Stakeholder involvement in water management using Object-oriented Bayesian networks and economic models in Spain.

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1. Introduction and context

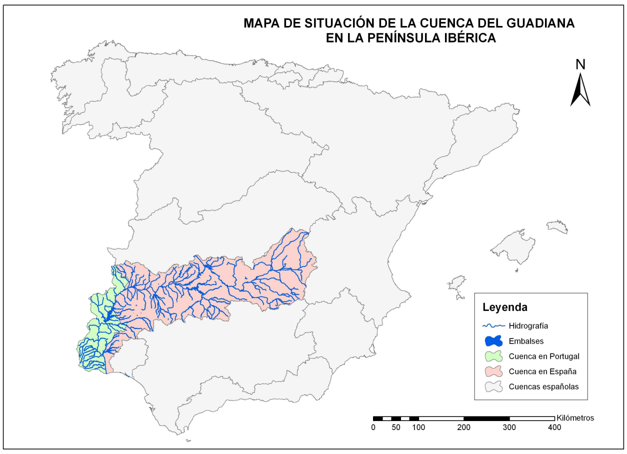
To meet an ever increasing demand for water, many arid and semiarid countries have in the past few decades been encouraged to develop ground water resources on an intensive basis. Ground water exploitation has traditionally been undertaken by individual farmers, with minimum public involvement (Llamas and Martinez-Santos 2005). In some cases uncontrolled expansion has lead to the over exploitation of the groundwater resource, a situation that has been allowed to develop largely through the lack of coordination between water administrators and water users (Fornés et al. 2005).

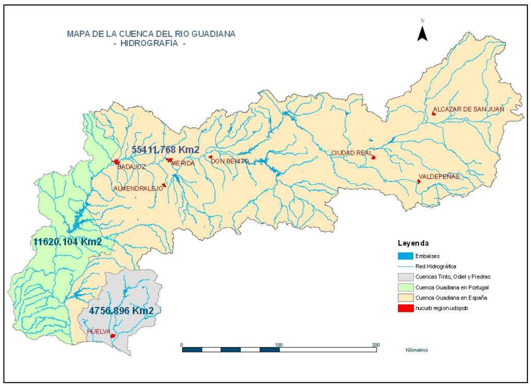
In order to develop sustainable management agendas to help cope with the challenges posed by these overexploited areas the implementation of integrated water resource management policies has been encouraged In Europe this has been accomplished through the implementation of the Water Framework Directive (WFD) in 2000. The WFD fully endorses the concept of "Integrated Water Resources Management" (IWRM) and represents a change in the way that water resource issues are handled (Pahl-Wostl et al. 2008).

Study area: the conflict between irrigation development and environmental sustainability

The Upper Guadiana basin covers an area of 18,900 km^2, and is situated in the central plateau of Spain (see Figure 1).

Figure 1 Location of the Guadiana basin





SOURCE: Confederación Hidrográfica del Guadiana

The climate in this area shows a low annual precipitation, unevenly distributed throughout the year. Agriculture is the main water user, accounting for 90-95% of total water consumption. But the region is also has sites of environmental importance. The catchment contains wetlands which have been declared *biosphere reserve* by UNESCO, and protected by the RAMSAR convention because of their rich biodiversity (De la Hera 2002). Ground water is the major source of water supply both for agriculture and domestic use.

In the past few decades extensive development of irrigation has taken place, encouraged, among other factors, by the decrease in drilling costs and by the use of EU subsidies that have encouraged high value water intensive crop production (Varela-Ortega et al. 1998, Varela-Ortega et al. 2003). This has led to important socio-economic development of the area, but also to the over-exploitation of the Western Mancha aquifer and to serious damage to environmentally important sites, especially the internationally renowned 'Tablas de Daimiel' wetlands (Coleto et al. 2003).

