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How to link agricultural productivity, water availability and water demand in a risk context: a model for managing hydrological risks

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Abstract

The importance of water scarcity in irrigated agriculture in Spain provides the rationale for this paper, which analyses and evaluates the risk of water shortage on the economic result of this kind of agriculture. The main objective is to monitor this risk on a real-time basis. For this aim, we first estimated a number of regression models that explain irrigated agricultural productivity based on crop price indices, a time trend and water availability. These models, which correct for auto-correlation, yield good explanatory power. Second we carried out ex ante simulations of agricultural productivity using fitted distribution functions of water balance. 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 can be revised on a monthly basis before the beginning of the irrigation season. 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 water storage in years of scarcity. Different risk profiles are identified. For example, in Genil-Cabra 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.

Additional key words: drought management; irrigation; stochastic models; water productivity; water supply instability.

Resumen

Cómo vincular la productividad agrícola, la disponibilidad de agua y demanda de agua en un contexto de riesgo: un modelo para gestionar los riesgos hidrológicos

La importancia de la sequía sobre la agricultura de regadío es el fundamento de este artículo que analiza y evalúa el riesgo de escasez de agua sobre el resultado económico de este tipo de agricultura. El objetivo es controlar en tiempo real dicho riesgo. Se estiman diversos modelos de regresión que explican la productividad del regadío a través de un índice de precios ponderado para los principales cultivos, la tendencia y la disponibilidad de agua. Estos modelos, que se corrigen por auto-correlación, muestran una buena capacidad explicativa. En segundo lugar se llevan a cabo simulaciones ex-ante de la productividad del regadío empleando funciones ajustadas del balance de agua. Este marco metodológico proporciona la base para un sistema de gestión del riesgo de sequía en tiempo real a través de funciones de distribución de los resultados económicos esperados, que pueden ser revisadas de manera mensual antes del inicio de la campaña de riegos. Los resultados de la simulación demuestran que se pueden anticipar los efectos de las sequías, y por tanto, servir a los gestores del agua como complemento de los modelos hidrológicos para gestionar las reservas de agua en los años de escasez. Se identifican diferentes perfiles de riesgo. Por ejemplo en Genil-Cabra se comprueba la alta resiliencia del sistema después de eventos de sequía, mientras que en La Plana de Castellón el riesgo de abandono de tierras de regadío ha aumentado. En Genil-Cabra las pérdidas estimadas para la sequía de 2007 equivalen a 60 millones de euros. El modelo se aplica en algunas de las comunidades de regantes agrícolamente más relevantes de España.

Palabras clave adicionales: gestión de sequía; inestabilidad de la oferta de agua; modelos estocásticos; productividad del agua; riego.

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Abbreviations used: CDF (cumulative distribution function), DF (distribution function), IPV (irrigation production value), PDF (probability distribution function), PET (potential evapotranspiration), WA (water availability).

Introduction

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 (see Vogt and Somma, 2000; Rossi *et al.,* 2007; Iglesias and Blanco, 2008). While droughts and water shortages have the same origin, they are conceptually different. Shortages occur because droughts are poorly managed or because precipitation anomalies last longer than expected. Managing droughts is managing the risk of suffering water shortages, with the objective to avoid them or reduce their duration and magnitude.

Water infrastructure alleviates the effects of meteorological droughts, but requires the efficient management of reservoirs and aquifers together with demand management (Iglesias *et al.,* 2007, 2009). 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 smaller domains (Iglesias *et al.,* 2009). This knowledge must be combined with environmental information to mitigate both the economic and the environmental effects of drought in order to accomplish with this kind of protocol.

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 analysed by linking scarcity risks with the economic value generated by water, expressed in terms of social, environmental or economic services (Iglesias *et al*., 2003).

In a global context, climate change would alter drought risks (Quereda *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.

The aims of this paper are twofold. First, we estimate an econometric model to explain the variability in the economic performance of irrigated agriculture, using, among other explanatory variables, water availability in the irrigation districts (the water level in the reservoirs before the start of the irrigation season). The second objective was to develop a simple methodology to obtain the ex-ante probability distribution functions of the monthly value of agricultural production before the irrigation season starts. 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, the risk analysis model provides a variety of distribution functions for the expected economic results, which can be revised on a monthly basis before the beginning of the irrigation season. With this approach, possible drought impacts and early warning systems can be anticipated. Our methodology was applied to a representative sample of irrigation districts in various Iberian basins in Spain.

Study areas

The map in Figure 1 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 the most vulnerable to droughts and water scarcity.

To provide an idea of the monthly changes in supply availability and the importance of drought-risk analyses, we show the cumulative probability distribution functions for two districts, Genil-Cabra in the Guadalquivir basin in Andalusia and Zona Regable del Canal de Cinca in the Ebro basin in Aragón (Fig. 2). 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 permits the same approach to be used to track the ex-ante risk analysis of the economic performance for each district.

