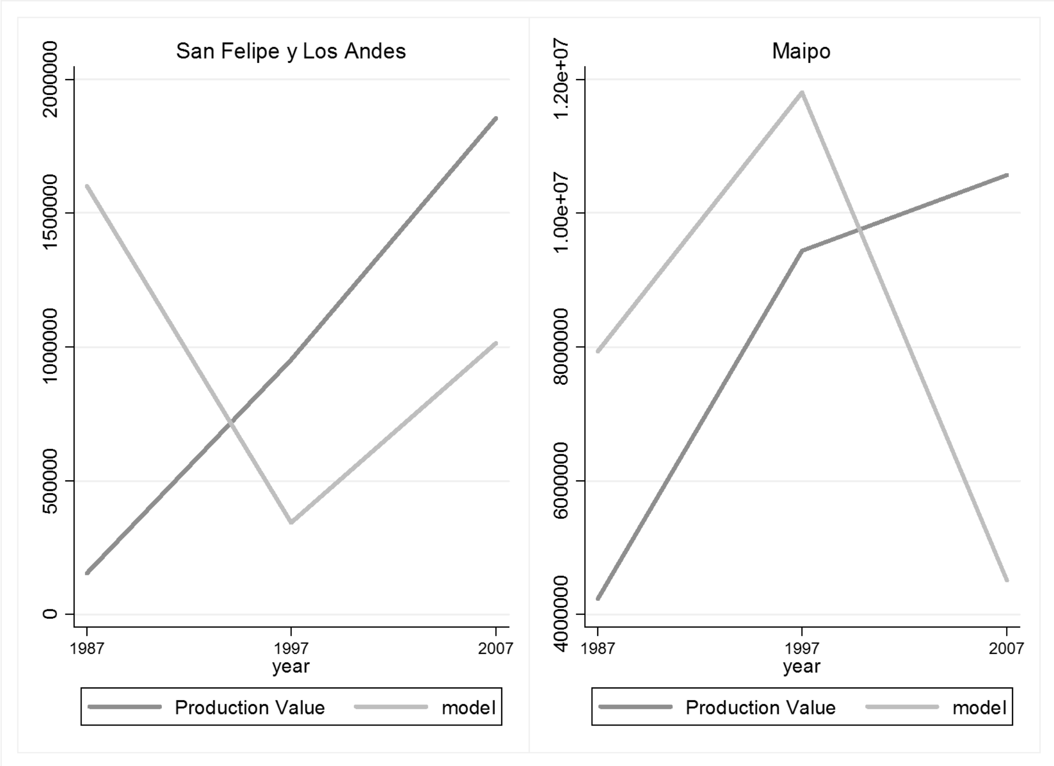
Figure 29. Predicted and Actual Output Value (Million of constant CLP of 2007)



Source: Own elaboration

Supporting this idea, Figure 30 presents the case of two ADUs of the Central Valley of Chile, the most important production area for fruit and horticultural exports. In both ADUs actual agricultural value steadily increases between 1987 and 2007. This can be explained not by the increase in the irrigation surface in these ADUs but with the changes in the land occupation. Some of the most profitable crops, during the study period, grew so as to cover most of the irrigated surface. This is the case of the red vineyards whose irrigation surface increased by almost 2000% and 200% in ADU *'San Felipe y Los Andes'* and *'Maipo'*, respectively. This significant increase in the irrigated surface in both ADUs occurred with little or no drought planning, thus increasing the ADU's agricultural drought vulnerability. In the case of the Maipo ADU, the growth rate of the red vineyard irrigated value falls 80% after the ENSO Cycle of 1997; however, the growth rate between 1997 and 2007 still lacks agricultural drought planning.

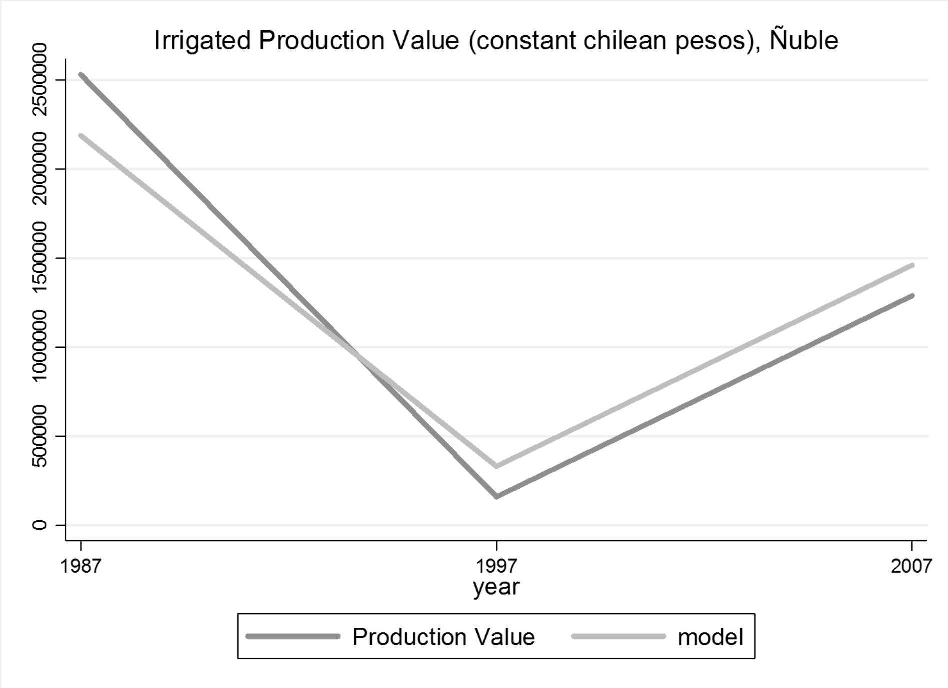
Figure 30. Predicted and Actual Output Value for two ADUs of the Central Valley Production Area (Million of constant CLP of 2007)



Source: Own elaboration

Finally, the ADU ́Ñuble' located in the south part of Chile, where actual and predicted output value decreases during 1997, is represented in Figure 31. As in other countries the vulnerability of the areas with endowed water resources turns to be high. This situation is probably caused by the dependence of the irrigation management unit to Ñuble River flows. Slight decreases in water flows or precipitations are unexpected and may cause negative impacts on productions, resulting in less scope for exploitation.

Figure 31. Predicted and Actual Output Value in ADU Ñuble (Million of constant CLP of 2007)



Source: Own elaboration

Most of the ADUs where the prices increase when the ENSO Cycle hits are located in the north part of the analyzed area in Chile, where water scarcity is more common. While the ADUs in the south are less affected by price rises but highly tied to water resources. La Niña drought produced negative impacts in economic terms all over the country. ADUs with more developed water markets are less affected by supply shocks but they remain vulnerable to drought conditions. These differences may indicate different vulnerability profiles related to the location and the weather characteristics of each zone. Northern ADUs are more sensible to price variability while southern ADUs are more vulnerable to water availability parameters. Management strategies would combine both parameters at a national level, but would have to put more emphasis in reducing price vulnerability in the north and water scarcity vulnerability in the south.

In order to correctly determine the economic impact of agricultural droughts one must simulate the specific situation of each ADU. This general model predicts accurately only for some ADUs; in these cases, differences in agricultural value are explained well by changes in hydrological, climatic, and economic variables. In other ADUs, however, these explanatory variables are not sufficient to accurately assess agricultural drought impacts.

6.5 Final remarks

Drought is a natural hazard characteristic of Mediterranean climate agriculture and, in the case of Pacific Basin Countries, highly correlated with ENSO Cycle signals. Agricultural droughts are the main type of drought affecting Chilean agriculture due to its lack of dams. The severity of these droughts is caused by a combination of both climate hazard (the occurrence of deficits in rainfall, snowfall, and water flows) and agricultural drought vulnerability (the productive, economic, and social characteristics that render farmers susceptible to water deficits). Additionally, the impact of drought varies regionally and over time.

This section provides a model to assess the economic impact of agricultural droughts on irrigated agriculture in different agro-climatic areas of Chile. The model estimates the changes in the value of irrigated agricultural production at the sub-basin level as a function of the minimum water flow, the accumulated precipitation, agricultural water demand for irrigated crops in each agricultural demand unit, and a price index of the major crops of each area. The estimated model presents a good overall goodness of fit and, thus, represents a basis for predicting agricultural performance when faced with a drought. Moreover, the model allows for the identification of the most vulnerable agricultural areas of the country.