In an attempt to control water abstractions, annual water exploitation plans have been implemented since 1989 but these have met with stiff social opposition, low compliance rates from farmers and high social and administrative costs (Varela-Ortega 2007). The current situation is mired in uncertainty and confusion. There is conflict between stakeholder groups, a high unknown number of illegal wells are scattered throughout the region and there is uncertainty regarding the real volume of water abstracted from the aquifer. None of this is conducive to effective groundwater management. In recent years, since the WFD came into effect, European legislation has served to reinforce national regulations and may help to reduce social cost (Varela-Ortega 2007). In this context, a new water management plan has been developed at regional level (C.H.G. 2007a), which considers new management solutions to deal with the situation.

2. Overview of participatory tools for decision making

In the Upper Guadiana basin, water managers face a problem regarding how to best manage the resource in the face of many conflicting interests and the uncertainty surrounding the potential impacts of different strategies. What is required is a Decision Support System (DSS) that enables them to simultaneously evaluate the impacts of optional strategies over a wide range of factors (economic, social, environmental). At the same time the design of the system requires the active involvement of all relevant stakeholder groups in order to foster a sense of ownership of the decision making process (Gurung et al. 2006, Lynam et al. 2007).

Some DSSs used in participation activities are based on multicriteria analysis, where stakeholder involvement may be needed to identify all possible management options and related indicators in order to select the most appropriate option (Giupponi et al. 2004, Mysiak et al. 2005). The Analytical Hierarchy Process (AHP) is one of the most widely used multicriteria analysis-based methods to address complex situations (Saaty 1990, Moreno-Jiménez 2002). Stakeholders participate in the process by quantifying preferences for different criteria (Parra-López et al. 2005). An alternative approach is multi-objective optimisation (MOO), a type of decision support system that elicits utility functions and the assignment of weights to the various attributes in the system from participating stakeholders (Marchamalo and Romero 2007, van Calker et al. 2006).

Finally, there are Bayesian networks (BN); these are DSS based on Bayes' probability theory, especially suited to the simulation of systems in which uncertainty is present due to imperfect or incomplete knowledge. They can be built with the participation of stakeholders, and have long been applied in fields such as medicine and artificial intelligence but only more recently in natural resources management (Cain 2001, Cain et al. 2003, Varis 1997, Domínguez Padilla et al. 2003, Martín de Santa Olalla et al. 2007). Further, key features include the ability to link different types of information (Jensen 2001, Bromley et al. 2005). But the main advantages of BNs over other tools are: 1) the graphical nature and visual simplicity of the technique, which facilitates interaction with stakeholders who have different backgrounds (Bacon et al. 2002, Batchelor and Cain 1999, Cain et al. 1999); 2) BNs explicitly take into account and openly represent uncertainty in decision making; and 3) they offer the opportunity to couple networks with other types of model. In this context, the option to link to economic models is particularly important.

3. Objectives of the research

The objective of this research is to construct a decision support system (DSS) for water management in Upper Guadiana Basin with the active involvement of stakeholders. This DSS is designed to identify sustainable socio-economic and environmental strategies for the region and to provide a platform for stakeholder participation in water management in the basin.