Methodology

The methodology used has two components. First, an econometric model was fitted in an attempt to explain

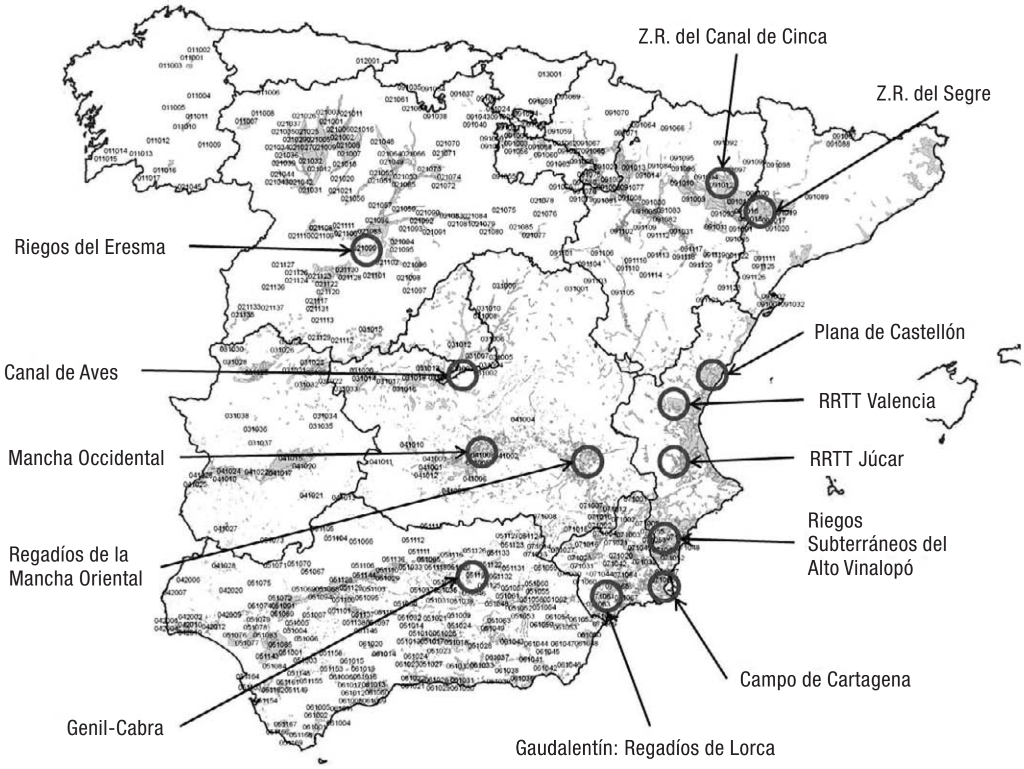


Figure 1. Locations of the Spanish irrigation districts considered. RRTT: traditional irrigation.

the variation in the irrigated production value. For this step, a general model was applied to each irrigation district. The second methodological component introduced the variability of water inflows into each storage system, which 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.

Econometric model

The econometric model explains the variation in the economic value of agricultural production with three explanatory variables: the water availability, the time

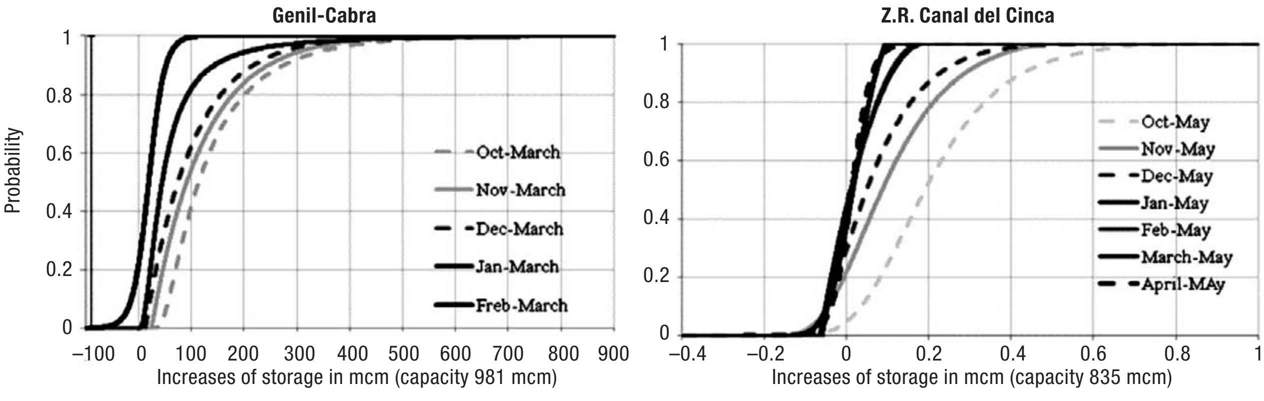


Figure 2. CDFs of stock increases in the reservoirs serving Genil-Cabra and Zona Regable del Cinca (see Table 2). mcm: million cubic meters.

trend and the crop prices received by farmers in each geographical unit of analysis. This is a general model in which the variable to be explained is the IPV_{it} (irrigated production value), which we estimated for each year (index t) and each district (index i). The model is defined for each unit i as follows:

$$IPV_{it} = a_i + b_i T_t + c_i WA_{it} + d_i Ip_{it} + u_{it} \qquad [1]$$

where $u_{it} = \varepsilon_{it} + \rho\varepsilon_{it-1}$; $E(\varepsilon_t) = 0$ and $\sigma_{it}^2 = \sigma_i^2$.

and where T_t is the time trend between 1996 and 2005, WA_{it} is the water availability variable and Ip_{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 (index n), obtaining disaggregated production values (in nominal euros), for irrigated crops in open-air fields and in greenhouses as well as the special cases of the irrigation of scattered trees and combined cultures of vineyards (See Fig. 3). Expressed in thousands of euros, it is calculated as follows:

$$IPV_{it} = \sum_{j=1}^{94} Suf_{nt} \times Yield_{nt} \times p_{nt} \qquad [2]$$

where Suf_{jt} is the irrigated surface in units I, t is the year, n (n, $n = 1,\ldots,94$) is the crop, $Yield_{nt}$ denotes the yield of each crop, unit and year and p_{nt} is the annual price for each crop.