The distinguishing feature of this approach is that a general and simple model is proposed to be used as an instrument to identify key variations of inputs that result in drought economic outputs. However the accuracy of the model's prediction varies geographically and, hence, there are other explanatory factors that the model does not consider which explain agricultural output value. And it is here more difficult to measure the accurate economic impact of droughts, as strong growth masked structural changes behind the losses that may be suffered. But, the strong growth of the sector allows also distinguishing between the followed trend and the decreases produced on drought years. Further research is required to determine a more flexible formulation of the agricultural output value function that allows for the identification of geographically specific factors which allow for a higher goodness of fit for all ADUs.

The geographic level chosen for the analysis is adequate to assess the economic impact of agricultural droughts because drought mitigation mechanisms are set at that level in Chile. First of all, the sub-basin is more accurate and consistent with water management in the system of tradable water use rights in Chile. Secondly, the availability of data at the sub-basin level allows researchers to develop a more precise analysis of different explanatory factors such as changes in crop surfaces, water supply and demand, and prices.

The results show that Chilean agriculture is vulnerable to agricultural droughts and price variations associated to ENSO Cycle signals. The economic impact of agricultural droughts depends on the geographic extension of this natural hazard. While a local community might experience significant losses due to a localized agricultural drought, at a regional or national scale there are farmers who benefit from increased commodity prices associated to ENSO Cycle signals. Attention must be paid to agricultural markets so as to insure flexible and efficient crop markets that compensate the negative effect on irrigators' total revenue of agricultural droughts. In the context of water use rights markets, emphasis must be placed on ensuring an efficient temporal water use rights market. In ADUs where water transfers is flexible, such as the Limarí basin (in the northern part of the country), agriculture is less vulnerable to water scarcity since water allocations can rapidly adjust to agricultural drought conditions. Different vulnerability profiles have been identified in relation to the location of the ADUs. While northern basins are more vulnerable to price variability, the southern ones are more prone to suffer water scarcity negative effects.

Drought economic negative effects have been seen as a decrease below the trend followed in the previous 20 years of the agricultural sector. The losses appear to be significant and therefore more prevention mechanisms are needed to avoid inefficient compensations to farmers once the damage is already suffered. Vulnerability of some areas shows how an integrated management of water resources along with other important factors may be an efficient way to avoid negative impacts.

Drought conditions are recurrent in many parts of Chile, in particular in the central and northern regions, and represent a natural hazard that is increasingly becoming more probable. It should not be viewed as merely a physical phenomenon, but rather the result of the interaction between a natural event and the demand placed on water supply by agricultural systems. The greater the water demand, all else equal, the more vulnerable agriculture is to droughts. And thus droughts must be managed along with water scarcity prevention plans.

Therefore more attention should be paid to demand management to improve water efficiency to meet the rapidly growing water demand in a cost-effective manner. The process of dealing with drought in a crisis management mode could be facilitated with knowledge on economic impacts, identification of the most vulnerable areas, and technology transfer that improves the preparedness and impact mitigation of agriculture. An additional challenge is to convince policy and other decision makers that investments in mitigation are more cost effective than post-impact assistance or relief programs. For this, good estimates of the economic impact caused by agricultural droughts are necessary as well as the identification of the determinants of agricultural vulnerability.

Part III:
Conclusions

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Main general findings

The importance of drought as a natural hazard has been highlighted in this study. Its intrinsic characteristics, slow onset and implied uncertainties, make their impacts difficult to measure, manage and mitigate. Yet, there is an urgent need to improve prevention and adaptive capacity to cope with drought impacts, because there will likely be more severe and extreme as a result of climate change. Drought is also a common phenomenon of Mediterranean climates and their impacts can be exacerbated if the affected area is also under water stress conditions, though these and droughts are essentially different situations. The impact of droughts and the implications of water scarcity multiply each other, augmenting the economic impacts on agriculture and the associated economic risks. In order to manage drought in water scarce countries a more precise knowledge of the impacts is required, delving into its extent, propagation and distribution among sectors.

This thesis represents an attempt to conduct a thorough study of the socio-economic impacts of drought on the agricultural sector and has included a complete view of their implications and risks in the agricultural sector. Comprehensive analyses present an unbiased view to inform policy makers and key stakeholders. Therefore this study contributes with information and relevant insights on droughts' socio-economic impacts and consequences. The conceptual framework has included the identification and distinction of direct, indirect, tangible and intangible impacts without which the understanding of drought consequences is incomplete. The scope of droughts and the identification and measurement of the impacts are analyzed also by theoretical and empirical models, provided by both a literature review and contributions of our own, affording a more accurate and realistic view of droughts.

By reviewing the methods, knowledge gaps have been identified. These gaps can be classified into two groups: (i) gaps on the impacts assessment, especially when the impacts are unrelated to the agricultural sector, and (ii) gaps in the attribution of impacts, the causality factor that is generally forgotten, if not assumed without adequate scrutiny. These two specifically identified problems may lead to unrealistic scenarios and to static formulation of models, the results of which would also lead to wrong inferences about drought impacts.

The specific findings of the thesis can be grouped in three main blocks that are explained below.

7.1.1 Conclusions related to the impact attribution models

Econometric models have been formulated to identify the economic, hydrological and climatic factors particularly affecting the agricultural sector under water deficit situations. Although the explanatory power of these models varied, there are many special cases where the models' fit is good enough to explain economic variations of the agricultural sector. Regarding irrigation, the vulnerability of the systems that rely more on surface water resources has been proved and the impacts directly related to water shortages on these areas are clearly identifiable. The models revealed the percentage of the production variation that can be attributable to droughts or to irrigation water shortages.

The main water-related explanatory variables selected for each application presented on the thesis illustrate different types of droughts. The Spanish drought indices and the reservoir levels are representative for hydrological droughts and the accumulated precipitation and the crops' water demand for the agricultural droughts. The majority of these variables are easy to obtain and analyze. Furthermore, the different levels of influence tested in this thesis present a multi-level scheme of drought management and impacts. This includes the evaluation of direct and indirect impacts at a river basin, province or irrigation district levels in Spain, or at the sub-basin level in Chile.

However, irrigation systems relying on groundwater sources reveal their developed resilience to drought economic impacts. Both irrigation districts and provinces primarily under these regimes were less affected by supply shocks. Attention must be paid, though, on avoiding groundwater depletion, as its dynamics is slower than the variations of surface water resources. By contrast, data on groundwater levels is not easily available, and many of the wells are not adequately monitored.

In addition to impacts attribution models based on their explanatory variables, the introduction of a risk perspective for the water explanatory variables is the natural extension for developing drought risk models. The study thus presents an integration of the econometric models into risk management models. These include water availability and water demand risks under uncertainty situations, and allow for performing ex – ante simulations of the direct economic impacts of drought to evaluate the risk posed by farmers and to obtain probability distribution functions of the interested variables. This risk at the provincial level appears more severe on those provinces where irrigation is mainly dependent on dams' water reservoirs like León or Huesca. But at the irrigation district level, where specific dams serving the area are identified the risk is idiosyncratic.

In the Chilean case the econometric model allows to identify key variations of water flows or precipitations in the irrigation agriculture that result in drought economic outputs. However the accuracy of the model's prediction varies geographically and, hence, there are other explanatory factors that the model does not consider which explain agricultural output value. Economic impact of droughts are identified in this case, but its measurement is more difficult because the model includes only a few years within a long period, and probably the strong growth of the country is concealing structural changes behind the losses that may be suffered by drought.

7.1.2 Conclusions supported by the quantitative results

Irrigated agriculture is constantly exposed to droughts, and the economic impacts suffered by it have been explained on this study from the provincial level to the irrigation district or the Agricultural Demand Unit levels. The measurement of the impacts provides a range of values where past drought events have had their impacts and therefore provides information in order to take either preventive or reactive measures to cover drought losses. The last drought suffered in Spain between 2005 and 2008 had left 186.19 million euros of loses just in the irrigation sector of the Ebro river basin and 100.15 million euros in rainfed agriculture. Losses accounted at the provincial level represented between the 22% and the 76% of the total yearly losses for the irrigation sector, and between the 12% and the 80% for the rainfed systems. While in absolute terms, these numbers do not attest for dramatic impacts, in relative terms they are very significant, and they are concentrate on a small number of agricultural landholdings.

