

# Modelling Spot Water Markets Under Uncertain Water Supply

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# MODELLING SPOT WATER MARKETS UNDER UNCERTAIN WATER SUPPLY

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## Abstract

Water availability in semiarid regions usually exhibits patterns of extreme variability. Even in intensively controlled basins, some users are subject to low levels of water reliability, and more vulnerable to periods of extreme scarcity. To reduce their risk exposure more flexible instruments, such as voluntary exchanges of water among users, are required. Recent changes in the Spanish water Law have given an initial impulse to allow for leases of water use rights. Properly designed and monitored, this instrument provides some flexibility to water management, and may increase the economic use efficiency as well as mitigate the adverse economic effects of droughts.

This paper looks at the risks and uncertainty dimensions of water markets, which have not been paid much attention in the literature. It analyses, from theoretical and empirical standpoints, the role that uncertainty plays in market participants' decisions and its impact on gains from trade.

Two models have been developed to carry out the empirical application. One is a stochastic and two-stage discreet programming model which simulates irrigators behaviour and the other is a spatial equilibrium model to compute market exchange and equilibrium. Water market price endogeneity is solved by an iterative process, which characterise price uncertainty from the results obtained from the spatial equilibrium model. Hydrological risk is characterised at the irrigation farm level through the variation of the water allowances served for irrigation. The application is performed on eleven irrigated farms in a district of the Guadalquivir Valley (Southern Spain).

It is shown how water availability uncertainty reduces farmers' benefits because of the fact that they must take ex – ante decisions. However, if market participation is allowed once water allowances become known, even at an uncertain price, the benefit losses are partly mitigated. From a methodological standpoint, these results suggest that the agricultural water market benefits estimates found in the literature may be undervalued as a result of omitting the option to participate in the market in the mix of possible strategies. Exchanging water in annual spot markets allows for the reduction of farmers' economic vulnerability caused by the variability and uncertainty of water supply within an irrigation season.

**Keywords:** uncertainty, farm modelling, water markets, water supply

# MODELLING SPOT WATER MARKETS UNDER UNCERTAIN WATER SUPPLY

## **1. Introduction**

Water availability in semi-arid regions usually exhibits patterns of extreme variability, which have been usually dealt with developing larger physical infrastructures. As costs of developments increase, the expansion of water supplies is limited. Even in highly controlled basins, some users are subject to low levels of water reliability, being vulnerable to periods of extreme scarcity. Water markets have been proposed as an instrument for dealing with water scarcity and justified from the point of view of economic efficiency. The potential welfare gains from the reallocation of water resources through voluntary exchange have been shown to be substantial (Vaux and Howitt, 1984; Rosegrant and Binswanger, 1994; Becker, 1995). These benefits are specially large when supplies are reduced by the occurrence of a drought, mitigating its economic impact (Miller, 1996).

Most empirical studies dealing with the analysis of the potential welfare gains of water markets have neglected the uncertain nature of water availability. Simulations of water markets outcomes have rarely taken into account that water variability may have an effect on market activity. Empirical evidence shows that uncertainty about the actual amount to which a water right holder is entitled can limit the development of permanent rights markets in favour of annual spot or option markets, as is the case in California, where the more insecure appropriative water rights are predominant (Howitt, 1998).

According to Antle's "risk-efficiency" hypothesis (1983), risk can affect economic efficiency both from the technical (productivity) or allocative (input decisions) points of view. In this sense, uncertain water availability influences the optimality of production decisions. In the present paper, we analyse the effect of uncertainty in water supply on the ex-ante optimal decisions and ex-post market efficiency of a participant in a spot water market.

Two models have been developed to carry out the empirical application. One is a stochastic two-stage discrete programming model that simulates irrigators' behaviour. The other is a spatial equilibrium model that computes market exchanges and equilibrium. Water market price endogeneity is solved by an iterative process, which allows to characterise price uncertainty from the results obtained from the spatial equilibrium model. Hydrological risk is characterised at the irrigation farm level through the variation of the water allowances served for irrigation. The application is performed on eleven irrigation farms belonging to an irrigation district of the Guadalquivir Valley (South Spain).

It is shown how water availability uncertainty reduces farmers' benefits because of the fact that they must take ex-ante decisions. However, if market participation is allowed once water allowances become known, even at an uncertain price, the benefit losses are partly mitigated. From a methodological standpoint, these results suggest that the agricultural water market benefits estimates found in the literature may be undervalued as a result of omitting the option to participate in the market in the mix of possible strategies. Exchanging water in annual spot markets allows for the reduction of farmers' economic vulnerability caused by the variability and uncertainty of water supply within an irrigation season.

## **2. Production decisions under uncertainty about water availability**

In irrigated agriculture, most decisions regarding cropping schedule and certain field operations are taken when the farmer is not sure about the amount of water available for irrigation. In many Mediterranean areas, the amount of water that corresponds to a farmer presents a high level of interannual variability, so agricultural producers generally face a considerable level of uncertainty about their final water allotment. Such uncertainty and farmers' attitudes toward risk, as well as many other stochastic factors inherent to agriculture production, influence their decisions and water use.

Uncertainty about water availability can be represented by a probability distribution of water allotments, which translates into a probability distribution of profits. Because of diminishing marginal productivity of water, profit reductions in dry years are greater than profit increases in years of above average water availability. The implication is straightforward: the bigger the variability the greater the cost it imposes on producers. Such cost comes from two different sources. First, profit variability caused by variability of the source of uncertainty. That is, the effect of risk on expected profit. Second, the effect of uncertainty on farmer's decisions, that is, the disutility of profit variability.

Just (1975) shows that risk can influence decisions of a risk-neutral producer if the random variable affect non-linearly the producer's objective function. When the relation between the source of variability and profit is linear, risk only affects risk-averse and risk-lovers producers, and the cost of uncertainty is given by profit variability and risk attitudes (Just, 1975; Babcock and Shogren, 1995). On the other hand, if risk enters non-linearly in the profit function, there is a cost derived of such risk even for risk-neutral producers (Just, 1975; Chambers, 1983; Babcock and Shogren, 1995), as expected profits are affected by risk. In such case it must also be accounted for how risk enters the profit function (Antle, 1983).

Few studies have dealt with uncertainty in water availability and their effect on production decisions. Howitt and Taylor (1993) analyse the case of a risk-averse producer that maximises her expected utility (which depends on profit) in a context of uncertainty about water availability. They show that the Value of Marginal Product of water in the optimum exceeds the expected shadow price of the resource, and water is used less intensively than under certainty for a price equal to its mathematical expectation. That is, production decisions are equivalent of those under certainty for an allotment below the mean allotment value.