The explanatory variable referring to the availability of irrigation water, WA_{it}, corresponds to the total volume of water used during the entire irrigation season. A weighted price index for each district has been calculated to isolate the variations in product value due to crop price variation (denoted by Ip_{it}). This index is weighted, taking into account the importance of each group of crops within each district and has been calculated using the formula:

$$Ip_{it} = \frac{\sum_{k=1}^{12} IPV\_tc_{ikt} * Ip_{kt}}{IPV_{it}} \qquad [3]$$

where IPV_tc_{ikt} is the total value of crop group k ($k = 1,\ldots,12$), which is representative of the crops grown in each district, and Ip_{kt} is the price index of crop group k published by the official statistical sources (MARM, 1995-2007).

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.

Analysis of economic drought risk

The proposed methodology is meant to evaluate the economic risk of water shortage for the irrigators. The stochastic variable, WA_{it}, is supposed to be partially responsive to the variations in the irrigated agriculture production values. It is, therefore, the instrument that connects the variability in water availability to the variability in the economic performance of the farming sector. In the following sections, we describe how WA_{it} was incorporated into the economic drought risk models.

Estimates of water demand variation

The aim of this part of the methodology was to evaluate variations in water demand. Based on the observed

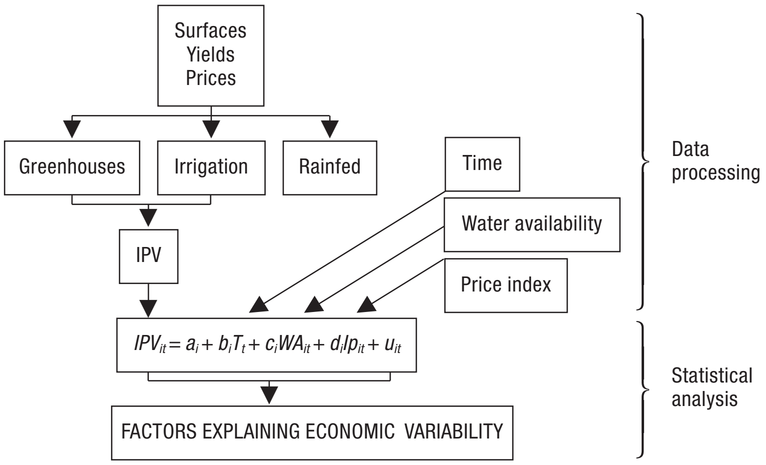


Figure 3. Modelling scheme for the economic model.

cropping patterns in each district between 1996 and 2005, two estimation procedures have been carried out. In *Dem1* (see Table 1), the «blue water» demand was estimated, taking into account the water balance based on 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 *et al.*, 2002).

The water demand variable *Dem2*, which provides the most accurate estimate of the demand, has been used in all districts. Therefore, $\tilde{D}_i$ (the stochastic demand variable from *Dem2*) 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 1 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.

The irrigation season 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.

In the first period, the ex-ante water shortage risk was evaluated. The water demand ($\tilde{D}_{i,t+1}$) was calculated to fulfil 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 remaining months of the season ($\Delta\tilde{D}^{j}_{i,t+1}$).

Table 1. Calculation of the irrigation water demand (in millions of m^3) with two procedures