4. Methodology

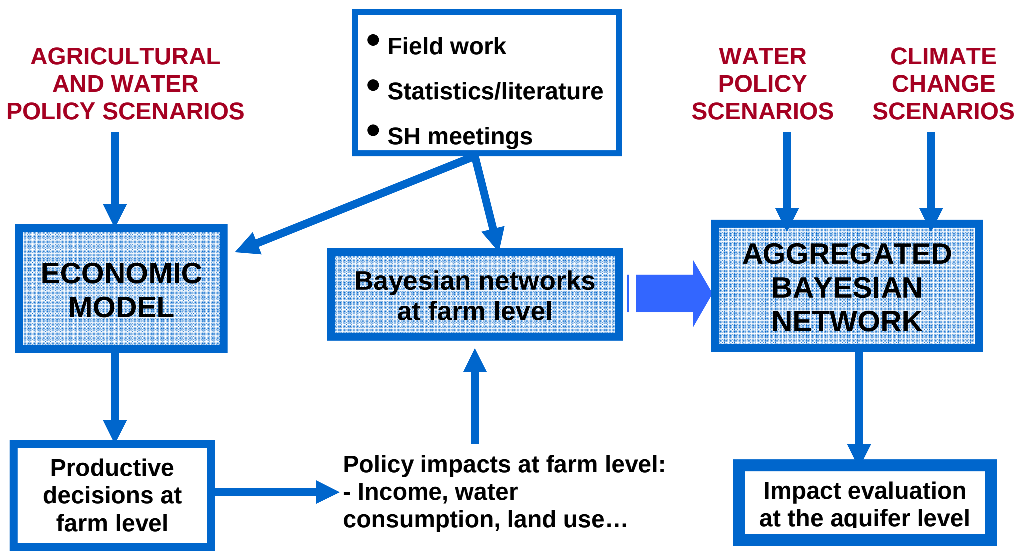
4.1. Methodological scheme

The participatory DSS designed for water management decision making in the Upper Guadiana has two main components:

- An object-oriented Bayesian network, which represents the water management system and allows different management options to be tested
- An agro-economic model, which reproduces farmers' behaviour when different policies are applied.

The agro-economic model is built at farm level (one model per farm type). The outputs from this model serve as input to BNs, which are also built at farm level. Individual networks representing each farm type are then aggregated into an object-oriented network, which is used to assess the impacts of the whole system, including all farm types, on the aquifer (see Figure 2).

Figure 2: Methodological scheme of the present research



BNs comprise a group of interrelated variables, which define the system. Each variable is characterized by its states, which are the different 'values' it can adopt. Links between variables are expressed through conditional probability tables that express the probability distribution of one variable through its different states, given the states of its parent variables. The information about conditional probabilities can be obtained from various sources: direct measurements, mathematical models, or if no other data is available, expert opinion. Once constructed, BNs can be used to identify the state of sub-groups of variables given the states of other variables on which the sub-group is dependant (parents), through the process called "probabilistic inference". The mathematical basis of this process is Bayes' Rule.

When A is conditionally dependant on B, then:

$$P(A \mid B) = P(B \mid A)\, P(A) / P(B)$$

As a basic input to the Bayesian network the results of a mathematical model have been used. (Varela-Ortega et al. 2006). The model is a farm-level, non-linear, mathematical representation of farmers' behaviour in response to different water and agricultural policies. The model maximizes a utility function (U) subject to technical, economic and policy constraints (g), and it includes a risk component that takes into account the effect of climate (affecting crop yields) and market uncertainties (affecting crop prices). The utility function is defined by a gross margin (Z) and a risk vector (R) that takes into account climate as well as market price variability.

The economic model can be summarized as follows:

Maximize $U = f(x)$, $f(x) = Z - R$

Subject to the following constraints $g(x) \in S_1$, $x \in S_2$

Where "x" is the vector of the decision-making variables or vector of the activities defined by a given crop-growing area and by an associated production technique, irrigation method and soil type (S). The problem-solving instrument used is GAMS

(General Algebraic Modeling System). The technical coefficients and parameters of the model were obtained from field work conducted in the study area during 2006 and 2007, consisting of surveys and interviews with various stakeholders in the basin. The model was calibrated and validated using as the calibration parameters the risk aversion coefficient, the comparative data on crop distribution, and the land and labour parameters in the study area.

For the development of the DSS, we depended on the stakeholders[1] selected during the NeWater project and on information obtained from them at a set of meetings held during the NeWater project between 2005 and 2007(Martínez-Santos et al. 2007, Varela-Ortega forthcoming).