### **3. Participation in a spot water market under uncertain water availability.**

The problem faced by an individual producer that participates in a competitive annual spot water market in absence of uncertainty, can be expressed as:

$$\text{Max}_w \pi_m(w) = \pi(w) + P_m(D-w) \quad [1]$$

where  $w$  is the amount of water used for production;  $D$  is the allotment the producer is entitled to;  $P_m$  is the market price for water;  $\pi_m(w)$  is the total profit function for the producer; and  $\pi(w)$  denotes the profits derived from producing using  $w$ .  $\pi(w)$  is a restricted profit function, with a negative second derivative (Chambers, 1988; Cornes, 1992), that can be defined as:

$$\pi(w) = \{ \max_z pq(w, z) - c'z / \forall w \} \quad [2]$$

where  $z$  is a vector of inputs other than water;  $p$  is output price;  $q(w, z)$  is the production function; and  $c'$  is the input costs vector. Therefore, it is assumed that profit function  $\pi(w)$  only depends on the amount of water used, being the optimal allocation of the inputs  $z$  implicit in the amount of water used. The term  $P_m(D-w)$  represents the cost incurred for buying water or the benefit of selling water in the market.

Participation of a producer in a water market is going to be influenced by all sources of risk and uncertainty. For example, if productive risk causes an excessive use of water, it can be assumed that it would reduce water supplied by sellers in the market, and increase water demanded by buyers. This is true as long as the market price for water is not greater (smaller) than the disutility for the producer that participates as a seller (buyer).

Turner and Perry (1997) analyse the hypothetical effect of uncertainty regarding water availability in the amount of water supplied by Oregon farmers for environmental purposes. Their empirical analysis focuses on how uncertainty influences the adoption of water saving strategies by farmers, so they can sell it on a market. Turner and Perry (1997) do not analyse the behaviour of potential buyers. Using recursive stochastic programming models, they conclude that if uncertainty is not considered in the modelling water supply is overestimated. Under uncertain water availability water supplied by sellers is therefore reduced.

In their previously mentioned paper, Howitt and Taylor (1993) assume that variability of allotments transforms into variability of the opportunity cost of water. In a competitive water market, the cost of using water for production is given by its market price, the purchase cost for the buyer and the opportunity cost for the seller that does not sell it. In such context, a change in allotment implies a change in market price only if it affects all users.

In this sense, it is important to clarify some points regarding the effect of allotment  $D$ . The amount of water available for a user determines the shadow price for water, and therefore her willingness to pay and to accept. An increase in water allotment, *ceteris paribus*, does not imply a change in the optimal amount of water used by a buyer, but increases the amount sold in the market (Dinar and Letey, 1991; Weinberg et al., 1995). Similarly, an increase in allotment reduces the amount to be bought in the market. The underlying assumption, that the market price does not change, is clearly unrealistic, as it is assumed that only the allotment of the producer considered changes. In practice, it can be expected that a significant variation in water availability affects market price for water, and therefore the optimal level of water use.

This implies that, assuming uncertainty regarding allotment  $D$ , but certainty regarding price for water, the optimal water use is identical to the case of certain water availability. However, if uncertainty about water allotment implies uncertainty regarding market price for water, then optimal production decisions differ from those taken under certainty.

For a risk-neutral producer first order conditions are given as:

$$\pi'(w) = E[P_m] \quad [3]$$

The existence of a market for water eliminates the effect of uncertainty regarding allotment  $D$ , as it transfers the uncertainty to the price of water to be formed in the market place. The problem is then reduced to that in which input price is uncertain. In reality, uncertainty about water availability still has an indirect influence, as water scarcity is what determines the market price for water, but as far as the analysis is concerned it does not.

The effect of uncertain input prices has been studied by Turnovsky (1969), Batra and Ullah (1974) and Blair (1974). Their main conclusion is that, under uncertainty regarding input price, input use and output are less (more) for a risk-averse (lover) producer than in absence of uncertainty. Batra and Ullah (1974) also show that under DARA, the effect of an increase in uncertainty (mean-preserving spread of the PDF) is a decrease in input use. An increasing variance-preserving spread is identical to an increase in input price under certainty.

In the following analysis it is assumed that a risk-averse producer faces uncertainty regarding water availability and therefore also regarding the market price for water. The producer has to decide the amount of water to use, and therefore the amount of water to buy or sell in the market. The risk-averse producer maximises its expected utility without being certain of the price of water, which is a random variable (probability distribution known), as:

$$\text{Max}_w E[U(\pi_m(w))] = E[U(\pi(w) - P_m(w-D))] \quad [4]$$

First order conditions for problem [4], that are derived in the appendix, imply that expected utility is maximised when marginal profit derived of the productive water use is more (less) than the expected market price for water. Under water price uncertainty, a producer that decides to use more water than its known allotment (a buyer) will use less water than it would under certainty for a price equals to  $E[P_m]$ . On the other hand, a producer that decides not to use her full allotment (a seller) will use more water than it would under certainty for a price equal to  $E[P_m]$ . This result is consistent with those of Batra and Ullah (1974) and Howitt and Taylor (1993). The result in the case of the sellers is also similar to the empirical results obtained by Turner and Perry (1997) for risk-neutral farmers. If buyers use less water than in absence of uncertainty, demanding less water, and sellers use more, supplying less, then the effect of uncertainty is a shift to the left in both water demand and supply. As a result, market activity is reduced. The effect on price is undetermined.

First order conditions imply that a producer takes initial production decisions such that the optimal water use is  $w_I^*$ , expecting to buy or sell an amount  $w_I^*-D$  in the water market. Such initial decisions determine the new restricted profit function, which can be expressed as:

$$\pi(w/w_I^*), \text{ where } \partial\pi(w/w_I^*)/\partial w \leq \partial\pi(w)/\partial w \quad [5]$$

Once uncertainty is resolved, allotment  $D_f$  and market price for water  $P_{mf}$  are known. Then the producer faces a problem that can be expressed as:

$$\text{Max}_w \pi(w/w_I^*) - P_{mf}(w-D_f) \quad [6]$$

First order conditions are given as:

$$\pi'(w/w_I^*) = P_{mf} \quad [7]$$

#### **4. Modelling Framework**

Some authors have criticised the excessive importance given in the literature to accounting for risk aversion in farm modelling with respect to other issues such as the inclusion of tactical responses or the characterisation of probability distributions (Hardaker et al., 1991; Pannell and Nordblom, 1998; Hardaker, 2000; Pannell et al., 2000; and Lien and Hardaker, 2001). According to their view, farmers are not that much interested in avoiding the risks they face, what is not always possible, as in foreseeing its effects and responding tactically by modifying their initial decisions as uncertainty is resolved (Marshall et al., 1997). This is independent of their attitudes toward risk. Even a risk-neutral farmer bears a cost from resource variability (Babcock and Shogren, 1995), so he is interested in responding to reduce such cost. This can be accounted for including tactical responses in farm programming models. In the case of uncertain water availability possible responses are changes in water applications to crops, crop abandonment, purchasing water, etc.