District	Variable	Mean	SD[1]	VC[2]	p5	p25	p50	N	Years
Eresma	Dem1	$8.74 \cdot 10^7$	$1.46 \cdot 10^7$	0.17	$6.37 \cdot 10^7$	$7.89 \cdot 10^7$	$8.85 \cdot 10^7$	10	1996-2005
	Dem2	$6.69 \cdot 10^7$	$1.32 \cdot 10^7$	0.20	$4.63 \cdot 10^7$	$5.66 \cdot 10^7$	$7.08 \cdot 10^7$	9	2001-2009
C. Aves	Dem1	$9.29 \cdot 10^7$	$1.55 \cdot 10^7$	0.17	$5.69 \cdot 10^7$	$8.65 \cdot 10^7$	$9.51 \cdot 10^7$	10	1996-2005
	Dem2	$4.82 \cdot 10^7$	$1.90 \cdot 10^7$	0.39	$2.45 \cdot 10^7$	$3.25 \cdot 10^7$	$4.72 \cdot 10^7$	10	2000-2009
M. Occidental	Dem1	$6.67 \cdot 10^8$	$1.14 \cdot 10^8$	0.17	$5.18 \cdot 10^8$	$5.60 \cdot 10^8$	$6.88 \cdot 10^8$	10	1996-2005
	Dem2	$5.78 \cdot 10^8$	$8.69 \cdot 10^7$	0.15	$4.58 \cdot 10^8$	$5.03 \cdot 10^8$	$5.84 \cdot 10^8$	10	2000-2009
Genil	Dem1	$2.67 \cdot 10^8$	$2.88 \cdot 10^7$	0.11	$2.17 \cdot 10^8$	$2.47 \cdot 10^8$	$2.69 \cdot 10^8$	10	1996-2005
	Dem2	$2.35 \cdot 10^8$	$3.37 \cdot 10^7$	0.14	$1.87 \cdot 10^8$	$2.23 \cdot 10^8$	$2.31 \cdot 10^8$	9	2001-2009
C. Carta	Dem1	$2.64 \cdot 10^8$	$1.62 \cdot 10^7$	0.06	$2.32 \cdot 10^8$	$2.52 \cdot 10^8$	$2.66 \cdot 10^8$	10	1996-2005
	Dem2	$2.69 \cdot 10^8$	$3.77 \cdot 10^7$	0.14	$1.96 \cdot 10^8$	$2.42 \cdot 10^8$	$2.71 \cdot 10^8$	10	2000-2009
Lorca	Dem1	$1.03 \cdot 10^8$	7,244,676	0.07	$8.93 \cdot 10^7$	$9.97 \cdot 10^7$	$1.02 \cdot 10^8$	10	1996-2005
	Dem2	$1.01 \cdot 10^8$	$1.25 \cdot 10^7$	0.12	$8.72 \cdot 10^7$	$8.99 \cdot 10^7$	$9.93 \cdot 10^7$	10	2000-2009
Plana	Dem1	$1.07 \cdot 10^8$	$1.96 \cdot 10^7$	0.18	$6.91 \cdot 10^7$	$9.48 \cdot 10^7$	$1.12 \cdot 10^8$	10	1996-2005
	Dem2	$7.98 \cdot 10^7$	$2.06 \cdot 10^7$	0.26	$5.24 \cdot 10^7$	$6.67 \cdot 10^7$	$7.66 \cdot 10^7$	10	2000-2009
RRTT[3] Valencia	Dem1	$1.05 \cdot 10^8$	$1.50 \cdot 10^7$	0.14	$7.25 \cdot 10^7$	$9.98 \cdot 10^7$	$1.07 \cdot 10^8$	10	1996-2005
	Dem2	$7.78 \cdot 10^7$	$1.95 \cdot 10^7$	0.25	$4.33 \cdot 10^7$	$6.81 \cdot 10^7$	$7.12 \cdot 10^7$	10	2000-2009
M. Oriental	Dem1	$5.52 \cdot 10^8$	$1.08 \cdot 10^8$	0.20	$4.41 \cdot 10^8$	$4.73 \cdot 10^8$	$5.35 \cdot 10^8$	10	1996-2005
	Dem2	$4.27 \cdot 10^8$	$8.12 \cdot 10^7$	0.19	$3.05 \cdot 10^8$	$3.60 \cdot 10^8$	$4.34 \cdot 10^8$	10	2000-2009
RRTT[3] Júcar	Dem1	$3.00 \cdot 10^8$	$3.82 \cdot 10^7$	0.13	$2.20 \cdot 10^8$	$2.70 \cdot 10^8$	$3.17 \cdot 10^8$	10	1996-2005
	Dem2	$2.26 \cdot 10^8$	$5.00 \cdot 10^7$	0.22	$1.49 \cdot 10^8$	$1.93 \cdot 10^8$	$2.21 \cdot 10^8$	10	2000-2009
Vinalopó	Dem1	$7.53 \cdot 10^7$	8,788,780	0.12	$5.98 \cdot 10^7$	$7.23 \cdot 10^7$	$7.61 \cdot 10^7$	10	1996-2005
	Dem2	$7.54 \cdot 10^7$	$1.46 \cdot 10^7$	0.19	$5.55 \cdot 10^7$	$6.67 \cdot 10^7$	$7.24 \cdot 10^7$	10	2000-2009
Cinca	Dem1	$3.90 \cdot 10^8$	$8.16 \cdot 10^7$	0.21	$2.57 \cdot 10^8$	$2.95 \cdot 10^8$	$4.30 \cdot 10^8$	10	1996-2005
	Dem2	$2.82 \cdot 10^8$	$3.16 \cdot 10^7$	0.11	$2.42 \cdot 10^8$	$2.43 \cdot 10^8$	$2.95 \cdot 10^8$	6	2004-2010
Segre	Dem1	$2.05 \cdot 10^8$	$1.40 \cdot 10^7$	0.07	$1.89 \cdot 10^8$	$1.92 \cdot 10^8$	$2.02 \cdot 10^8$	10	1996-2005
	Dem2	$1.50 \cdot 10^8$	$2.84 \cdot 10^7$	0.19	$1.17 \cdot 10^8$	$1.32 \cdot 10^8$	$1.38 \cdot 10^8$	10	2000-2009

[1] SD: standard deviation. [2] VC: variation coefficient. [3] RRTT: riegos tradicionales (traditional irrigation). *Source:* Own elaboration.

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. Thus, we divide the analysis into two different periods, the first one 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:

$$\tilde{R}^{h}_{i,1+t} = \bar{R}^{h}_{i,t} + \Delta\tilde{R}^{h}_{i,t+1} \qquad [4]$$

where $\tilde{R}^{h}_{i,1+t}$ 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, $\bar{R}^{h}_{i,t}$, 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 *h* months before the season begins. $\Delta\tilde{R}^{h}_{i,t+1}$ can be represented by a distribution function specific to the reservoir and *h*. This variable has been estimated using historical data 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 2 reports the probability distribution functions (PDFs) for the districts for which results are offered in the following sections.

Estimates of the water balance equation

The water balance was divided into the same two analysis periods as the water supply. Different assumptions were made for each stage. In the first period, we assumed that storage varies from month to month but

Table 2. Estimated probability distribution functions (PDFs) of the supply increases (in millions of m^3) of five districts and statistical values

District		Average	SD	Perc 5	Perc 25	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
RRTT[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

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

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:

$$\tilde{B}^h_{i,t+1} = \tilde{R}^h_{i,t+1} - \tilde{D}_{i,t+1} - \bar{S}_i \qquad [5]$$

$\tilde{B}^h_{i,t+1}$ 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. [5], monthly revisions are based only on the revisions of $\tilde{R}^h_{i,t+1}$, which, according to Eq. [4], originates from the monthly stock increases $\Delta\tilde{R}^h_{i,t+1}$. $\tilde{D}_{i,t+1}$ is the water demand distribution function for the entire upcoming irrigation season.

