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INTEGRATION OF BAYESIAN NETWORKS AND AGRO-ECONOMIC MODELS AS A DECISION SUPPORT SYSTEM FOR WATER MANAGEMENT IN THE UPPER GUADIANA BASIN

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1. INTRODUCTION

The population growth is producing an increase in water resources demand, which often cannot be met by the offer. This problem becomes more critical when the responsible organisations do not settle new management options (Sumpsi et al, 2001). Considering that agriculture is the activity that consumes the highest part of the resource, water management in the agricultural sector becomes crucial when looking for the sustainability of the resource. In Spain, where 80% of available water resources are used for irrigation, water scarcity has been aggravated by European policies that have encouraged further development of irrigation (Varela et al, 1998)

As a response to the increase in water demand, nearly all arid and semiarid countries have developed along the last decades an intensive use of ground water (Llamas, 2005). Lowering costs of drilling and water abstraction have allowed the development of irrigation for many small farmers. Contrasting with big hydraulic infrastructures developed for surface water, the initiative in ground water has been taken traditionally by the farmers themselves, with low public involvement. This has lead in some cases to the over exploitation of the resource, aggravated by the lack of coordination between water administration and water users (Fornés, de la Hera and Llamas, 2005).

Face to all these problems, the development of integrated policies has been encouraged in the last years, aiming at a sustainable management of water resources that considers all implications that such management can have over the social, economic, environmental, etc. aspects. In this context, the Water Framework Directive (WFD) has been developed, which provides some compulsory guidelines for the Member Countries, with the aim of achieving a sustainable management of water resources. The WFD represents a change in management systems, which are understood now as management of the demand, as well as the obligation of reaching the cost effectiveness of the measures (Varela-Ortega, 2007). The WFD adopts the philosophy of the "Integrated Water Resources Management" (IWRM). There are many definitions of IWRM, but all of them include two aspects (Bromley et al, 2005): (I) Management decisions must take into account the implications that these decisions will have in the whole system, and not only in the resource itself. In order to take decisions that satisfy all of those concerned with water, the decision maker should take into account all those implications and consider different criteria. (II) It must include the participation of stakeholders in the decision making. This is considered an essential requirement so that management decisions will be accepted by all involved in water use. Furthermore, these can contribute with additional information that managers do not have. As well, they will provide their own views, contributing to increase the diversity of criteria.

This research is developed under the activities held by the UPM team in NeWater project ("New Approaches to Adaptive Water Management under Uncertainty". One of the activities proposed in the project is the use of Bayesian networks as an instrument for decision making support. This tool has been chosen due to its usefulness in the resolution of conflictive situations related to catchments' management, because it is able to link different aspects concerning water management at farm level and making the up-scaling afterwards at basin level, where a balance is aimed between farm income and environmental welfare.

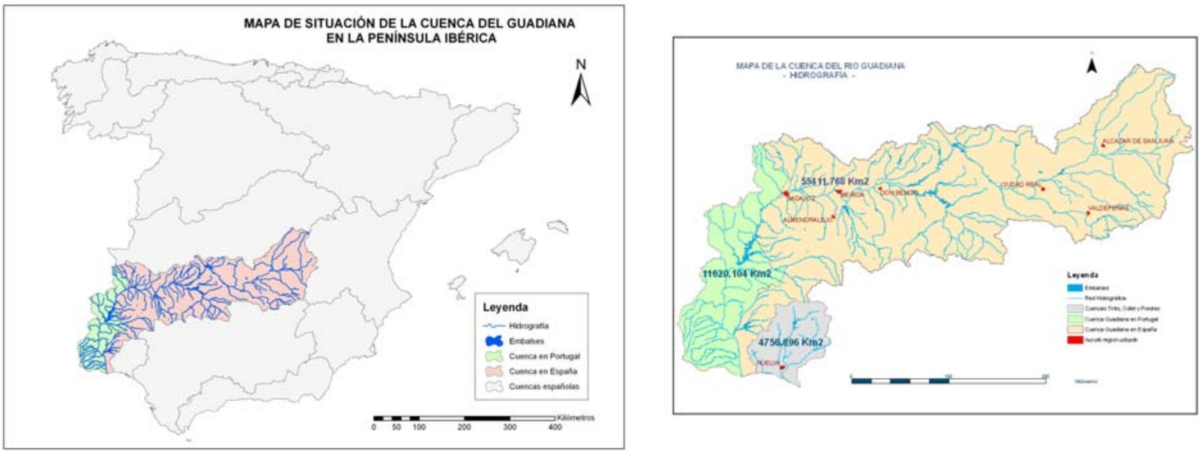
[1] Activity developed within NEWATER Project "New Approaches to Adaptive Water Management under Uncertainty", FP6-2003-GLOBAL-2-SUSTDEV-6.3.2-511179-2, DG Research. European Commission.
[2] Special acknowledgement is due to the Spanish Ministry of Science and Technology, which has co-financed this research through the funds given through the project SEJ2005-25755-E: "Análisis de la gestión integrada del agua en la agricultura: efectos socio-económicos, ambientales e institucionales", complementary to NeWater.