However, economic losses directly associated with water shortages in the Chilean context were more difficult to measure. The liberalized agriculture markets and the El Niño-Southern Oscillation (ENSO) had significant effects on product prices. There is evidence that ENSO has important and statistically significant effects on agricultural prices in the sub-basins analyzed in Chile. It has been shown how agricultural prices of some of the country's most important crops were disproportionately high during the drought period associated with the ENSO in 1997. Avocado was 100% higher, and grapes, wine, or red apples were around 40% higher, in comparison to the available data for the study. While a local community might experience significant losses due to a localized agricultural drought, at a regional or national scale there are farmers who benefit from increased commodity prices, due to agricultural supply reductions produced by extended agricultural droughts, which are associated to ENSO Cycle signals.

Direct impacts are transmitted in the economy. The analysis of the transmission of supply shocks between primary production and the related users of those productions provides relevant insights to assess vulnerability of each sector in different geographical contexts. In general, a 1% reduction of available water for irrigation has an impact on production values from a minimum of 0.01% in Lleida to a maximum of 0.20% in Zaragoza. The last one is transmitted to an impact of 227.3 million euros of Aragon Agri-food GVA. But, it has to be considered that the actual reductions of water availability occurred during 2005-2008 drought amounted to a maximum of 97% (the reduction is calculated in relation to the normalcy boundary of 0.5 of drought index). This was the case of Huesca in 2005 which accounts for a clear example of how these impacts on water availability for irrigation are transmitted to Agri-food Gross Value Added. Variations of 97% in water availability (in relation to the 0.5 drought index average) produced a 9.83% impact on irrigation production, which was translated into a 3.99% impact on Gross Value Added, which is 107.8 million euros. The transmission between rainfed productions and GVA seems less important because the economic value of this kind of productions represents a smaller percentage of total GVA. However, these impact transmission measurements indicate that the food processing industry is only slightly affected by shocks in the supply sector.

From the vulnerability perspective, differences of drought risk profiles have been identified. Water reservoir levels vary significantly within the year but there is more variation in the short term (as we approach the start of the irrigation) and with a much smaller average. Among the main river basins in Spain, Duero and Ebro have the greatest average increases of reservoir levels between the beginning of the hydrological year and the beginning of the irrigation season (both equivalent to about 24% of storage capacity), whereas the Mediterranean basins Júcar and Segura have the smallest (10.25% and 11.11%, respectively). Both the average and variance of winter storage increases are essential to define and analyze hydrological drought vulnerability, because they describe the risk borne by different stakeholders. It illustrates the risk exposure of irrigators at different times before land allocation decisions are made among competing crops. And also, the River Basin Authorities are affected by this risk exposure as long as they may take management decisions proactively within this frame.

Some other illustrative insights can be drawn from the province of Cordoba case study. The integration between the risk model and the economic output for the irrigated agriculture show that updating the projections from October to February results in a reduction of both probability tails and a negligible effect on the expected value, improving the accuracy of the projection of irrigated production value. While the statistical model predicted an economic output of 283 million euros for Cordoba in 2005, the realized result was 278 million euros. For the irrigation community analyzed in Córdoba (Genil-Cabra) in 2007 (a dry year for this area), the probability distribution function of the economic output shifts leftwards month after month, covering an "economic distance" (until the beginning of the irrigation season) of almost 60 million euros. In February of 2007, the stochastic variation in the economic output for the district is no longer dependent on the water availability but on other sources of variation, like output prices or variability in yields. This way the models afforded a timely and accurate projection of the economic impacts, with a possibility of revising and updating them as the season approaches on monthly, or even weekly, basis.

Along with the attribution of the impacts, the monthly updating on the risk analysis are perhaps the most innovative elements of the thesis. It is also important to highlight that the models developed here to address the drought problem can be transferable to other agricultural regions. Both the impact and the risk perspective can be applicable in other river basins to assist management strategies and for the identification of drought economic effects and the isolation of them from other sources of variation. Furthermore, the risk models allow for anticipating the economic impacts, which has been one of the major gaps when assessing droughts.

The natural extensions of this work are the development of actual risk management instruments, including insurance, derivatives or option contracts. These types of instruments would permit transferring part of the risks to the financial, insurance or reinsurance markets. Additionally, the integration of simple econometric models into drought indicator systems would be also a challenge to achieve better alert plans.

7.1.3 Conclusions related to the empirical contexts: Spain and Chile. Differences in management and policy strategies

Water and drought management in the different case studies have also been the focus of the thesis. Policy differences and management distinctions on water scarcity and drought between Spain and Chile make the analysis of the impacts very different. From a global perspective, in Mediterranean-climate and developed countries the prevention of drought impacts would be more effective where the institutional framework surrounding this issue is designed to permit this kind proactive management. In Spain, where drought management strategies are robust and fairly well developed, drought impacts are prevented or mitigated through different strategies. Chile mitigates their impacts through ex-post compensatory payments that are generally difficult to calculate and somehow inefficient. These strategies do not help in improving adaptation or prevention strategies, and moreover if the attribution of caused damaged is not correctly calculated the payment objective is neither fair nor efficient.

The identification of the parameters defining drought risk is essential for the geographical analysis. Different types of drought under different scenarios generate diverse impacts. Types of drought are identified through the climatic characteristics and the production systems of each geographical area. For example, hydrological droughts are the main type of drought to be analyzed in Spain, while agricultural droughts and El Niño and La Niña effects are the main objective of analysis in Chile. All of them share the characteristic of recurrence with no exact return period, which increases the need of prevention. This is linked to the identification of the factors that influence more the final economic impacts of drought events. Price of products has proven to be very important in Spanish provinces like Huesca, Lleida, Navarra, Zaragoza, or the areas of Chile with high aggregated value. This is another crucial finding of the thesis: as the price of the products is affected by the supply shocks, farmers growing horticultural and fruit crops both in Chile and in Spain obtain a natural hedge resulting from reduced supplies and higher prices. The omission of price effects in evaluating drought shocks in the farm sector leads to overestimations of drought impacts. Unfortunately, Input-Output or Computable General Equilibrium models, while sufficiently disaggregate to learn about sectoral impacts of drought, are not capable of modeling the micro impacts of agricultural sectors in which dozens of perishable and seasonal products are produced.

Current drought policies in Spain are fairly efficient. In particular, the step taken with the Drought Management Plans (2007) changed the supply oriented policies to the demand management side. DMPs, based on very detailed analysis of the hydrological systems referred to the smallest possible management unit, provide a set of thresholds (normal, pre-alert, alert and emergency) with pre-arranged and predefined actions. They are truly contingent planning. Although the droughts analyzed here had occurred before the implementation of the Plans, there was a deep knowledge of managing droughts that permitted avoiding much of the impacts.

By contrast, in Chile significant steps applying demand management principles are required to reduce drought impacts and to achieve better management strategies. Some of the findings of this study will help in assessing economic, social and environmental vulnerability to drought and water scarcity as well as to evaluate the risk profiles produced by the differences in vulnerability between the different regions analyzed.

7.2 Policy recommendations

Several policy implications can be outlined from the thesis conclusions. The recommendations are grouped in reference to the thesis' parts. First some recommendations that can be drawn from the impacts review, and then some from the models applied. Most of the recommendations in the first group are related to general frameworks for drought policy design, and the second group contains more specific suggestions for innovative tools or relevant management elements.

7.2.1 Recommendations drawn from the general introduction and impacts review (Part I)

- *Information for policy makers*

As it has been repeated all over the thesis there is a need for more information in order to assist policy makers. Policy design must rely on accurate information and impacts assessments. The development of more drought related studies would help in understanding and preventing the impacts produced by such a natural hazard. Among the important information needed for policy performance, there has been identified a gap in the consideration of all types of impacts. Indirect and intangible impacts are also commonly forgotten. This kind of information can be used for instance in the development of more accurate preventive drought alert thresholds, to correctly define compensatory payments or preventive drought measures for indirectly affected sectors.

- *Accurate evaluation of impacts*

Drought impacts can be measured through a variety of methodologies, but more accurate methods are needed in order to better estimate the real losses produced by the lack of water. Simple econometric models can be used to measure the relation between the decrease in the main water variables and the decrease of agricultural economic outputs. These models can be referred to exactly the same administrative boundaries than the water management systems. However, in the thesis it is shown that even the provincial level provides almost the same explanatory power than models fitted for the agricultural demand units. These models could be integrated into water decision bodies in order to prevent excessive economic impacts. Demand management agents and officers in river basins should have models to anticipate the impacts of drought and inform drought committees with actual and updated projection of losses, including direct, indirect and intangible impacts.