— Stochastic water balance once the irrigation season has begun

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

$$\tilde{B}^{h+1}_{i,t+1} = \bar{R}^h_{i,t} - \bar{S}_i - \Delta\tilde{D}^j_{i,t+1} \quad j > h \qquad [6]$$

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

Risk analysis of the economic performance of the irrigation district

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 Fig. 4). Those values

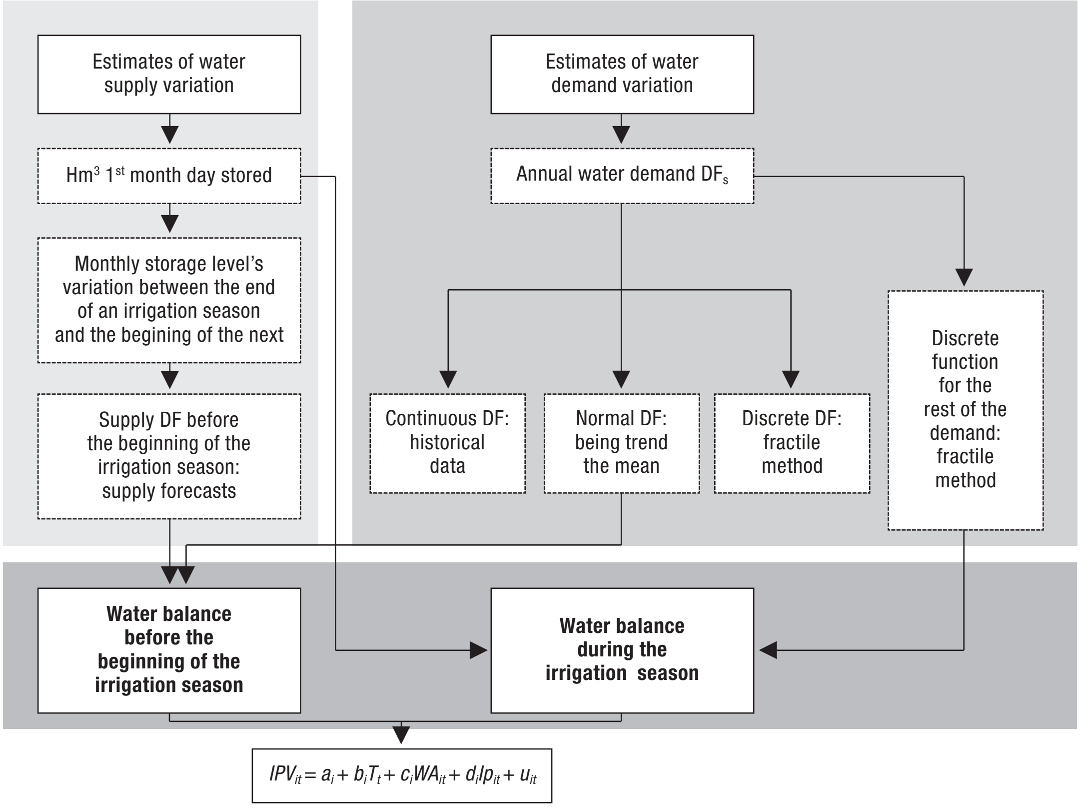


Figure 4. Scheme of the risk analyses. DF: distribution function.

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.

— Districts with stable irrigated acreage

Based on Eqs. [5] and [6], 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:

$$I\tilde{P}V^h_{i,t+1} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i p75(\tilde{B}^h_{i,t+1}) + \hat{d}_i Ip^e_{i,t} + \tilde{u}_{i,t} \quad \text{with} \quad \tilde{u}_{i,t} = \tilde{\varepsilon}_{i,t} - \hat{\rho}\tilde{\varepsilon}_{i,t-1} \qquad [7]$$

where $p75(\tilde{B}^h_{i,t+1})$ is the 75th percentile of $\tilde{B}^h_{i,t+1}$, $Ip^e_{i,t}$ is the moving average of the price indices in 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:

$$I\tilde{P}V^h_{i,t+1} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i(\tilde{R}^h_{i,t+1} - S_k) + \hat{d}_i Ip^e_{i,t} + \tilde{u}_{i,t} \qquad [8]$$

— 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:

$$Suf_{i,t} = a_i + b_i T + c_i WA_{i,t} + d_i \left(WA_{i,t}\right)^2 + \varepsilon_{i,t} \qquad [9]$$

Then, Eq. [7] was used to simulate the irrigated surface as follows:

$$S\tilde{u}f^h_{i,t+1} = \hat{a}_i + \hat{b}_i T_t + \hat{c}_i(\tilde{B}^h_{i,t+1}) + \hat{d}_i(\tilde{B}^h_{i,t+1})^2 + \tilde{\varepsilon}_{i,t} \qquad [10]$$

where $S\tilde{u}f^h_{i,t+1}$ is the stochastic irrigated surface dependent on the water balance (Eq. [9]). In the second stage, the model $IPV_{i,t} = a_i + b_i Suf_{i,t} + \varepsilon_{i,t}$ was fitted and subsequently used for the stochastic simulation:

$$I\tilde{P}V^h_{i,t+1} = \hat{a}_i + \hat{b}_i S\bar{u}f_{i,t} + \tilde{\varepsilon}_{i,t} \qquad [11]$$

Stochastic simulation

The main objective was to translate the stochastic nature of the water stock changes into economic evaluations in the form of probability distributions. The modelling 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, $\tilde{B}^h_{i,t+1}$. 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 modelling errors involved in the causation effects that must also be taken into account. In sum, our 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.