After these meetings a participatory process was organized with the specific aim of developing the Bayesian networks, as shown in Table 1:

Table 1: Stakeholder meetings included in the participatory process for the development of the Bayesian networks in the Upper Guadiana basin

DATE	FORMAT OF MEETINGS	CONTENT
May 2007	2 Group meetings: (1) farmers + agric. Administration; (2) environmental NGOs + water Administration.	- Methodology explanation - Definition of variables - Elaboration of preliminary network
January 2008	Individual interviews	- Definition of states of variables - Definition of CPTs
February 2008	Plenary meeting	- Validation of the BN - Completion of CPTs
April 2008	Plenary meeting	- Validation of preliminary results
November 2008	Plenary meeting	- Presentation of final results

[1] Within stakeholder groups, the following are included: representatives of the Irrigation Communities, Farmers' Associations, environmentalists, Guadiana River Basin Authority (RBA), Castilla la Mancha Agricultural Council, and other independent groups.

4.2. Development of the DSS

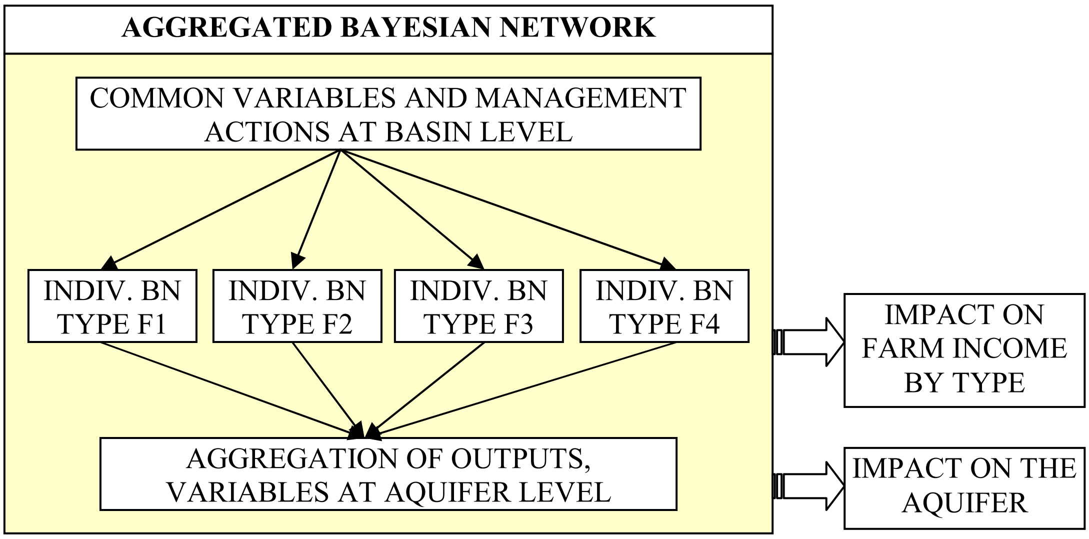
The first steps in DSS development were the implementation of fieldwork, database analysis and the definition of a farm typology for the Upper Guadiana region. Next, the development of the economic model described above, defined at farm level. After this, the Bayesian networks were constructed with input from the stakeholders, following the guidelines set out in the EU project MERIT (Bromley 2005). According to these guidelines, the process of construction of a Bayesian network should include the following stages:

1) Definition of the problem and selection of an appropriate spatial and temporal approach.
2) Identification of variables, possible actions and adequate indicators.
3) Design of a preliminary network.
4) Data collection
5) Definition of the states of variables
6) Construction of the conditional probability tables
7) Validation of the network with the stakeholders

The overall process is not linear, but there must be feedback loops when new evidence appears during construction of the model.

The BNs were developed at the farm level, and then aggregated using an Object-Oriented network methodology (Koller and Pfeffer 1997, Bangsø and Wuillemin 2000). Although there are no known examples of this type of construction in natural resources management, it has been chosen because it provides the opportunity to represent repetitive structures in the same model and to analyse the system at different scales simultaneously. The aggregation process identifies common variables for all the farm types and uses them as inputs for each individual BN, and then aggregates some of the results in a joint output network, as shown in Figure 3:

Figure 3: Schematic representation of the aggregated, object-oriented Bayesian network of the Upper Guadiana basin



This structure enables the impact of different management actions on the economy of each farm type to be evaluated and, at the same time, the joint impact of all farm types on the aquifer. The advantage of the object oriented network in this case is to allow the simultaneous analysis of impacts at different scales, which is extremely useful in our context.