Pannell et al. (2000) review studies that deal with the inclusion of tactical responses in farm modelling using discrete stochastic programming. The inclusion of the possibility of tactically adjusting production decisions results in an increase in expected profit ranging between 10 and 20%. On the other hand, including risk aversion reduces expected profit between 1 and 3%. The reason is that the profit function is flat near the optimum, so risk aversion modifies optimal decisions but barely affects results in terms of farmers' welfare. For discrete variables the effect of risk aversion is usually larger. This means the welfare improvement effect of risk avoidance is relatively small (Pannell et al., 2000).

Modelling tactical responses has a greater effect on model output because such responses tend to occur in extreme situations, when the effect of variability in expected profit is much greater than the effect of risk, and decisions are modified to a larger extent than if risk aversion alone is considered (Hardaker et al., 1991; Babcock and Shogren, 1995; Pannell et al., 2000). Incorporating risk aversion in a model affects production decisions, but does not improve substantially the results obtained with a model that assumes risk neutrality, at least if the objective is to evaluate policies or make recommendations (Lien and Hardaker, 2001). If the objective is to accurately predict behaviour, risk aversion is more important, but still secondary to other risk related issues such as tactical behaviour (Hardaker, 2000).

Uncertainty regarding water supply affects production decisions taken at the beginning of the cropping season, some of which can be later modified or adjusted. In such a situation, the key issue to consider is the set of possible strategies and tactical responses the producer can use as uncertainty is resolved. Entering a water market is not a marginal decision but a tactical response to face uncertainty relating water supply.

There is an important conceptual issue that arises when considering water uncertainty in a water market model. In spot water markets, as market price for water depends on water availability, uncertainty about allotments results in uncertainty about the market price for water. The problem is not that of uncertain resource availability but of uncertain input price.

Most studies dealing with water transfers in a context of water uncertainty analyse the effect of such uncertainty on farmer's willingness to accept for water to transfer it for non-agricultural uses (Taylor and Young, 1995; Turner and Perry, 1997; Willis and Whittlesey, 1998). They derive farmers' supply for water under uncertainty parameterising either the price of water (and computing the amount of water sold for each price) or water allotments (and computing dual values of water). None of them considers uncertainty in water price.

Such uncertainty has implications in the behaviour of farmers. Market participation is a tactical response to a surplus or deficit of water with respect to expected water available, and must be considered in the set of possible activities. If market outcome is to be simulated based on farmer's decisions, not only uncertainty regarding water availability but also regarding water price has to be considered. Otherwise, water exchanges would be simulated based on a behaviour that does not take into the account the possibility of entering the market.

Farmers' decisions in presence of uncertainty in water allotment and market price for water have been simulated using a Stochastic Programming with Recourse (SPR) modelling approach. Many authors coincide in that SPR or Discrete Stochastic Programming (DSP), as developed by Cocks (1968) and Rae (1971), is the most adequate method to represent resource uncertainty. It allows to simulate the sequential nature of productive decisions taken in a context of uncertainty regarding water availability (Turner and Perry, 1997). DSP has been used by Taylor and Young (1995), Turner and Perry (1997) and Keplinger et al. (1998) to model uncertainty in water available for production in irrigated agriculture.

Marshall et al. (1997) use the distribution method to analyse the optimal drainage recirculation strategy for a representative dairy farm in New South Wales in a context of uncertain water availability. They include the possibility of selling or purchasing water at an exogenous constant price as a tactical response but they do not model market exchanges.

Market equilibrium models are usually solved using endogenous price models, such as the ones developed by Enke (1951), Samuelson (1952) and Takayama and Judge (1964) to solve the problem of equilibrium in spatially separated markets. Such type of models have been used to simulate water allocation and water market exchanges in the papers by Flinn and Guise (1970), Vaux and Howitt (1984), Booker and Young (1994) and Becker (1995).

In this sense, the model used to simulate the water market maximizes economic surplus derived from market participation by all users, and can be written as:

$$\text{Max } \sum_i \left[ \int_0^{m_i^*} f_i(m_i) dm_i \right] \quad [8a]$$

$$\text{s.t: } \quad \Sigma_i m_i \leq 0 \quad [8b]$$

$$-m_i \leq D_i \quad \forall i \quad [8c]$$

where  $f_i(m_i)$  is the inverse demand function for water for user  $i$  (marginal profit);  $m_i = w_i - D_i$  is the amount of water bought ( $m_i > 0$ ) or sold ( $m_i < 0$ ) in the market by user  $i$ ;  $w_i$  is the total amount of water used by user  $i$ . First restriction forces market equilibrium making all amounts supplied greater or equal than amounts demanded. The second restriction impedes a user to sell in the market an amount of water greater than her allotment  $D_i$ . Market price for water is derived as the dual value of the first restriction.

This model yields an optimal allocation of water among users, that is equivalent to that of a central planner that knows each user's water demand function. Such allocation presents Kaldor-Hicks optimality with respect to the initial one in which each user can only use her initial allotment. If compensation among users takes places at the market equilibrium price, then the final allocation of water would be Pareto-optimal (Calatrava, 2002).

In the present study, only water supply risk has been considered. The analysis here is centred on uncertainty about water availability, the main risk-related issue of interest for farmers in the area, so other sources of risk are not included.

In the Guadalquivir River Basin, water allotment for farmers are usually determined in spring, after fall and winter rains, so uncertainty about water supply directly affects production decisions regarding crops that are planted on autumn (winter crops), and indirectly affects crops planted on spring through crop substitution effects. To account for this uncertainty on allotment and its effect on crop scheduling decisions two different stages are considered. On a first stage, crops are scheduled under uncertainty assuming perfect information with respect to the probability distribution of both water availability and water prices. On a second stage, farmers may, once the definitive allotment is known, modify to a certain extent those initial decisions. Winter crops considered are hard wheat, soft wheat, sugar beet, potato and garlic. The other crops are cotton, corn, sunflower, citrus and olive tree.

Decision variables are surface and water devoted to each crop in each stage. Surface devoted to winter crops on the first stage can not be modified, while surface devoted to the rest of the crops can be reallocated. If  $s$  denotes the state of nature and  $i$  denotes the farm, this problem can be stated as follows:

$$\text{Max } \sum_s \text{Prob}_s \pi_{is} \quad [9a]$$

Subject to:

$$-\pi_{is} + \sum_k S_2 S_{2iks} [F_k(w_{2iks})(P_k + UE_k - CRT_k) - C(S_{2ik}) - CR_k w_{2iks}] - CF_i - PM_s M_{2is} = 0 \quad \forall s \quad [9b]$$

$$\sum_k S_{1ik} \leq SAU_i \quad [9c]$$

$$\sum_k S_{2iks} \leq SAU_i \quad \forall s \quad [9d]$$

$$\sum_k S_{2iks} w_{2iks} - M_{2is} \leq SAU_i D_s \quad \forall s \quad [9e]$$

$$S_{1i} \text{ "fallow"} = \alpha S_{1i} \text{ "COP"} \quad [9f]$$

$$S_{2i} \text{ "fallow"}_s = \alpha S_{2i} \text{ "COP"}_s \quad \forall s \quad [9g]$$

$$S_{1i} \text{ "hard wheat"} \leq CTD_i SAU_i \quad [9h]$$

$$S_{1i} \text{ "winter"} = S_{2i} \text{ "winter"}_s \quad \forall s, k \in \text{"winter"} \quad [9i]$$

$$S_{1ik}, S_{2iks}, w_{1ik}, w_{2iks} \geq 0 \quad \forall k, s \quad [9j]$$

where:

$S_{1ik}$  is the area assigned on stage 1 by farm  $i$  to crop  $k$ ;

$S_{2iks}$  is the area assigned on stage 2 by farm  $i$  to crop  $k$  under state of nature  $s$ ;

$w_{1ik}$  is the amount of water applied on stage 1 by farm  $i$  to crop  $k$ ;

$w_{2iks}$  is the amount of water applied on stage 2 by farm  $i$  to crop  $k$  under state of nature  $s$

$F_k(w_{ik})$  is the crop-water response function for crop  $k$ ;

$P_k$  is market price for crop  $k$ ;

$UE_k$  is the per hectare UE payment for crop  $k$ ;

$C_{ik}(S_{ik})$  is the cost function for crop  $k$  and farm  $i$  (excludes irrigation, harvest, transportation and fixed costs);

$CRT_k$  are harvest and transportation costs for crop  $k$ ;

$CR_k$  are irrigation costs for crop  $k$ ;

$CF_i$  are fixed costs for farm  $i$ ;

$SAU_i$  is the total area of farm  $i$ ;

$\text{Prob}_s$  is the probability of state of nature  $s$ ;

$D_s$  is water allotment per hectare under state of nature  $s$ ;

$PM_s$  is market price for water under state of nature  $s$ ;

$M_{2is}$  is the amount of water traded in the market in stage 2 by farm  $i$  under state of nature  $s$ ;

$\alpha$  is the percentage of land devoted to set-aside in order to receive the area payments;

$CTD_i$  is hard wheat quota for farm  $i$  in proportional terms.

If only uncertainty in water availability was considered, expressions [9b] and [9e] can be rewritten as:

$$-\pi_{is} + \sum_k S_2 S_{2iks} [F_k(w_{2iks})(P_k + UE_k - CRT_k) - C_{ik}(S_{ik}) - CR_k w_{2iks}] - CF_i = 0 \quad \forall s \quad [9b]$$

$$\sum_k S_{2iks} w_{2iks} \leq SAU_i D_s \quad \forall s \quad [9e]$$

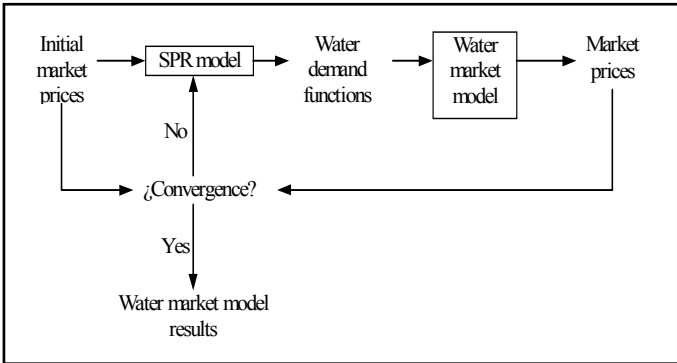


The farm model has been calibrated to observed crop schedules for each farm type using Positive Mathematical Programming (Howitt, 1995). The previous model determines optimal decisions for stage 1. A second model is used to derive inverse water demand functions for each farm. This model takes those initial decisions as given and computes optimal second stage decisions for different water allotments ranging from 0 to 10,000 m<sup>3</sup>/ha, but without considering costs or revenues from the water market. That is, the model obtains the profit derived from the optimal crop schedule for each possible level of water use. From these profit functions inverse water demand functions are obtained and used to simulate water exchanges in the market using a spatial equilibrium model such as the one in [8].

The water market model provides with the optimal allocation of water for each level of water availability ( $D$ ), that is the amount of water bought or sold by each farm ( $m_i$ ) and the equilibrium price for water ( $P_m$ ). Profit from water use is calculated from the previously estimated profit functions using the amount of water used ( $SAU_iD + m_i$ ) as argument; revenue or cost from selling or buying water in the market is calculated as  $-m_iP_m$ . Their sum is the total profit for each farm.

The problem is which values to assign to the  $PM_s$  parameter (market price for water under each state of nature) in the decision model, as this price is clearly endogenous in the problem. No data about real market prices are available. Beare et al. (1999) use a pricing mechanism that determine water prices as a function of water availability. As perfect information has been assumed, an iterative process can be used instead to solve this problem, process commented below and depicted in figure 1.

Figure 1



First, some initial values for water price under each state of nature are used to characterise uncertainty regarding water price. Then the farm model is run using those initial prices and profit and inverse water demand functions are obtained. Market exchanges are simulated using those functions, and the equilibrium prices obtained are used to characterise uncertainty in the farm model. This process is repeated until prices obtained from the market model converge to those used in the model from which demand functions were derived. The convergence criteria is that market prices obtained for each state of nature differ in less than 0.001 euros/m<sup>3</sup> from those prices used to characterise uncertainty in the SPR model.

The empirical application has been performed on eleven irrigated farms belonging to an irrigation district in the Guadalquivir River Basin (Southern Spain). Farms range from 2 to 188 hectares and differ on their fixed assets, irrigation technologies and cropping patterns.

Water uncertainty has been characterised using data, from the period 1978-2000, on water stocks and releases for the dam from which the irrigation district is served and individual water allotments. At stage 1 (autumn), the level of water stored in the dam is in its lower yearly levels. When this level is above 60 Hm<sup>3</sup> the final allotment available for farmers when the irrigation season starts (in spring) can be determined with a 99% probability. For levels below 60 Hm<sup>3</sup> water supply reliability is very low, as the final allotment depends

entirely on winter rains which are subject to high variability. Table 1 shows the two scenarios of uncertainty in allotment depending on the dam stock level at the beginning of autumn. Modelling has been performed for both scenarios, and solved using CONOPT2 of GAMS.

Table 1. Scenarios of water uncertainty within a season.