Results

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

Econometric models

The dependence of the value of irrigated crops in the selected districts on water availability was measured via the econometric model (Eq. [1]). 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. [1] 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 4 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, WA, provide generally good but somewhat ambiguous results.

The results of the econometric analysis varied 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. We estimated alternative equations including aquifer levels, but the results were no better.

The trend (year) is 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 modelling 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.

Drought economic risks

To make clear the need of risk analysis, Table 3 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 (Ebro, Aragón), one in the south, Genil-Cabra (Guadalquivir, Andalusia) and two more in the eastern Mediterranean regions, Riegos Tradicionales de Valencia (Jucar, Valencia) and Plana de Castellón (Jucar, Valencia). The table includes the monthly probability revisions, with numbers in italics, in the cases in which the season's prospect improved, and in bold 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.

In Genil-Cabra from 2002 to 2005, demand should have been fully met, according to our probability calculations. 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

Table 3. Probabilities of not meeting the stochastic irrigation water demand

Irrigation season	Genil-Cabra (Guadalquivir, Andalusia)							RRTT Valencia (Júcar, Valencia)						
	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.

Table 4. Econometric estimations of economic results with two water demands (based on Eq. [1]: $IPV = a_i + b_i T_i + c_i WAit + d_i Ip_{it} + u_{it}$)

District	Dem 1					Dem2				
	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
RRTT Júcar	0.84	10	–11,908.86**	–95.91	297.04	0.90	10	–12,010.36**	–173.32	398.54
RRTT 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
Zona Regable 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

* $p < 0.05$. ** $p < 0.01$.

from which the crops' water demand is estimated. While in this paper the demand was based on the observed cropping patterns, which may have already included less-demanding crops, García Vila *et al.* (2008) optimised 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 behaviour 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 subsidised crops and perhaps too old to recognise 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 1, this section presents the economic results for each district represented in probabilistic terms. Figure 5 shows a plot of the CDFs of the economic results for our 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). 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 5, especially in Genil-Cabra and Plana de Castellón. In the first case, in a dry year 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.

The upper part of Figure 6 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 second upper right panel of Figure 5, 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. The lower part of Figure 6 shows a plot of the entire set of economic forecasts for this district.