4.3. Simulations

Once the network is set up, different water management scenarios are selected and run. These alternative actions are simulated by fixing the states of relevant input variables, which then generate a distribution of probabilities for those child variables selected as indicators.

The object of the exercise is to identify the way in which farm income and groundwater levels respond to changes in those factors considered to be responsible for overexploitation in the region. These factors include the types of policy implemented and the degree of compliance of the farmers with those policies. Among the policies considered are those included in the regional water management plan (C.H.G. 2007a). The main policy tool here is the purchase of irrigation rights by the RBA from irrigators at different price levels. With respect to the CAP, we have simulated the impact of partially decoupled subsidies, which is the policy currently being implemented. Simulations have been made to reflect the impact of the Water Abstraction Plan for the current year (C.H.G. 2007b).

To simulate different scenarios the states of input variables have been fixed, and the response of output variables such as water level (aquifer recovery[2]) and farm income noted. Different scenarios tend to give rise to opposite responses in the two main output variables; as income increases, so aquifer recovery declines. In this way the trade off between the two factors can easily be evaluated for different scenarios. In these simulations, the following variables have been selected as input variables:

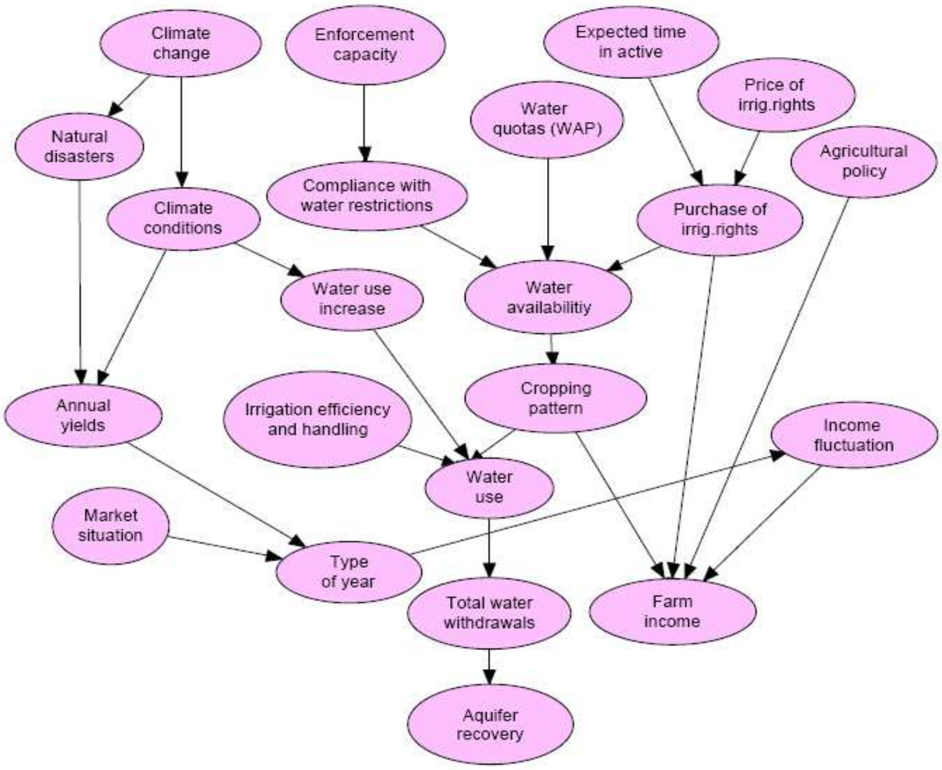
(1) Policies implemented: purchase of irrigation rights from farmers by the RBA, simulating several offer prices, and

(2) The enforcement capacity of the RBA to make farmers comply with water restrictions.