- *Water scarcity and drought*

The difference between water scarcity and drought has been emphasized in this thesis. Both phenomena have important consequences on the economic performance of regions or even countries. More target oriented policy guidance is needed to manage droughts under already water stressed regions. Alternatively, better practices are needed to soften critical situations of water scarcity, and therefore to reduce the vulnerability to drought of these regions. Management implications on this issue are large, and they represent a challenge for future drought policies.

7.2.2 Policy recommendations learned from the impact attribution models (Part II)

- *Monitoring and alert systems*

The proposed methodological approach has provided a draft tool for assessing economic impacts of drought in terms of risk. The probability of water supply can be easily predicted before the start of the irrigation season, because the data of reservoir levels is available at a weekly basis and historical data provide probability distribution functions of runoff and inflows. This variability is integrated into the economic models to provide a range of values that may inform both water users and the decision making bodies. Therefore risk management tools are suggested, and not too difficult to be implemented and interpreted. We thus recommend that the set of already developed drought indices be employed in simple regression models of agricultural production to obtain ex-ante projections of drought impacts, and use the arsenal of hydrological variables, and distribution functions to monitor the economic impacts as well, building on the thesis' modeling approach.

- *Different sectors' vulnerability*

The thesis results show differences in vulnerability between irrigation and rainfed systems, and also between agricultural production and Agri-food Industry. Possible policy alternatives may be focused on reducing this vulnerability to mitigate drought impacts and to achieve better levels of adaptive capacity to face droughts. Lessons learned from each case study show for example how the vulnerability of irrigation systems is reduced as they diversify their water sources. Systems relaying on surface and groundwater sources are less affected by supply reservoir shocks. More emphasis should be placed on indirect effects mitigation.

- *Drought indices*

Drought indices have been used for the analysis in one of the applications of the thesis, and they have revealed some inaccuracy. While they are designed to draw the main water supply sources for each area, they are finally simplified only to surface sources which entail quite a distance from reality. Models fitted with drought indices reveal no high relation between alert or pre-alert stages and drought impacts.

7.3 Limitations and opportunities for further research

The problems found during the development of the research can be summarized as follows, together with some suggestions to solve them. We also mention some associated opportunities to continue the research around drought impacts with especial attention on improving the assessments.

- *Data availability*

To design and perform the econometric models a considerable amount of data is necessary. In the case of Spain, most of the provincial data was easily accessible, except for the groundwater levels that were obtained directly from personal communications with the Ministry of Environment. The provincial data on crops surfaces and prices is consistent through years, however when the level of analysis becomes smaller the data becomes scattered and slightly inconsistent. For instance, the Demand Management Units do not overlap with administrative units (*comarcas*, provinces, or municipalities). In the case of Chile, the availability of data is less developed in comparison to Spain. Data on surfaces is only collected in a systematic way through the Agrarian Census (performed once every 10 years) and the prices are available at very different units of measurement depending on the reported product. A huge effort was made in data processing in both case studies (countries). As a recommendation, data collecting can be improved by the competent authority.

- *Accuracy of drought indices*

Spanish current drought indices are designed to represent the water availability scheme for the irrigation surface of each management areas. However, they are mainly simplified to the regulated reservoir levels. It is understood that the compilation of information about all water sources is not an easy task, but we also believe that more emphasis can be put in improving this compilation. The analysis performed on this thesis has revealed the non significance of many of these indices when explaining economic output of irrigation, and thus we recommend the improvement them in order to generate better threshold schemes. It is proposed to come with a more realistic representation of the phenomena including all (or at least more than one) sources of water used on each management area. Demand side measurements and diversification of sources are relevant issues to be incorporated to the indices.

- *Problems found with poor models' fitting*

Some weaknesses must be admitted with the statistical fit in some of the models. Chapter 4 includes a shorter time period for the regressions than Chapter 5, and the significance of the main explanatory variables results better in the first one. This obstacle could be solved by the inclusion of more data (extended availability of time series) or by the inclusion of more precise explanatory variables. An attempt of improving the performance was made introducing the drought indices as explanatory variables instead of the reservoir levels of the basin, and the results were not as good as expected. The models can be reformulated with different data sets and perhaps use more sophisticated statistical techniques.

- *Analysis of all types of impacts*

To analyze all types of impacts an important amount of time and effort than was available should have been invested. The time limitation is specially marked when it refers to the measurement of social and intangible impacts that are evaluated through indirect mechanisms. To conduct a comprehensive study of the impacts either a multidisciplinary research or an integration of projects is needed. While the importance of considering all impacts has been highlighted along the thesis, a balance must be found between accurate measurements and complete estimation of losses. Even if the measurement of indirect or intangible losses is not as accurate enough, they must be at least considered. Further research may try to include second order effects as well as intangible losses for the design of any policy.

- *Models' sophistication*

The models proposed here can be seen as the basis for more sophisticated analysis of impacts and risks. This complexity is required for a better interpretation of the economic variables fluctuations, and can be achieved through the introduction of relevant explanatory variables if appropriate or through the improvement of the probability distribution functions measuring risks.

References

AEMET (Agencia Estatal de Meteorología), 2009. Provincial rainfall data series.

Adams P.D., Horridge M., Madden J. and Wittwer G., 2002. Drought, regions and the Australian economy between 2001-02 and 2004-05. Centre of Policy Studies/IMPACT Centre Working Papers.

Alcalá Agulló F. and Sancho Portero I., 2002. Agua y producción agrícola: un análisis econométrico del caso de Murcia. Revista española de estudios agrosociales y pesqueros, 197:129-159.

Alcon F., Pedrero F., Martin-Ortega J., Arcas N., Alarcon J. and de Miguel M., 2010. The non-market value of reclaimed wastewater for use in agriculture: a contingent valuation approach. Spanish Journal of Agricultural Research, 8:187-196.

Aldaya M.M., Garrido A., Llamas M.R., Varelo-Ortega C., Novo P. and Casado R.R., 2010. Water footprint and virtual water trade in Spain. In: A. Garrido and M.R. Llamas (eds.), Water policy in Spain, CRC Press, Leiden, The Netherlands, pp: 49-59.

Alevy J.E., Cristi O. and Melo O., 2012. Right-to-Choose Auctions: A Field Study of Water Markets in the Limari Valley of Chile. Agricultural and Resource Economics Review, 39(2):213-226.

Allen K., 2003. Vulnerability reduction and the community-based approach, in Pelling (ed.). Natural Disaster and Development in a Globalizing World, pp:170-184.

AMS Council, 1997. American Meteorological Society Policy statement: Meteorological drought. Bull.Amer.Meteor.Soc, 78:847-849.

AQUASTAT F., 2009. FAOSTAT Database on Water and Agriculture FAO, Rome.

Askew L.E. and Sherval M., 2012. Short-Term Emergency or Recurring Climatic Extreme: A Rural Town Perspective on Drought Policy and Programs. Australian Journal of Public Administration, 71:290-302.

Báez K., 2010. El Potencial del Seguro Indexado en Chile: Una Aplicación a la Gestión del Riesgo de Sequía en Pastos. Thesis.

Bahamondes M., 2003. Poverty-Environment Patterns in a Growing Economy: Farming Communities in Arid Central Chile, 1991-99. World Development, 31:1947-1957.

Bakker K., 2012. Water Security: Research Challenges and Opportunities. Science, 337:914-915.

Bakker K.J., 2000. Privatizing Water, Producing Scarcity: The Yorkshire Drought of 1995. Economic Geography, 76: 4-27.

Bateman I.J., Day B.H., Georgiou S. and Lake I., 2006. The aggregation of environmental benefit values: Welfare measures, distance decay and total WTP. Ecological Economics, 60:450-460.

Bauer C.J., 1998. Slippery propperty rights: Multiple water uses and the neoliberal model in Chile, 1981-1995. Natural Resources Journal, 38(1): 109155.

Bauer C.J., 2005. In the image of the market: the Chilean model of water resources management. International Journal of Water, 3:146-165.

Bergh J.v.d. and Nijkamp P., 1998. Economic Aspects of Global Change Impacts and Response Strategies in the Coastal Zone of the Netherlands. Journal of Coastal Conservation, 4:161-168.

Berrittella M., Hoekstra A.Y., Rehdanz K., Roson R. and Tol R.S.J., 2007. The economic impact of restricted water supply: A computable general equilibrium analysis. Water research, 41:1799-1813.

Blamey R., Gordon J. and Chapman R., 1999. Choice modelling: assessing the environmental values of water supply options. Australian Journal of Agricultural and Resource Economics, 43:337-357.