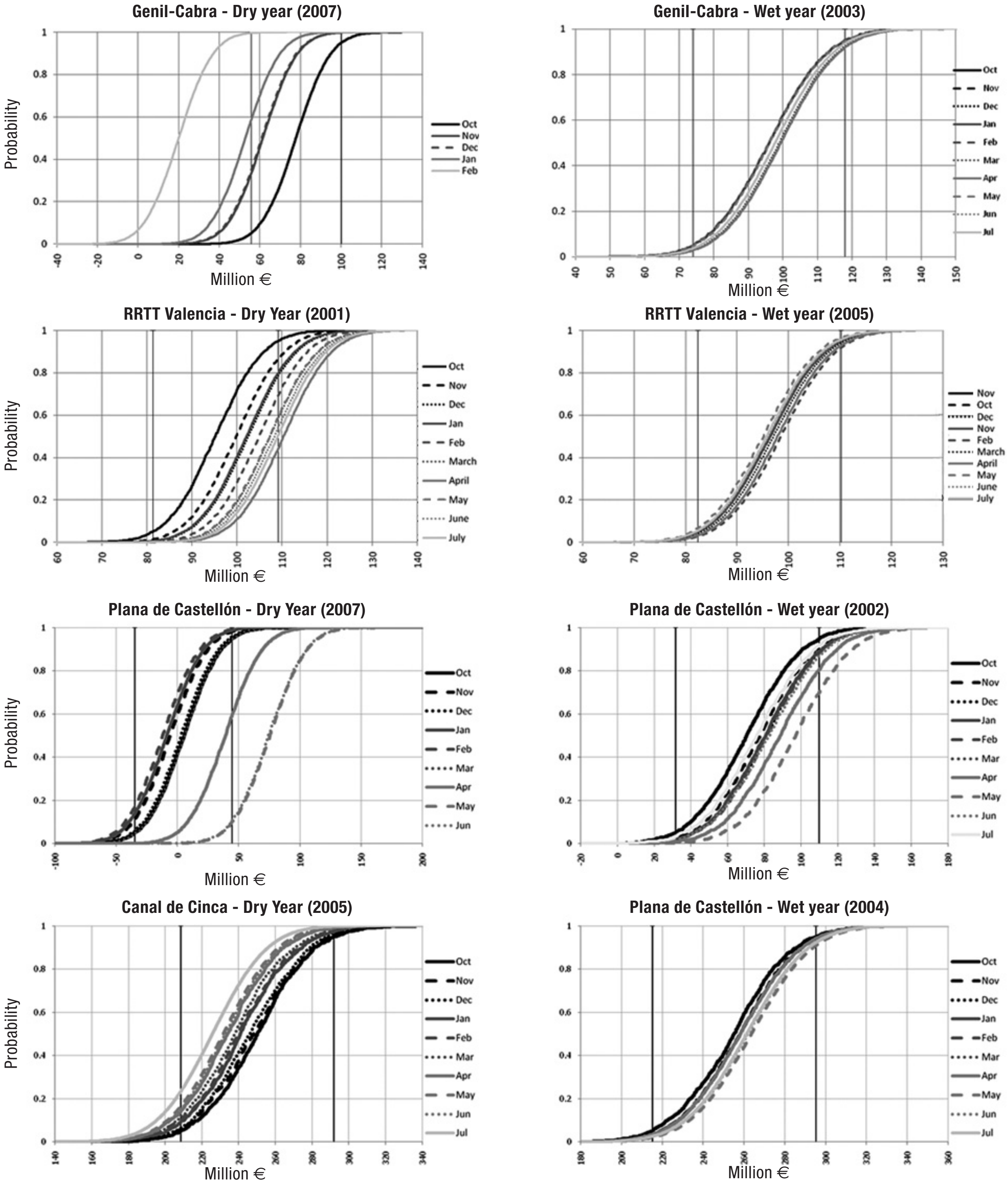


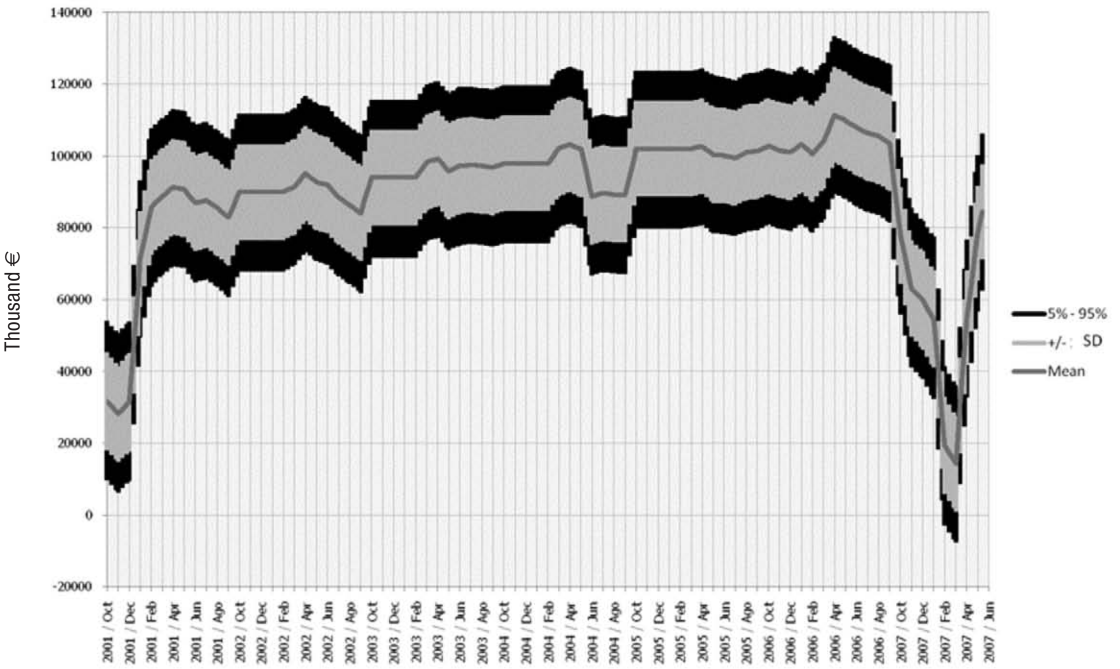
Figure 5. Cumulative distribution function (CDF) of the economic results (in million €) for four irrigation districts in a wet year (right) and in a dry year (left).

The plot exhibits a downward trend that was captured by the regression model formulated by Eq. [1] and was taken into account in the simulation models described by Eqs. [4] through [6]. Nonetheless, each season differs from the others in its risk profile.

Discussion

Irrigated agriculture in Spain is exposed to water scarcity risks and drought impacts. The importance and frequency of drought periods makes economic risk

Genil-Cabra October 2001 through June 2007



Plana de Castellón October 2001 through June 2007

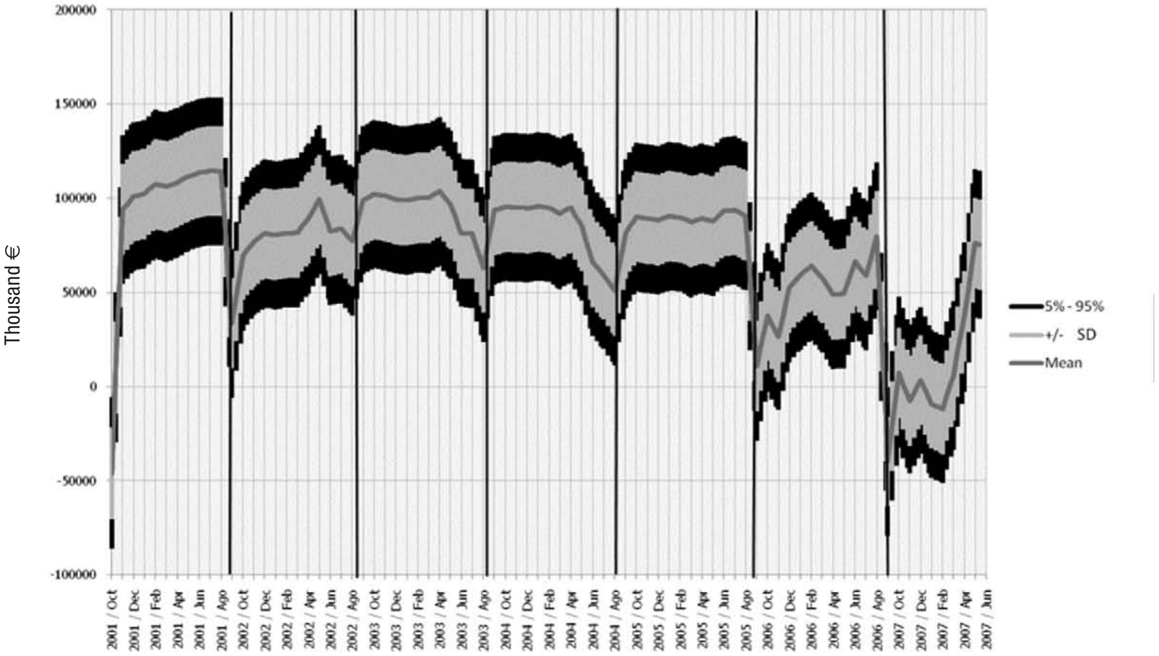


Figure 6. Economic forecasts for Genil-Cabra and Plana de Castellón.