The Bayesian network constructed using the data and opinions provided by stakeholders, together with data obtained from the economic model developed by UPM is shown in Figure 4.

[2] Water levels have declined by up to 30m in the past 30 years; a full recovery will thus require a rise of this amount

Figure 4: Individual Bayesian network, representing one of the farm types of the Upper Guadiana basin



5. Main results

The results of BN simulations are presented as probability distributions which have been extracted from the output variables. In Table 2, two input variables, 'Enforcement Capacity' and 'Prices offered by RBA for irrigation rights' is shown. Each variable has 2 states: e.g. for the variable 'Enforcement Capacity' the states are High Capacity, and Low Capacity. For each combination of states for these two variables the probability distribution for three output variables, '% Purchase', 'Farm Income', and 'Aquifer Recovery' is given. These distributions are shown as the % likelihood of each variable being in any particular state. For example, when 'Enforcement Capacity' is in the Low Capacity state and 'Prices offered by the RBA' are in the Low Prices state, then the probability of the output variable '% Purchase' being in its Yes state is 5.4% and in the No state 94.6%.

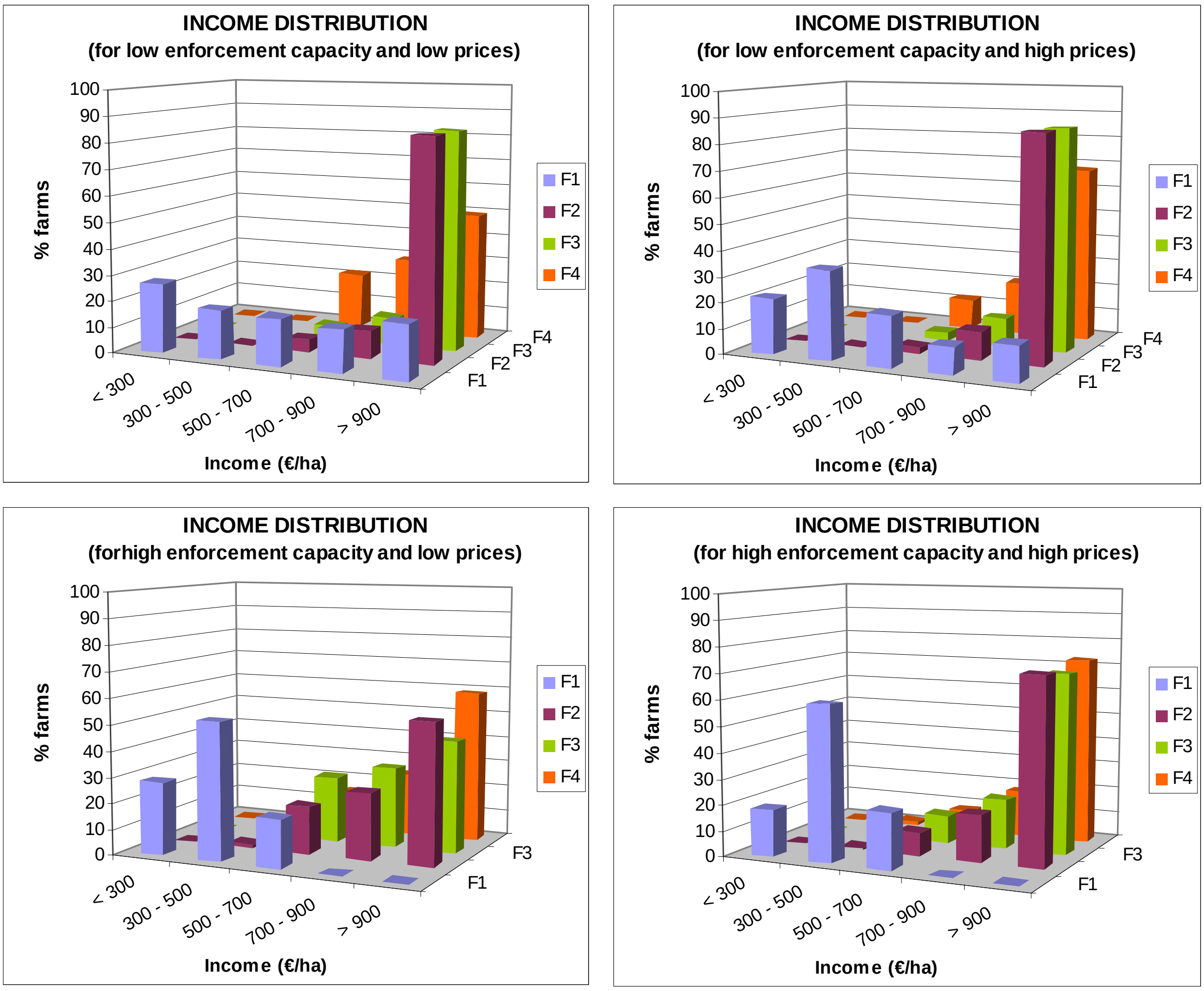
Table 2: Results of Bayesian network simulations: '% of purchase of irrigation rights', 'distribution of farm income' and 'probability of aquifer recovery' as a result of the different levels of prices paid by the RBA for the irrigation rights and different levels of the enforcement capacity of the RBA to make farmers comply with water restrictions