Blanco I., 2010. Economic-hydrologic analysis of water management strategies for balancing water forn nature and water for food: Implications for the Guadiana River Basin, in Spain. Thesis.

Boatable F., 1993. The value of clean water: the public's willingness to pay for boatable, fishable, and swimmable quality water. Water Resources Research, 29:2445-2454.

Booker J.F., Michelsen A.M. and Ward F.A., 2005. Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin. Water resources research., 41:p. W02026 (15p.).

Boterril L.C. and Wilhite D.A. (eds.), 2005. From disaster response to risk management: Australia´s national drought policy. Dordrecht : Springer, pp:209.

Brunner A.D., 2002. El Nino and world primary commodity prices: warm water or hot air? Review of Economics and statistics, 84:176-183.

Calatrava J. and Garrido A., 2005. Modelling water markets under uncertain water supply. European Review of Agricultural Economics, 32:119-142.

Calzadilla A., Rehdanz K. and Tol R.S.J., 2010. The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. Journal of Hydrology, 384:292-305.

Camacho E., 2012. La modernización de los regadíos: Ahorro de agua versus incremento consumo de energía.Oral presentation in Jornada Técnica sobre Coste Energético y Producción de Energía en Comunidades de Regantes, Madrid 2012.

Carroll N., Frijters P. and Shields M.A., 2009. Quantifying the Costs of Drought: New Evidence from Life Satisfaction Data. Journal of Population Economics, 22: 445-461.

Cavallo E. and Noy I., 2009. The economics of natural disasters: a survey. Inter-American Development Bank Working Paper, 124.

CCSP, 2008. Weather and Climate Extremes in a Changing Climate Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. Synthesis and Assessment, 33.

CEDEX, 2011. Evaluación del impacto del cambio climático en los recursos hídricos en régimen natural, Madrid, Spain.

CHE (Confederación Hidrográfica del Ebro), 2011. Borrador del Plan Hidrológico del Ebro.

Chóliz J.S., Bielsa J. and Cazcarro I., 2009. La agricultura y el agua en el sistema productivo. Análisis de su importancia en la economía aragonesa a través de una Matriz de Contabilidad Social. In: Gómez-Limón et al. (eds.), la Economía del agua de riego en España: una perspectiva regional, Fundación Cajamar, El Ejido (Almería), pp: 163-178.

CIREN, 2010. Evapotranspiration and temperature data series. Available at: http://www.ciren.cl/web/ [Last accessed: 2010]

Ciriacy-Wantrup S.V., 1947. Capital returns from soil-conservation practices. Journal of farm economics 29:1181-1196.

CONHAZ, 2012. Costs of Natural Hazards. Assessing the costs to droughts. Science Policy Brief.

Craik W. and Cleaver J., 2011. Modern Agriculture Under Stress - Lessons from the Murray-Darling. In: A. Garrido y H. Ingram (eds.), Water for Food in a Changing World. Routledge, Londres, pp:207.

Cunderlik J.M. and Simonovic S.P., 2007. Inverse flood risk modelling under changing climatic conditions. Hydrological Processes, 21:563-577.

Dankers R., Feyen L., Christensen O.B. and Roo A., 2006. An integrated modeling framework to assess future changes in flood and drought risk on a pan-European scale. Geophisical Research Abstracts, 8.

De Stefano L. and Llamas M.R., (eds.) 2012. Water, Agriculture and the Environment in Spain: Can We Square the Circle? CRC Press, Leider, The Nederlands.

Decaluwe B., Patry A. and Savard L., 1999. When water is no longer heaven sent: Comparative pricing analysis in a AGE model. Cahiers de travail 99, 5.

Del Saz-Salazar S., Hernández-Sancho F. and Sala-Garrido R., 2009. The social benefits of restoring water quality in the context of the Water Framework Directive: A comparison of willingness to pay and willingness to accept. Science of the Total Environment, 407:4574-4583.

DEWFORA, 2012. Improoved Drought Early Warinig and Forecasting to strengthen prepardness and adaptation to dorughts in Africa. Project funded under the Seventh Framework Programme (FP-7) under the theme (ENV 2010.1.3.3-1). EU FP-7 Grant Agreement number: 265454.

DGA, Dirección General de Aguas and PUC, Pontificia Universidad Católica de Chile, 1997. Análisis del Impacto Económico Originado por las Sequías Hidrológicas, pp: 37.

DGA, Dirección General de Aguas, 2010. Water flow data series measured on main river stations. Available at: http://dgasatel.mop.cl/ [Last accessed: 2010]

Ding Y., Hayes M. and Widhalm M.M., 2011. Measuring Economic Impacts of Drought: A Review and Discussion. Disaster Prevention and Management, 20(4):434-446.

Dirección Meteorológica de Chile, 2012. Fenómeno de El Niño. http://www.meteochile.gob.cl/nino_nina/nino_nina_descripcion_nino.html. [Last accessed: 2012].

Dono G. and Mazzapicchio G., 2010. Uncertain water supply in an irrigated Mediterranean area: An analysis of the possible economic impact of climate change on the farm sector. Agricultural Systems, 103:361-370.

Donoso G., 2006. Water markets: case study of Chile's 1981 Water Code. Ciencia e investigación agraria: revista latinoamericana de ciencias de la agricultura, 33:157-171.

Downing T., Patwardhan A., Mukhala E., Stephen L., Winograd M. and Ziervogel G., 2003. Vulnerability assessment for climate adaptation. UNDP Adaptation Policy Framework Technical Paper.

Draper A.J., Jenkins M.W., Kirby K.W., Lund J.R. and Howitt R.E., 2003. Economic-Engineering Optimization for California Water Management. Journal of Water Resources Planning and Management, 129(3):155-164.

Edwards B., Gray M. and Hunter B., 2009. A sunburnt country: the economic and financial impact of drought on rural and regional families in Australia in an era of climate change. Australian Journal of Labour Economics, 12:109-131.

EEA, 2012. Climate change, impacts and vulnerability in Europe 2012. An indicator-based report. , EEA Report 12/2012.

ENSURE, 2009. Relation between systemic and physical vulnerability and relation between systemic, social, economic, institutional and territorial vulnerability. Enhancing resilience of communities and territories facing natural and natech hazards, Del. 2.1.2.

Estrela T. and Vargas E., 2012. Drought Management Plans in the European Union. The Case of Spain. Water Resources Management 26:1-17.

European Commission, 2012a. Report on the Review of the European Water Scarcity and Droughts Policy.

European Commission, 2012b. Water Scarcity and Droughts in the European Union, 2012.

European Commission, 2012c. A Blueprint to Safeguard Europe's Water Resources.

European Commission, 2007a. Communication to the European Parliament and the Council–Addressing the challenge of water scarcity and droughts in the European Union, 2007, COM(2007) 414 final. SEC(2007) 993, SEC(2007) 996. Report from the Commission to the European Parliament and the Council, Brussels.

European Commission, 2007b. Commission staff working document. Accompanying document to the Communication to the European Parliament and the Council–Addressing the challenge of water scarcity and droughts in the European Union, Impact Assessment, COM/2007/04141 final. Report from the Commission to the European Parliament and the Council, Brussels.

FAOSTAT, 2010. Crops' yields data series for Chilean agriculture. Available at: http://faostat.fao.org/site/339/default.aspx [Last accessed: 2010]

Feng S., Li L.X., Duan Z.G. and Zhang J.L., 2007. Assessing the impacts of South-to-North Water Transfer Project with decision support systems. Decision Support Systems, 42:1989-2003.

Fernández B., Donoso G., Luraschi M., Orphanópoulos D. and Salazar C., 1997. Estimación del Impacto Económico Asociado a Sequias Hidrológicas. Sextas Jornadas del Comité Chileno para el Programa Hidrológico Internacional, 25.

Frey, B. S., Luechinger, S., & Stutzer, A., 2010. The Life Satisfaction Approach to Environmental Valuation. Annual Review of Resource Economics, 2(1): 139-160.

García-Vila M., Lorite I., Soriano M. and Fereres E., 2008. Management trends and responses to water scarcity in an irrigation scheme of Southern Spain. Agricultural Water Management, 95:458-468.

Garrido A., Rey D. and Calatrava J., 2012. Water trading in Spain. In: L. De Stefano and M.R. Llamas (eds.), Water, Agriculture and the Environment in Spain: can we square the circle? CRC Press, Madrid, pp: 205-216.

Garrido A. and Gómez-Ramos A., 2008. Risk sharing mechanisms supporting planning and policy. In: Iglesias A., Cancelliere A., Cubillo F., Garrote L., Wilhite D., (eds.), Coping with drought risk in agriculture and water supply systems Springer, USA.