analyses based on sound attribution models of drought effects especially useful. Such an approach can assist water managers in running reservoirs and storage facilities and agricultural stakeholders in preparing for water scarcity. We showed that water variables can be used to monitor hydrological and operational droughts and that they are robust to support complementary economic risk analyses. The variation in the value of harvests from the irrigated surfaces can be explained by a trend, a representative price index of the crops grown in each unit (district) and a hydrological variable based on the water balances. With this approach, the economic effects of water scarcity can be isolated from other causes of lower economic output (a downward trend due to structural factors, such as reductions in farmland, and price volatility, which do not have any relationship to water availability). We found differences in crop value variability across districts that could be attributed to hydrological variables.

Our regression models provide 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 some districts, the causation models are not sufficiently robust to assure confidence in the stochastic simulation. The water balance provides a risk dimension that can be monitored on a monthly basis.

The hydrological variable (monthly water balance) can be traced weekly almost on a real time basis. By inserting the stochastic changes in the storage levels on a monthly basis into the regression models, we developed risk models that connect the hydrological variability to the resulting economic variability. Just as the hydrological state is subject to stochastic processes, the economic performance of the sector relying on it can be stochastically connected to the former. An accurate drought attribution model must separate out other sources of production variability, the prices of the crops chief among them.

By looking at a vast array of hydrological, agronomical and geographical features, represented by the 13 irrigation districts included in the study, different drought risk profiles were identified.

Drought risk analysis can vary depending primarily on the water supply and secondarily on weather characteristics. We can conclude that the revisions of ex-ante projections are the key to having accurate information. We have emphasised the ease of these calculations and their potential for ex-ante drought management in all areas analysed.

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 supply risks to the financial, insurance or reinsurance markets.

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References

ADAMS P.D., HORRIDGE M., MASDEN J., WITTWER G., 2002. Drought, regions and the Australian economy between 2001-02 and 2004-05. Australian Bulletin of Labour 28(4), 233-249.

ALLEN R.G., PEREIRA L.S., RAES D., SMITH M., 2002. Crop evapotranspiration: guidelines for computing crop water requirements. Irrig Drain Paper 56. FAO, Roma. 301 pp.

CUNDERLIK J.M., SIMONOVIC S.P., 2007. Inverse flood risk modelling under changing climatic conditions. Hydrol Process 21, 563-577.

FENG S., LI L.X., DUAN Z.G., ZHANG J.L., 2007. Assessing the impacts of South-to-North Water transfer project with decision support systems. Decis Support Syst 42(4), 1989-2003.

GARCÍA-VILA M., LORITE I.J., SORIANDO M.A., FERERES E., 2008. Management trends and responses to water scarcity in an irrigation scheme of Southern Spain. Agr Water Manage 95(4), 458-468.

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

GARRIDO A., LLAMAS M.R., VARELA-ORTEGA C., NOVO P., RODRÍGUEZ-CASADO R., ALDAYA M., 2010. Water footprint and virtual water trade in Spain. Springer, USA. 151 pp.

GÓMEZ-RAMOS A., GARRIDO A., 2004. Formal risk sharing mechanisms to allocate uncertain water resources: the case of option contracts. Water Resour Res 40, 311-320.

IGLESIAS E., BLANCO M., 2008. New directions in water resources management: the role of water pricing policies. Water Resour Res 44, 6-17.

IGLESIAS E., GARRIDO A., GÓMEZ-RAMOS A., 2003. Evaluation of drought management in irrigated areas. Agr Econ 29, 211-229.

IGLESIAS E., GARRIDO A., GÓMEZ-RAMOS A., 2007. An economic drought management index to evaluate water institutions: performance under uncertainty. Aust J Agr Resour Econ 51, 17-38.

IGLESIAS A., GARROTE L.,CANCELLIERE A., CUBILLO F.,WILHITE D.A., 2009. Coping with drought risk in agriculture and water supply system. Springer, NY.

LEHNER B., DÖLL P., ALCAMO J., HENRICHS T., 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.

MARM, 1995-2007. Anuarios de Estadística del Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain. [In Spanish].

QUEREDA J., MONTÓN E., ESCRIG J., RUESCAS A.B., MOYÁ B., 2005. Cambio climático y situaciones de sequía en la región mediterránea. Millars, Espai i Història 28, 55-68. [In Spanish].

ROSSI G., CASTIGLIONE L., BONACCORSO B.,2007. Guidelines for planning and implementing drought mitigation measures. In: Methods and tools for drought analysis and management (Rossi *et al.*). Springer. pp. 325-347.

VOGT J.V., SOMMA F., 2000. Drought and drought mitigation in Europe. Advances in natural and technological hazards research. Kluwer Acad Publ, Dordrecht. 336 pp.

WU H., WILHITE D.A., 2004. An operational agricultural drought risk assessment model for Nebraska, USA. Nat Hazards 33, 1-21.