Scenario 1 Stock < 40 Hm <sup>3</sup>		Scenario 2 40 Hm <sup>3</sup> < Stock < 60 Hm <sup>3</sup>	
Allotment (m <sup>3</sup> /ha)	Probability	Allotment (m <sup>3</sup> /ha)	Probability
4,900	0.250	5,500	0.4445
4,500	0.125	5,200	0.1111
4,000	0.125	4,500	0.2222
3,000	0.250	3,100	0.2222
500	0.125		
0	0.125		

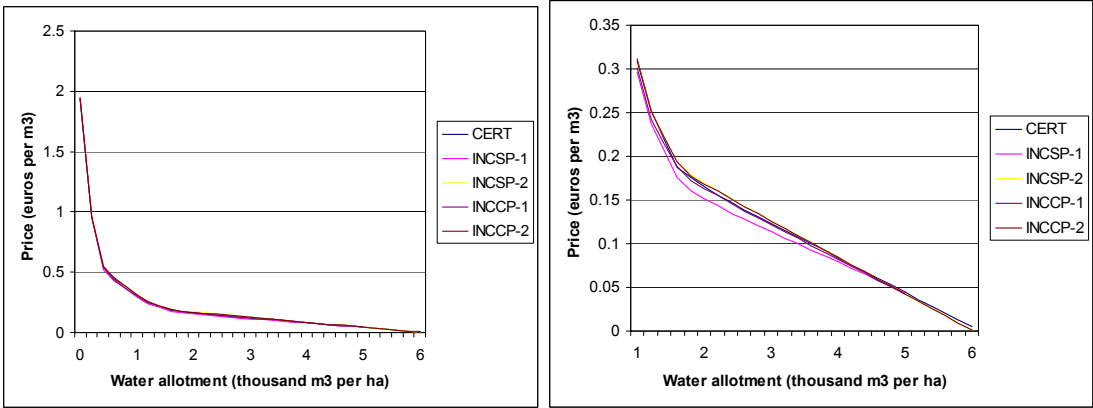
**5. Results**

Results from the SPR model that includes market participation as a tactical response (INCCP model) are compared with results from other two models: the first one is a certainty model in which allocation decisions are taken in absence of uncertainty (CERT model); the second is a SPR model in which only uncertainty regarding water availability has been considered (INCSP model; uncertainty in water price not considered). These three models provide profit and inverse water demand functions under different modelling assumptions that are used to simulate market exchanges. The results presented here refer to market outcome for each model assumption (shown on table 2). Due to space limitations some of the results cannot be shown and will be just commented to focus on the most important results, those of the market. They are shown in a longer version of the paper.

Table 2. Models and assumptions.

Model	Uncertainty regarding water availability	Market as a tactical response (price uncertainty)	Scenario of uncertainty (shown in table 2)
CERT	NO	NO	None
INCSP-1	YES	NO	1
INCSP-2	YES	NO	2
INCCP-1	YES	YES	1
INCCP-2	YES	YES	2

Figure 2. Market equilibrium price for water (full allotment range and detail)



Profits obtained for each level of water availability are higher for the model CERT (absence of uncertainty) than for the other models. When the option to participate in the water

market is included as a tactical response profit increases with respect to when only water uncertainty without tactical response is considered. Profits are also lower for uncertainty scenario 1 than for scenario 2. Patterns for the rest of the farms are similar. Water demand functions obtained are more inelastic under uncertainty.

Equilibrium prices for water are similar for all models as it can be seen in figure 3. Only for model INCSP-1 (tactical response not included and uncertainty scenario 1) water prices are clearly lower. When uncertainty is higher, production decisions result in lower marginal profits from water use and water is less valued, therefore reducing its scarcity price. If water market is included as a tactical response then decisions result in higher water values and equilibrium price raise to similar levels than in absence of uncertainty. Table 3 shows market positions for all farm types and levels of water allotment.

Table 3. Market positions for all farms and models.

Allotment ( $10^3\text{m}^3/\text{ha}$ )	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
0,1	S*	S*	S*	S*	S*	S*	S*	S*	S*	B	B
1	S*	S*	S*	S*	S*	S*	B	B	B	B	B
2	S*	S	B	B	S	S*	B	B	B	B	B
3	S	S	B	B	S	S	B	B	B	B	B
4	S	S	B	B	S	S	B	B	B	B	B
5	B	B	B	B	S	S	S	S	S	B	B
6	B	B	B	S	S	S	S	S	S	B	B

Nota: S denotes seller; B denotes buyer; S\* means the whole allotment is sold. In the six framed values market position is switched to buyer in those models with tactical response.

Table 4. Percentage of total water available in the Irrigation district exchanged in the market for each level of water allotment (all models).

Allotment <sup>1</sup>	Water available in the whole ID <sup>2</sup>	CERT	INCSP-1	INCSP-2	INCCP-1	INCCP-2
0	0	0	0	0	0	0,00
0.2	1.226	92.82	92.82	92.82	92.82	92.82
1	6.129	67.96	67.96	67.96	67.96	67.96
2	12.258	40.93	42.46	39.53	39.66	39.54
3	18.387	20.59	22.49	18.79	19.02	18.83
4	24.516	10.07	10.47	8.94	9.36	9.05
5	30.645	5.67	6.10	4.16	4.64	4.42
6	36.777	5.30		4.01		4.28

<sup>1</sup> Thousand  $\text{m}^3/\text{ha}$ . <sup>2</sup>  $\text{Hm}^3$

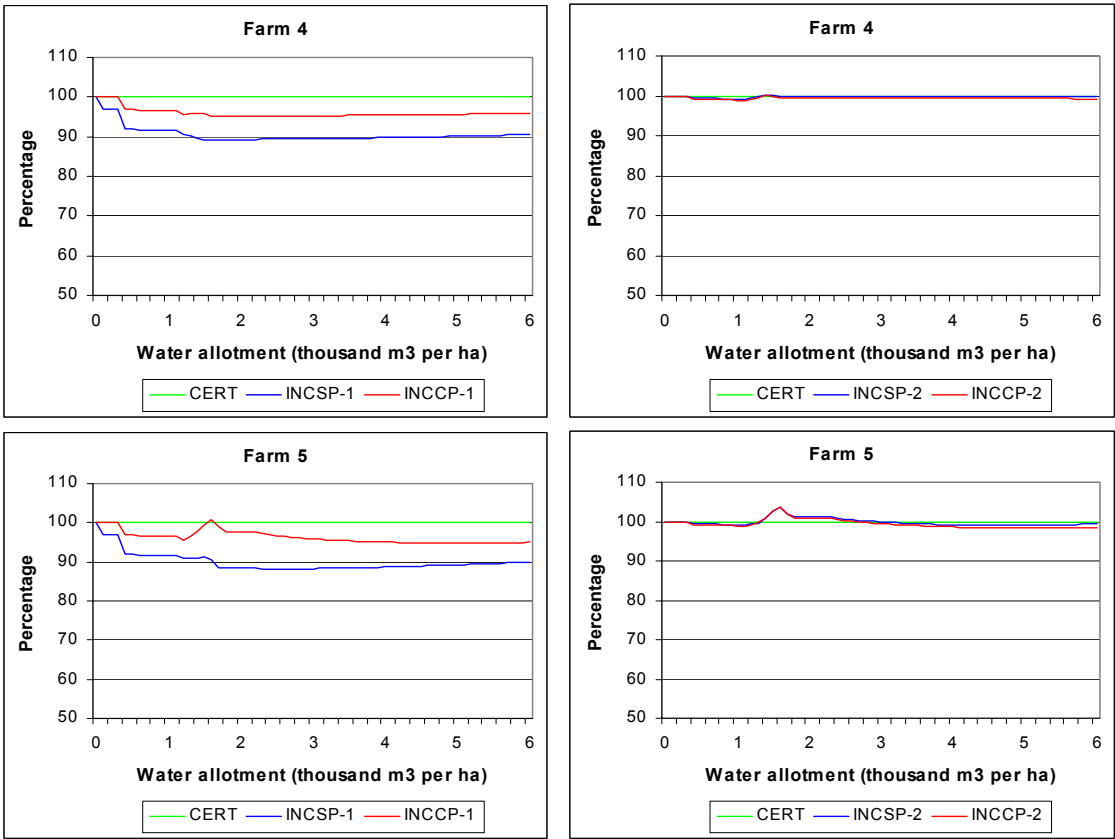
Table 4 shows the percentage of total water available exchanged in the market for each model and uncertainty scenario. Exchanges are higher for low levels of water availability, when differences in marginal values of water are greater. For allotment levels above  $4200 \text{ m}^3/\text{ha}$  (mean allotment), exchanged volumes represent less than 10% of total water availability. This is consistent with the literature on water markets, in the sense that in years of normal availability market activity is reduced. Uncertainty slightly reduces market activity.