Garrido A., Gil M. and Gómez-Ramos A., 2010. Disentangling the social, macro and microeconomic effects of agricultural droughts: An application to Spanish irrigated agriculture. In: Options Mediterranéenes and CIHEAM (eds.), Economics of Drought and Drought Preparednesss in a Climate Change Context.

Genius M., Hatzaki E., Kouromichelaki E., Kouvakis G., Nikiforaki S. and Tsagarakis K., 2008. Evaluating consumers' willingness to pay for improved potable water quality and quantity. Water Resources Management, 22:1825-1834.

Giansante C., Aguilar M., Babiano R., Garrido A., Gómez-Ramos A., Iglesias E., Lise W. and Moral L., 2002. Institutional Adaptation to changing risk of water scarcity in the Lower Guadalquivir basin. Natural Resources Journal, 42(3):521-563.

Gil M., Garrido A. and Gómez-Ramos A., 2009. Análisis de la productividad de la tierra y del agua en el regadío español. In: Gómez-Limón et al. (eds.), la Economía del agua de riego en España: una perspectiva regional, Fundación Cajamar, El Ejido (Almería), pp: 163-178.

Gil M., Garrido A. and Gomez-Ramos A., 2011. Economic analysis of drought risk: An application for irrigated agriculture in Spain. Agricultural Water Management, 98:823-833.

Gil-Sevilla M., Garrido A. and Gomez-Ramos A., 2010. How to link agricultural productivity, water availability and water demand in a risk context: a model for managing hydrological risks. Spanish Journal of Agricultural Research, 8:207-220.

Gómez C.M., Tirado D. and Rey-Maquieira J., 2004. Water exchange versus water work: Insights from a computable general equilibrium model for the Balearic Islands. Water Resources Research, 40(10):10502-10513.

Goodman D.J., 2000. More reservoirs or transfers? A computable general equilibrium analysis of projected water shortages in the Arkansas River Basin. Journal of Agricultural and Resource Economics, 25(2):698-713.

Haider W. and Rasid H., 2002. Eliciting public preferences for municipal water supply options. Environmental Impact Assessment Review, 22:337-360.

Hao L., Zhang X. and Liu S., 2012. Risk assessment to China's agricultural drought disaster in county unit. Natural Hazards, 61(2):1-17.

Harou J.J., Medellín-Azuara J., Zhu T., Tanaka S.K., Lund J.R., Stine S., Olivares M.A. and Jenkins M.W., 2010. Economic consequences of optimized water management for a prolonged, severe drought in California. Water Resources Research, 46:W05522.

Hartmann T., Di Bella C. and Oricchio P., 2003. Assessment of the possible drought impact on farm production in the SE of the province of Buenos Aires, Argentina. ISPRS journal of photogrammetry and remote sensing, 57:281-288.

Hatton MacDonald D., Morrison M.D. and Barnes M.B., 2010. Willingness to pay and willingness to accept compensation for changes in urban water customer service standards. Water Resources Management, 24:3145-3158.

Hearne R. and Donoso G., 2005. Water institutional reforms in Chile. Water Policy, 7:53–69.

Helldén U. and Eklundh L., 1988. National Drought Impact Monitoring-A NOAA NDVI and precipitation data study of Ethiopia. Lund Univ. Press.

Hensher D., Shore N. and Train K., 2005. Households' willingness to pay for water service attributes. Environmental and Resource Economics, 32:509-531.

Hernández-Mora N, Gil M. and Garrido A., 2013. A Comprehensive Assessment of the Socio-economic Impacts of Droughts: The 2004-08 drought in the Ebro River basin, Spain. In preparation.

Holmgren M., Scheffer M., Ezcurra E., Gutiérrez J.R. and Mohren G.M.J., 2001. El Niño effects on the dynamics of terrestrial ecosystems. Trends in Ecology & Evolution, 16:89-94.

Horridge M., Madden J. and Glyn W., 2003. Using a highly disaggregated multi-regional syngle-country model to analyse the impacts of the 2002-03 drought on Australia. Centre of Policy Studies/ IMPACT Centre Working Papers.

Howitt R.E., Medellín-Azuara J., MacEwan D. and Lund J.R., 2012. Calibrating disaggregate economic models of agricultural production and water management. Environmental Modelling & Software, 38:244-258.

Iglesias Martínez E. and Blanco Fonseca M., 2008. New directions in water resources management: The role of water pricing policies. Water Resources Research, 44:7-27.

Iglesias A., Cancelliere D., Gabiña D., López-Francos A., Moneo M. and Rossi G. (eds.), 2007a. Medroplan drought management guidelines.

Iglesias A., Garrote L., Flores F. and Moneo M., 2007b. Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resources Management, 21:775-788.

Iglesias A., Moneo M., Garrote L. and Flores F., 2007c. Drought and water scarcity: current and future vulnerability and risk. In: Garrido A, Llamas M R. (eds.), Water policy in Spain, resources for the future. Washington DC.

Iglesias E., Garrido A. and Gómez-Ramos A., 2007d. Economic drought management index to evaluate water institutions' performance under uncertainty. Australian Journal of Agricultural and Resource Economics, 51:17-38.

Iglesias E., Garrido A. and Gomez-Ramos A., 2003. Evaluation of drought management in irrigated areas. Agricultural Economics, 29(2):211-229.

Incerti G., Feoli E., Salvati L., Brunetti A. and Giovacchini A., 2007. Analysis of bioclimatic time series and their neutral network-based classification to characterise drought risk patterns in South Italy. International Journal of Biometeorology, 51(4):253-263.

INDAP, 2009. Unidad de Gestión de Riesgos, Informe sobre los principales riesgos agroclimáticos que afectan a la pequeña agricultura, 1.

INE (Instituto Nacional de Estadística, España), 1995-2007. Agri-food Gross Value Added data series. Available at: http://www.ine.es/jaxi/tabla.do?per=12&type=db&divi=EIE&idtab=13 [Last accessed: 2012]

INE (Instituto Nacional de Estadística, Chile), 2010. Consumer Price Index data series. Available at: http://www.ine.cl/canales/chile_estadistico/familias/precios.php [Last accessed: 2010]

IPCC, 2001. Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC C.C., 2007. The Physical Science Basis: Summary for Policymakers-Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). IPCC Secretariat, WMO, Geneva.

ISDR, 2009. Risk and poverty in a changing climate. Global Assessment Report on Disaster Risk Reduction.

Jaksic F.M., 2009. Ecological effects of El Niño in terrestrial ecosystems of western South America. Ecography, 24:241-250.

Jaksic F.M., 1998. The multiple facets of El Niño/Southern oscillation in Chile. Revista Chilena de Historia Natural, 71:121-131.

Jenkins M.W., Lund J.R. and Howitt R.E., 2003. Economic losses for urban water scarcity in California. Journal of the American Water Works Association, 95:58-70.

Kallis G., 2008. Droughts. Annual Review of Environment and Resources, 33:85-118.

Kirby M., Connor J.D., Bark R.H., Qureshi E. and Keyworth S., 2012. The economic impact of water reductions during the Millennium Drought in the Murray-Darling Basin. No. 124490, Australian Agricultural and Resource Economics Society.

Kirchhoff S., Colby B.G. and LaFrance J.T., 1997. Evaluating the performance of benefit transfer: an empirical inquiry. Journal of Environmental Economics and Management, 33:75-93.

Klein K.K. and Kulshreshtha S.N., 1989. Economic impacts of small-scale irrigation under drought conditions in northwestern saskatchewan: An application of the agricultural drought impact evaluation model. Agricultural Systems, 30:205-215.

Kogan F., 2011. ENSO Impact on Vegetation. Use of Satellite and In-Situ Data to Improve Sustainability, 20:165-171.

Koss P. and Khawaja M.S., 2001. The value of water supply reliability in California:: a contingent valuation study. Water Policy, 3:165-174.

Krol M.S. and Bronstert A., 2007. Regional integrated modelling of climate change impacts on natural resources and resource usage in semi-arid Northeast Brazil. Environmental Modelling and Software, 22(2):259-286.

Kunkel K.E., Pielke R.A. and Changnon S.A., 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. Bulletin - American Meteorological Society, 80:1077-1098.

Le Houérou H.N., 1996. Climate change, drought and desertification. Journal of Arid Environments, 34:133-186.

Lehner B., Döll P., Alcamo J., Henrichs T. and Kaspar F., 2006. Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. Climatic Change, 75:273-299.