	Enforcement capacity	Low capacity	High capacity	Low capacity	High capacity
	Prices offered by RBA for irrigation rights	Low prices	High prices	Low prices	High prices
% Purchase	Yes	5,4	50,9	29,8	68,9
	No	94,6	49,1	70,2	31,1
Farm income (average)	< 300	5,9	4,8	6,2	4,0
	300-500	4,1	7,6	12,6	13,7
	500-700	12,9	9,3	19,4	12,1
	700-900	17,5	13,8	21,1	14,4
	> 900	59,6	64,5	40,7	55,8
Aquifer recovery	Before 2027	12,0	49,3	36,2	64,0
	Before 2050	7,1	8,5	13,7	10,0
	Later/never	80,9	42,2	50,1	26,0

Results show that the highest probability of attaining recovery of the aquifer level before 2027 is when the price paid for the irrigation rights is high and the capacity of enforcement of the RBA is also high.

With respect to income for the average farm, the model shows reductions of between 5 and 10% when the enforcement capacity of the RBA is high, compared to the income with a low capacity of enforcement. However, variations in income distribution are not the same for all farm types, as shown in Figure 5

Figure 5: Income distribution per farm type, as a function of the capacity of enforcement of the RBA to make farmers comply with water restrictions and the prices paid by the RBA for the irrigation rights



The results show that farm type F1 (small size, monoculture of vineyard) is the most affected by the increase of the enforcement capacity, while income for the larger farms is more affected by the price of irrigation rights.

6. Conclusions

- Bayesian networks have been shown to meet the requirements of the Water Framework Directive by: (1) Simultaneously being able to take into account all aspects of water use in the basin including the hydrological, socio-economic and environmental dimensions, (2) Being able to actively involve users and stakeholders in the decision making process, to increase public participation, and to foster social learning.

- Object-oriented models have the additional advantage of being able to incorporate impacts at different scales. In our example it proved possible to evaluate the impact of each individual type of farm in isolation, but also on the joint effects of all types of farms at the regional level.
- BN simulations have shown that the capacity of enforcement of the RBA to make farmers comply with water restrictions is a key element in water level recovery. It is not possible to achieve a reasonable probability for recovery of the aquifer if any one of two factors is missing: 1) high level of prices offered for the irrigation rights, and 2) high capacity of enforcement of the RBA.
- The compliance with water restrictions inevitably leads to some loss in farm income, which is especially important for small vineyard farms. This could be avoided by additional measures to encourage quality production or improve marketing.

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