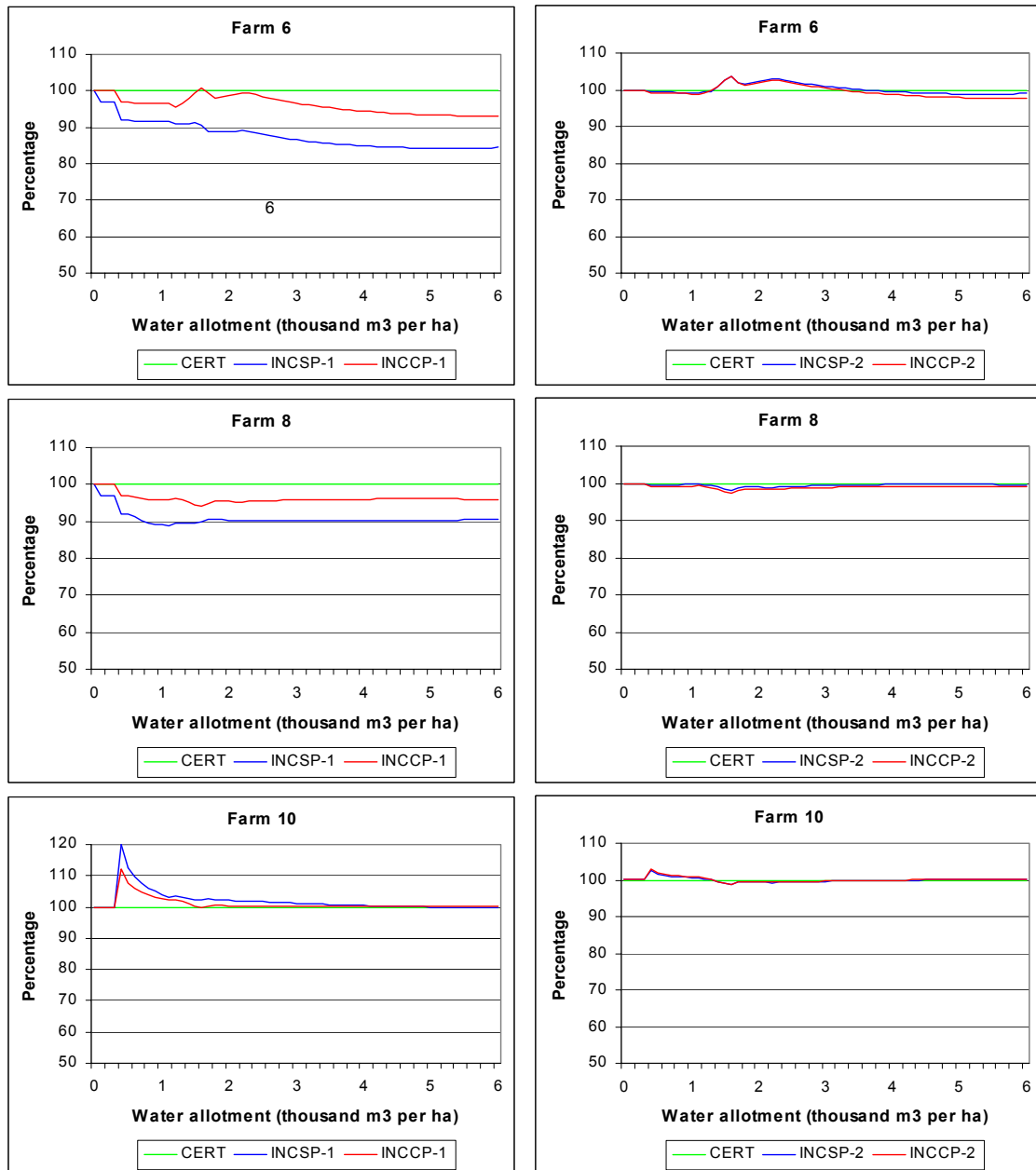
With respect to profits achieved by farms through market participation, the model without uncertainty (CERT) provides smaller percent increases of profit. The models with market included as a tactical response result in higher percent profit increases than model that only consider uncertainty in water supply. That is, considering the possibility of entering the market as a tactical response results in production decisions that improve the potential of water markets to increase farm profits. From a decisional point of view, the possibility of entering an ex-post water market reduces the perception farmers have about water availability risk, reducing the effect of uncertainty on production decisions. Furthermore, this effect is greater under uncertainty scenario 1 (higher uncertainty).

Similar conclusions can be derived from figures 3, that show the level of profits achieved through the water market under each scenario and model assumption for each level of water allotment. Profits are expressed as a percentage of the profit obtained from the model without uncertainty (CERT, represented by a green flat line at level 100%). For reasons of space figures corresponding to some of the farms, whose patterns are similar to those shown have been skipped. Differences found among farms and scenarios deserve some comments.

Under uncertainty scenario 1, profit is generally below that of model CERT. Profits when market has been considered as a tactical response (model INCCP-1) are greater than profits when it has not (model INCSP-1). In some cases, differences are small, but in others, as for farms 5 and 6, inclusion of the market as a tactical response allows to eliminate most of the negative effect that uncertainty has on decisions and profit achievable through the water market. There is one exception to this general pattern. Farms 10 and 11 present higher profit with than without uncertainty. The reason is that the stochastic decision model does not allow them to reallocate their land among crops as all their area is permanently devoted to citrus and olive trees respectively. The effect of uncertainty over their market profits is indirectly given by the effect of such uncertainty on the rest 9 farms and therefore on the market equilibrium and outcome. For model INCSP-1 uncertainty reduces market profit for the other 9 farms that take less efficient decisions than under certainty, and market price is reduced. As farms 10 and 11 are always water buyers, this allows them to increase their market profit as they purchase water at a lower price. For model INCCP-1 the other 9 farms take more adequate production decisions and water is more valuable. Then farms 10 and 11 buy water more expensively and their profit gets reduced. For uncertainty scenario 2, differences among models are slight, being the effect of uncertainty and modelling assumptions very small.