Leontief W., (ed.) 1986. Input-output economics. Oxford University Press, USA.

Logar I. and van den Bergh J.C.J.M., 2012. Methods to Assess Costs of Drought Damages and Policies for Drought Mitigation and Adaptation: Review and Recommendations. Water Resources Management, 10.1007/s11269-012-0119-9:1-14.

Loomis J.B., 1992. The evolution of a more rigorous approach to benefit transfer: benefit function transfer. Water Resources Research, 28:701-705.

Lopez-Gunn E. and Ramón Llamas M., 2008. Re-thinking water scarcity: Can science and technology solve the global water crisis? , 32:228-238.

Lorite I., Mateos L., Orgaz F. and Fereres E., 2007. Assessing deficit irrigation strategies at the level of an irrigation district. Agricultural Water Management, 91:51-60.

Lozano G., Pulido M. and Andreu J., 2007. Case Study Report Serpis SERPIS RIVER (Jucar River Basin District), Spain.

MAGRAMA, 2009. Hydrological Bulletins. Available at: http://servicios3.magrama.es/BoleHWeb/inicio.jsp [Last accessed: 2011]

MAGRAMA, 1995-2007. Agricultural Statistics Yearbooks. Available at: http://www.magrama.gob.es/es/estadistica/temas/estad-publicaciones/anuario-de-estadistica/ [Last accessed: 2011]

Markandya A., Mysiak J., Palatnik B.M., Balzarolo D. and Martin-Ortega J., 2010. Economic and social impacts of drought and demand side options–state of the art review. Xerochore project background document.www.feem-project.net/xerochore.

Martin-Carrasco F., Garrote L., Iglesias A. and Mediero L., 2012. Diagnosing Causes of Water Scarcity in Complex Water Resources Systems and Identifying Risk Management Actions. Water Resources Management, 2012:1-13.

Martínez-Cachá A. (ed.), 2004. Impacto económico de las sequías en el sureste agrario español. Universidad Católica San Antonio, pp: 187.

Martin-Ortega J., Giannoccaro G. and Berbel J., 2011. Environmental and resource costs under water scarcity conditions: an estimation in the context of the European Water Framework Directive. Water Resources Management, 25(6):1-19.

Martin-Ortega J. and Berbel J., 2010. Using multi-criteria analysis to explore non-market monetary values of water quality changes in the context of the Water Framework Directive. Science of the Total Environment, 408:3990-3997.

Martin-Ortega J. and Markandya A., 2009. The costs of drought: the exceptional 2007-2008 case of Barcelona. BC3.Basque Centre for Climate Change: Working Paper Series.

MEDROPLAN, (ed.) 2009. Coping with drought risk in agriculture and water supply systems: Drought management and policy development in the Mediterranean. Springer.

Mejías P., Varela-Ortega C. and Flichman G., 2004. Integrating agricultural policies and water policies under water supply and climate uncertainty. Water Resources Research, 40:W07S03.

MINAGRI, 2009. Municipios Chilenos declarados en Emergencia Agrícola (1998-2008).

Mishra A.K. and Singh V.P., 2010. A review of drought concepts. Journal of Hydrology, 391:202-216.

MMA, 2007. Comité de expertos en sequía: La sequía en España, directrices apra minimizar su impacto. MMA.

Molina C.H., 2000. Efectos causados por la sequia al sector agricola y la respuesta del gobierno [1994-1999].

Moore M.R. and Negri D.H., 1992. A multicrop production model of irrigated agriculture, applied to water allocation policy of the bureau of reclamation. Journal of Agricultural and Resource Economics, 17(1):29-43.

Morilla C.R., Diaz-Salazar G.L. and Cardenete M.A., 2007. Economic and environmental efficiency using a social accounting matrix. Ecological Economics, 60:774-786.

Mysiak J., 2012. The value of knowing better. The role of disaster impact assessment for the risk management. Final Conference PREEMPT project.

NASA, 2012. Earth Observatory. The Global Heat engine. http://earthobservatory.nasa.gov/Features/SSTNDVI/sst_ndvi4.php. [Last accessed: 2012].

Nebiker S., 2006. Using risk-based forecasts to improve water supply reliability. Operating Reservoirs in Changing Conditions - Proceedings of the Operations Management 2006 Conference:411.

Nicholls R.J., Hoozemans F.M.J. and Marchand M., 1999. Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Global Environmental Change, 9:S69-S87.

NOAA, 2012. National Oceanic and Atmospheric Administration (US). Historic El Niño and La Niña events. http://www.esrl.noaa.gov/psd/enso/mei/#ElNino , 2012.

ODEPA, 2010. Agricultural product prices data series. Available at: http://www.odepa.gob.cl/jsp/menu/coyuntura/coyuntura_terminales.jsp;jsessionid=894505B9B7D5BBBA324BCE7EE392B7C9. [Last accessed: 2010].

Pacific Institute, 2010a. Total Renewable Freshwater Supply, by Country.

Pacific Institute, 2010b. Freshwater Withdrawals by Country and Sector.

Peck D.E. and Adams R.M., 2010. Farm-level impacts of prolonged drought: is a multiyear event more than the sum of its parts? Australian Journal of Agricultural and Resource Economics, 54:43-60.

Peck D.E. and Adams R.M., 2007. The persistence of drought impacts across growing seasons: a dynamic stochastic analysis. In 101st Seminar, July 5-6, 2007, Berlin Germany (No. 9253). European Association of Agricultural Economists.

Pérez y Pérez L. and Barreiro-Hurlé J., 2009. Assessing the socio-economic impacts of drought in the Ebro River Basin. Spanish Journal of Agricultural Research, 7:269-280.

Potgieter A.B., Hammer G.L., Meinke H., Stone R.C. and Goddard L., 2010. Three putative types of El Nino revealed by spatial variability in impact on Australian wheat yield. Journal of climate, 18(10):1566-1574.

PREEMPT, 2012. Policy-relevant assessment of socio-economic effects of droughts and floods. Guidance Document, Venice, Italy.

PREEMPT, 2011. Policy-relevanT Assessment of Socio-economic Effects of Droughts and Floods. Del. E1: Assessment Report of de Preventive Measures in Place.

Quenani-Petrela E., Noel J.E. and Mastin T., 2007. A Benefit Transfer Approach to the Estimation of Agro-Ecosystems Services Benefits: A Case Study of Kern County, California. California Institute for the Study of Specialty Crops:1.

Quereda Sala J., Montón Chiva E., Escrig Barberá J., Ruescas Orient A.B. and Moyá Cantavella B., 2005. Cambio climático y situaciones de sequía en la región mediterránea. Millars, Espai i Història, 28:55-68.

Quiroga Gomez S., Garrote de Marcos L., Iglesias Picazo A., Fernández-Haddad Z., Schlickenrieder J., Pedrosa L., Mosso C. and Sánchez-Arcilla A., 2011. The economic value of drought information for water management under climate change: a case study in the Ebro basin. Natural Hazards and Earth System Sciences, 11:643-657.

Quiroga Gomez S., Fernández-Haddad Z. and Iglesias Picazo A.L., 2010. Risk of water scarcity and water policy implications for crop production in the Ebro Basin in Spain. Hydrology and earth system sciences, 7:5895-5927.

Quiroga S. and Iglesias A., 2009. A comparison of the climate risks of cereal, citrus, grapevine and olive production in Spain. Agricultural Systems, 101:91-100.

Qureshi M.E., Ahmad M.D., Whitten S.M. and Kirby M., 2012. A multi-period positive mathematical programming approach for assessing economic impact of drought in the Murray-Darling Basin, Australia. In 2012 Conference (56th), February 7-10, 2012, Freemantle, Australia (No. 124418). Australian Agricultural and Resource Economics Society.

Raje D., Dhobe P. and Deshpande A., 2002. Consumer's willingness to pay more for municipal supplied water: a case study. Ecological Economics, 42:391-400.

Ritcher G.M. and Semenov M.A., 2005. Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks. Agricultural Systems, 84(1):77-97.

Roibás D., García-Valiñas M.Á and Wall A., 2007. Measuring welfare losses from interruption and pricing as responses to water shortages: an application to the case of Seville. Environmental and Resource Economics, 38:231-243.

Rosegrant M.W., Ringler C., McKinney D.C., Cai X., Keller A. and Donoso G., 2000. Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin. Agricultural Economics, 24:33-46.

Rosegrant M.W. and Gazmuri R., 1995. Reforming Water Allocation Policy Through Markets in Tradable Water Rights: Lessons from Chile, Mexico and Califormia. Cuadernos de economía: Latin American Journal of Economics, 32(97):33-58.

Rosegrant M.W. and Binswanger H.P., 1994. Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation. World Development, 22:1613-1625.

Rosine J. and Walraven N., 1989. Drought, Agriculture and the Economy. Federal Reserve Bulletine, 75.

Rossi G., Castiglione L. and Bonaccorso B., 2007. Guidelines for planning and implementing drought mitigation measures. Methods and Tools for Drought Analysis and Management, 62:325-347.

Rubio Calvo E., Abad J., Gimeno Y., García M. and Oliva C., 2006. Repercusión de la Sequía en los Riegos del Alto Aragón.

Salami H., Shahnooshi N. and Thomson K.J., 2009. The economic impacts of drought on the economy of Iran: An integration of linear programming and macroeconometric modelling approaches. Ecological Economics, 68:1032-1039.

SASI Group (University of Sheffield) and Mark Newman (University of Michigan), 2012. World wide freshwater resources. , Map 102.

Schoengold K., Sunding D.L. and Moreno G., 2006. Price elasticity reconsidered: Panel estimation of an agricultural water demand function. Water Resources Research, 42(9):W09411.

Schuh G.E., 1962. An econometric investigation of the market for hired labor in agriculture. Journal of Farm Economics, 44:307-321.

Sheffield J., Wood E.F. and Roderick M.L., 2012. Little change in global drought over the past 60 years. Nature, 491:435-438.

Sidibé Y., Terreaux J.P., Tidball M. and Reynaud A., 2012. Coping with drought with innovative pricing systems: the case of two irrigation water management companies in France. Agricultural Economics, 43(s1):141-155.

Smakhtin V., Revenga C., Döll P., Tharme R., Nackoney J. and Kura Y., 2004. Taking into account environmental water requirements in global-scale water resources assessments. Iwmi, Comprehensive assessment research report 2.

Social Security, 1999-2007. Datos de trabajadores por cuenta propia y ajena de la rama Agraria. Available at: http://www.seg-social.es/Internet_1/Estadistica/Est/AfiliacionAltaTrabajadores/index.htm [Last accessed: 2011]

Tagel G., van der Veen A. and Maathuis B., 2011. Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. International Journal of Applied Earth Observation and Geoinformation, 13:309-321.

Tallaksen L.M. and Van Lanen H.A.J., (eds.) 2004. Hydrological drought: processes and estimation methods for streamflow and groundwater. Elsevier Science Limited.

Thurow T.L. and Taylor Jr C.A., 1999. Viewpoint: the role of drought in range management. Journal of Range Management, 52(5):413-419.

Tobarra P., 2008. Gestión del recurso natural agua en situaciones de información asimétrica e incertidumbre, Working paper.

UNISDR, 2004. Living with risk: a global review of disaster reduction initiatives. International Strategy for Disaster Reduction. United Nations Publications.

Valencia Delfa J.L., Saa Requejo A., Gascó Montes J.M. and Tarquis Alfonso A.M., 2010. Universal Multifractal description applied to precipitation pattern in the Ebro River Basin. Climate Research, 44:17-25.

Valiñas M.ÁG., 2003. La eficiencia de las políticas sobre la demanda de agua: bienestar y sequía. In Hacienda pública y convergencia europea: X Encuentro de Economía Pública, Santa Cruz de Tenerife 2003. Universidad de la Laguna, Spain.

Varela-Ortega C., Blanco-Gutiérrez I., Swartz C.H. and Downing T.E., 2011. Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: An integrated hydro-economic modeling framework. Global Environmental Change, 21:604-619.

Varela-Ortega, C., Esteve, P., Bharwani, S., & Downing, T. E., 2007. Public policies for groundwater conservation: a vulnerability analysis in irrigation agriculture. In First International Conference on Adaptive and Integrative Water Management (CAIWA), pp:12-15.

Varela-Ortega C., M Sumpsi J., Garrido A., Blanco M. and Iglesias E., 1998. Water pricing policies, public decision making and farmers' response: implications for water policy. Agricultural Economics, 19:193-202.

Vásquez W.F., Mozumder P., Hernández-Arce J. and Berrens R.P., 2009. Willingness to pay for safe drinking water: Evidence from Parral, Mexico. Journal of environmental management, 90:3391-3400.

Vicente-Serrano S.M., Beguería S., Gimeno L., Eklundh L., Giuliani G., Weston D., El Kenawy A., López-Moreno J.I., Nieto R. and Ayenew T., 2012. Challenges for drought mitigation in Africa: The potential use of geospatial data and drought information systems. Applied Geography, 34:471-486.

Vicente-Serrano S.M. and Cuadrat-Prats J., 2007. Trends in drought intensity and variability in the middle Ebro valley (NE of the Iberian peninsula) during the second half of the twentieth century. Theoretical and applied climatology, 88:247-258.

Vogt J. and F. Somma. (eds.), 2000. Drought and Drought Mitigation in Europe. Dordrecht: Kluwer academic publishers.

Ward F. and Booker J., 2006. Economic impacts of instream flow protection for the Rio Grande Silvery Minnow in the Rio Grande Basin. Reviews on Fisheries Science, 14(1-2):187-202.

Ward F.A. and Pulido-Velazquez M., 2012. Economic Costs of Sustaining Water Supplies: Findings from the Rio Grande. Water Resources Management, 86(10):2883-2909.

Ward F.A. and Pulido-Velázquez M., 2008. Efficiency, equity, and sustainability in a water quantity–quality optimization model in the Rio Grande basin. Ecological Economics, 66:23-37.

Warren D.E., Ehlen M.A., Loose V.W. and Vargas V.N., 2010. Estimates of the Long-Term US Economic Impacts of Global Climate Change-Induced Drought.

Westhoff P., 2008. Farm Commodity Prices: Why the Boom and What Happens Now? Choices, 23:6-10.

Wilhite D.A., 2007. Preparedness and Coping Strategies for Agricultural Drought Risk Management: Recent Progress and Trends. In: Sivakumar, MVK and Motha, RP (eds.), Managing Weather and Climate Risks in Agriculture, pp:21-38.

Wilhite D.A., Svoboda M.D. and Hayes M.J., 2007. Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. Water Resources Management, 21:763-774.

Wilhite D.A., (ed.) 2005. Drought and water crises: science, technology and management issues. CRC.

Wilhite D.A., 2000. Drought as a natural hazard: concepts and definitions. Drought, A global assessment, 1:3-18.

Wilhite D.A. and Glantz M.H., 1985. Understanding: The drought phenomenon: The role of definitions. Water International, 10:111-120.

Wilhite D.A. (ed.), 1993. Drought Assessment, Management and Planning; Theory and Case Studies, pp:316.

Wipfler L., van Lanen H., Ludwig F., Tallaksen M., Fleig K., Niemeyer S., Sauquet E. and Ramos M., 2009. Extended Guidance Document on the Natural System & Drought. Xerochore project Deliverable, 1.

WMO, 1975. Drought and Agriculture. Report of the, Technical Note No.138.

Woo C.K., 1994. Managing water supply shortage:: Interruption vs. pricing. Journal of Public Economics, 54:145-160.

World Bank (2011) Chile: Diagnóstico de la gestión de los recursos hídricos. The World Bank, Washington, DC. http://www.dga.cl/eventos/Diagnostico gestion de recursos hidricos en Chile_Banco Mundial.pdf.

World Water Council, 2012. Water Crisis, Water Stress Indicator, 2012.

Wu H. and Wilhite D.A., 2004. An operational agricultural drought risk assessment model for Nebraska, USA. Natural Hazards, 33.

XEROCHORE, 2010. An exercise to assess research needs and policy choices in areas of drought, Science Policy Brief. How to deal with drought?.

Xiao-jun W., Jian-yun Z., Shahid S., ElMahdi A., Rui-min H., Zhen-xin B. and Ali M., 2012. Water resources management strategy for adaptation to droughts in China. Mitigation and Adaptation Strategies for Global Change:1-15.

Young G., Zavala H., Wandel J., Smit B., Salas S., Jimenez E., Fiebig M., Espinoza R., Diaz H. and Cepeda J., 2010. Vulnerability and adaptation in a dryland community of the Elqui Valley, Chile. Climatic Change, 98:245-276.

Yun S., Jun Y. and Hong S., 2012. Social perception and response to the drought process: a case study of the drought during 2009–2010 in the Qianxi'nan Prefecture of Guizhou Province. Natural Hazards:1-13.