Figures 3. Water market profits for each assumption and scenario considered (percentages of profit in absence of uncertainty CERT=100).





## 6. Conclusions

It has been shown analytically that the possibility of entering a spot water market eliminates the effect of the uncertainty directly derived from variable water availability. It influences production decisions taken by a risk-averse producer indirectly through its effect on market price for water. If ex-ante production decisions by a market participant are considered, buyers will tend to use less water in the optimum and sellers will tend to use more water than in absence of uncertainty. As a result, both water demanded by buyers and water supplied by sellers are reduced and become more inelastic. Once uncertainty is resolved, the farmer can modify her initial production decisions, to reduce water use and sell it or to increase water use by entering the market as a buyer.

The main conclusion of the empirical application is methodological and relates to the inclusion of the possibility of participating in the market at an uncertain price as a tactical response available for farmers. It has been shown that farmers' profits are smaller the greater uncertainty is. If water markets are introduced as a tactical response in decision models then profits achieved through the market are greater than if only water uncertainty is modelled,

specially when uncertainty is higher. This result proves that hypothetical estimations of potential gains from trading water may be undervalued, as they do not include the option to participate in them as a strategy in the decision process from which market participants' behaviour is derived.

There is a clear implication from the strategic point of view in the results obtained. Risk derived from taking production decisions under uncertain water supply gets reduced if farmers can enter an ex-post water market to complete their allotment or to sell surplus water, even at an uncertain price, as initial production decisions are more adequate.

The inclusion of the tactical behaviour reduces the negative effect of uncertainty in terms of profit, making the resource more valuable, increasing water prices and reducing water exchanges. This favours those farms with annual crops, the ones more affected by uncertainty, specially those that are big water sellers. For farmers with permanent crops, who are potential water buyers, the inclusion of the water market as a tactical response worsens their market profits as the other farms respond more adequately to uncertainty and the resource gets more expensive. It can be said that uncertainty benefits those producers that are not affected by it and that, if the other farmers' decisions are not properly modelled, profit achieved by the former is overvalued.

In sum, it has been shown both theoretically and empirically that annual spot water markets allow reducing economic vulnerability for farmers derived from variability and uncertainty regarding water supply. If something is to be highlighted is the need to further analyse how the economic organisation of agriculture, and specially the access to productive resources, affects the economic risk faced by farmers. The existence of water markets in agriculture is a change, whose consequences go beyond the mere welfare increase. The possibility to exchange water re-orientates farmers' decisions in a double way: it allows them to sell surplus water or to complete their allotment, but it also forces them to reconsider the profitability of all farm activities. The more relevant conclusions refer precisely to the implications of strategic nature that water markets have for users that operate in a context of water scarcity and, more importantly, of great uncertainty.

### **Appendix. Expected utility maximisation by a participant in a spot water market.**

Expected utility of profit for a participant in a spot water market can be expressed as:

$$E[U(\pi_m(w))] = E[U(\pi(w) - P_m(w-D))] \quad [a1]$$

First order conditions are derived in a similar fashion to those for the problem of maximising expected utility of a producer under output price uncertainty (Sandmo, 1971; Silberberg, 1990) and under water availability uncertainty (Howitt and Taylor, 1993).

Taking derivatives in [a1], first order conditions are derived:

$$E[U'(\pi_m)(\pi'(w) - P_m)] = 0 \quad [a2]$$

Factoring condition [a2]:

$$E[U'(\pi_m)\pi'(w)] = E[U'(\pi_m)P_m] \quad [a3]$$

Subtracting  $E[U'(\pi_m) \bar{P}_m]$  from both sides of expression [a3]:

$$E[U'(\pi_m)(\pi'(w) - \bar{P}_m)] = E[U'(\pi_m)(P_m - \bar{P}_m)] \quad [a4]$$

Since  $E(\pi_m) = \pi(w) - \bar{P}_m(w-D)$ , adding  $(\bar{P}_m - P_m)(w-D)$  to both sides of this expression:

$$E(\pi_m) + (\bar{P}_m - P_m)(w-D) = \pi(w) - \bar{P}_m(w-D) + (\bar{P}_m - P_m)(w-D) \quad [a5]$$

$$E(\pi_m) + (\bar{P}_m - P_m)(w-D) = \pi(w) - P_m(w-D) = \pi_m \quad [a6]$$

where:

$$\pi_m = E(\pi_m) + (\bar{P}_m - P_m)(w-D) \quad [a7]$$

If  $\bar{P}_m > P_m$  and  $w > D$ , then  $\pi_m > E(\pi_m)$ , and, from the properties of the utility function,  $U'(\pi_m) < U'(E(\pi_m))$ , and therefore:

$$U'(\pi_m)(\bar{P}_m - P_m) < U'(E(\pi_m))(\bar{P}_m - P_m) \quad [a8]$$

[a8] also holds for  $\bar{P}_m < P_m$  and  $w > D$ .

For  $w < D$ , and any possible value of  $(\bar{P}_m - P_m)$ , then:

$$U'(\pi_m)(\bar{P}_m - P_m) > U'(E(\pi_m))(\bar{P}_m - P_m) \quad [\text{a9}]$$

From expressions [a8] and [a2.38] are obtained [a10] and [a11] respectively:

$$E[U'(\pi_m)(\bar{P}_m - P_m)] < U'(E(\pi_m))E(\bar{P}_m - P_m) \quad [\text{a10}]$$

$$E[U'(\pi_m)(\bar{P}_m - P_m)] > U'(E(\pi_m))E(\bar{P}_m - P_m) \quad [\text{a11}]$$

As  $E(\bar{P}_m - P_m) = 0$ , the [a10] and [a11] imply conditions [a12] and [a13] respectively:

$$E[U'(\pi_m)(\bar{P}_m - P_m)] < 0 \quad [\text{a12}]$$

$$E[U'(\pi_m)(\bar{P}_m - P_m)] > 0 \quad [\text{a13}]$$

Substituting [a12] and [a13] in [a4], expressions [a14] and [a15] are respectively obtained:

$$E[U'(\pi_m)(\pi'(w) - \bar{P}_m)] > 0 \quad \text{for } w > D \quad [\text{a14}]$$

$$E[U'(\pi_m)(\pi'(w) - \bar{P}_m)] < 0 \quad \text{for } w < D \quad [\text{a15}]$$

Implying that:

$$\pi'(w) > \bar{P}_m \quad \text{for } w > D \quad [\text{a16}]$$

$$\pi'(w) < \bar{P}_m \quad \text{for } w < D \quad [\text{a17}]$$

## References.

- Anderson, J.R., Dillon, J.L. and Hardaker, B. (1977). *Agricultural decision analysis*. Iowa State University Press, Ames. 344 pp.
- Antle, J.M. (1983). Incorporating Risk in Production Analysis. *American Journal of Agricultural Economics* **65**(5): 1099-1106.
- Babcock, B. A. and Shogren, J.F. (1995). The cost of agricultural production risk. *Agricultural Economics* **12**(2): 141-150.
- Batra, R.N. and Ullah, A. (1974). Competitive firm and the theory of input demand under price uncertainty. *Journal of Political Economy* **82** (3): 537-548.
- Beare, S.C., Bell, R. and Fisher, B.S. (1998). Determining the value of water: the role of risk, infrastructure constraints and ownership. *American Journal of Agricultural Economics* **80** (5): 916-940.
- Becker, N. (1995). Value of moving from central planning to a market system: lessons from the Israeli water sector. *Agricultural Economics* **12** (1): 11-21.
- Blair, R.D. (1974). Random input prices and the theory of the firm. *Economic Inquiry* **2** (3): 214-225.
- Booker, J.F. and Young, R.A. (1994). Modeling Intrastate and Interstate Markets for Colorado River Water Resources. *Journal of Environmental Economics and Management* **26**(1): 66-87.
- Calatrava, J. (2002). *Los mercados de agua en la agricultura y el riesgo económico: Una aplicación en el valle del Guadalquivir*. Doctoral dissertation. Department of Agricultural Economics, Universidad Politécnica de Madrid.
- Cocks, K.D. (1968). Discrete Stochastic Programming. *Management Science* **15**: 72-79.
- Cornes, R. (1992). *Duality and modern economics*. Cambridge University Press. Cambridge. 290 pp.
- Chambers, R.G. (1983). Risk in Agricultural Production: Discussion. *American Journal of Agricultural Economics* **65**(5): 1114-1115.
- Chambers, R.G. (1988). *Applied production analysis*. Cambridge Univ. Press. Cambridge. 331 pp.
- Dinar, A. and Letey, J. (1991). Agricultural water marketing, allocative efficiency and drainage reduction. *Journal of Environmental Economics and Management* **20**: 210-223.
- Easter, K.W., Rosegrant, M.W. and Dinar, A. (eds) (1998). *Markets for Water: Potential and Performance*. Kluwer Academic Publishers, Boston, 297 pp.
- Enke, S. (1951). Equilibrium between spatially separate markets: solution by electric analogue. *Econometrica* **19**: 40-47.
- Flinn, J.C. and Guise, J.W.B. (1970). An application of spatial equilibrium analysis to water resource allocation. *Water Resources Research* **6**(2): 398-409.
- Hardaker, J.B. (2000). *Some issues in dealing with risk in agriculture*. Working Paper 2000-3. School of Agricultural and Resource Economics, University of New England, Armidale.
- Hardaker, J.B., Pandey, S. and Patten, L.H. (1991). Farm planning under uncertainty: a review of

- alternative programming models. *Review of Marketing and Agricultural Economics* **59**(1): 9-22.
- Howitt, R. (1998). Spot prices, option prices, and water markets: an analysis of emerging markets in California, en K. W. Easter, M. Rosegrant and A. Dinar, eds., *Markets for Water: Potential and performance*. Kluwer Academic Publishers, New York.
- Howitt, R. and Taylor, C.R. (1993). Some Microeconomics of Agricultural Resource Use. In G.A. Carlson, D. Zilberman and J.A. Miranowski, editores, *Agricultural and Environmental Resource Economics*. Oxford University Press, Oxford.
- Just, R.E. (1975). Risk aversion under profit maximization. *American Journal of Agricultural Economics* **57**(2): 347-352.
- Keplinger, K.O., McCarl, B.A., Chowdhury, M.E. and Lacewell, R.D. (1998). Economic and Hydrologic Implications of Suspending Irrigation in Dry Years. *Journal of Agricultural and Resource Economics* **23**(1): 195-205.
- Lien, G. and Hardaker, J.B. (2001). Whole-farm planning under uncertainty: impacts of subsidy scheme and utility function on portfolio choice in Norwegian agriculture. *European Review of Agricultural Economics* **28**(1): 17-36.
- Marshall, G.R., Jones, R.E. and Wall, L.M. (1997). Tactical opportunities, risk attitude and choice of farming strategy: an application of the distribution method. *Australian Journal of Agricultural and Resource Economics* **41**(4): 499-519.
- Miller, K.A. (1996). Water Banking to Manage Supply Variability. In D.C. Hall, ed., *Advances in the Economics of Environmental Resources, Vol. 1: Marginal Cost Rate Design and Wholesale Water Markets*. JAI Press, Greenwich. 224 pp.
- Pannell, D.J. and Nordblom, T.L. (1998). Impact of risk aversion on whole-farm management in Syria. *Australian Journal of Agricultural and Resource Economics* **42**: 227-247.
- Pannell, D.J., Malcolm, B. and Kingwell, R.S. (2000). Are we risking too much? Perspectives in farm modelling. *Agricultural Economics* **23**(1): 69-78.
- Rae, A.N. (1971). Problem Stochastic Programming, Utility, and Sequential Decision Problems in Farm Management. *American Journal of Agricultural Economics* **53**(3): 448-460.
- 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.
- Samuelson, P.A. (1952). Spatial price equilibrium and linear programming. *American Economic Review* **42**(2): 283-303.
- Sandmo, A. (1971). On the Theory of the Competitive Firm under Price Uncertainty. *American Economic Review* **61**(1): 65-73.
- Silberberg, E. (1990). *The structure of economics: A mathematical analysis*. 2ª edición. McGraw-Hill, New York. 686 pp.
- Takayama, T. and Judge, G.C. (1964). Spatial equilibrium and quadratic programming. *Journal of Farm Economics* **46**(1): 67-93.
- Taylor, R. G. and Young, R.A. (1995). Rural-to-urban water transfers: measuring direct foregone benefits of irrigation water under uncertain water supplies. *Journal of Agricultural and Resource Economics* **20**(2): 247-262.
- Turner, B. and Perry, G.M. (1997). Agricultural to instream water transfers under uncertain water availability: a case study of the Deschutes river, Oregon. *Journal of Agricultural and Resource Economics* **22**(2): 208-221.
- Turnovsky, S.J. (1969). The behaviour of a competitive firm with uncertainty in factor markets. *New Zealand Economic Papers* **3**(1): 52-58.
- Vaux, H.J. and Howitt, R.E. (1984). Managing Water Scarcity: An Evaluation of Interregional Transfers. *Water Resources Research* **20**(7): 785-792.
- Weinberg, M., C. L. Kling, and Wilen, J.E. (1995). Water markets and water quality. *American Journal of Agricultural Economics* **75**(2): 278-291.
- Willis, D.B. and Whittlesey, N.K. (1998). Water Management Policies for Streamflow Augmentation in an Irrigated River Basin. *Journal of Agricultural and Resource Economics* **23**(1): 170-190.