2. CONTEXT OF THE RESEARCH

2.1. Description of the area of study

The Guadiana basin includes 67,133 km^2, 55,513 km^2 of which belong to the Spanish territory. The Upper Guadiana basin corresponds to the area between the head of the river and the Jabalón river, which is 18,900 km^2, situated in 4 different provinces.

Figure 1: *Location of the Guadiana basin*



SOURCE: Confederación Hidrográfica del Guadiana

The area presents a Mediterranean-continental climate, with high inter-annual variability of temperatures. Precipitations are scarce, with an average of 415 mm/year, unevenly distributed mainly between spring and autumn.

Regarding the hydro-geological features of the Upper Guadiana, it presents a flat relief, with a not well-defined drainage network and a significant presence of aquifers. The hydrological regime is characterized by a complex interaction, under natural conditions, between surface and ground water (Martínez-Cortina and Cruces, 2005; Bromley et al, 2001). It comprises six hydro-geological units, which occupy 16,000 km^2.

Table 1: *Hydro-geological units in the Upper Guadiana basin*

Hydro-geological units		Surface (km^2)
UH 04.01	Sierra de Altomira	2.951
UH 04.02	Lillo-Quintanar	1.072
UH 04.03	Consuegra-Villacañas	1.409
UH 04.04	Western Mancha	5.261
UH 04.05	Ciudad Real	1.086
UH 04.06	Campo de Montiel	2.791

SOURCE: Confederación Hidrográfica del Guadiana

The main unit, from the hydro-geological as well as from the economic point of view, is Western Mancha. 2/3 of total groundwater abstracted in the region comes from this unit, which has originated serious problems of over-exploitation (Llamas, R. and Martínez-Santos, P., 2006). There are some small dams, such as El Vicario and Peñarroya, but most water resources used come from ground water exploitation.

The Upper Guadiana basin presents the characteristics of a rural area. In 2005, the population was 570,000 hab (CHG, 2006) and the population density 26 hab/km^2, quite below the national average (78 hab/km^2). Such population is distributed all over the area, without big cities. Agriculture provides 21% of employment, and up to 38% in Western Mancha aquifer area (compared to 7% in Spain) (Llamas and Martínez-Santos, 2006). The high development of irrigation has kept the population stable, presenting an average age which is lower than in the most other Spanish rural areas.

In the Upper Guadiana basin, agriculture consumes 90-95% of total water resources. Regarding irrigated surface, there is often disagreement between different sources, varying between 189,450 and 262,868 ha. According to the Water Authority (CHG, 2006), the estimations about irrigated land are 160,000 ha of regulated irrigated land and 40,000 ha illegal (mainly vineyard). Focusing on Western Mancha aquifer, it has 6,889 irrigated farms, with 17.22 ha average size. 90% of irrigation equipments are by sprinklers or drip, only 10% furrow. The River Basin Authority estimates agricultural water consumption, from SIAR ("Servicio Integral de Asesoramiento al Regante") data, in 355 Hm^3/year (CHG, 2005), for the 130,000 ha of irrigated land.

Table 2: *Surface per crop in 2005, estimated by GIS techniques, in the Upper Guadiana basin and in the over-exploited perimeters (Western Mancha, Sierra de Altomira and Campo de Montiel)*

UPPER GUADIANA BASIN		OVER-EXPLOITED PERIMETERS[3]	
CROPS	SURFACE (ha)	CROPS	SURFACE (ha)
Garlic	3.597,32	Garlic	2.754,12
Onion	3.914,10	Onion	2.684,88
Vegetables	2.826,41	Vegetables	2.163,91
Maize	4.951,82	Maize	3.396,14
Melon	6.667,07	Melon	6.667,07
Potato	1.108,71	Potato	848,83
Pepper	2.426,71	Pepper	1.857,90
Sugar beet	3.214,63	Sugar beet	2.205,20
Tomato	401,99	Tomato	307,76
Vetch	1.181,58	Vetch	789,27
Vigneyard (goblet)	125.385,89	Vigneyard (goblet)	84.592,48
Vigneyard (trellis)		Vigneyard (trellis)	
Irrigated, spring, annual crops with very high water requirements.	33.508,83	Irrigated, spring, annual crops with very high water requirements.	18.833,12
Irrigated, spring, annual crops with high water requirements.	13.889,08	Irrigated, spring, annual crops with high water requirements.	10.593,07
TOTAL	203.074,14	TOTAL	137.693,75

SOURCE: Confederación Hidrográfica del Guadiana, 2007

From the environmental point of view, it should be highlighted that the Upper Guadiana contains 250 km^2 of wetlands (Llamas and Martínez-Santos, 2006), some of which have been declared *biosphere reserve* by the UNESCO, due to the high biodiversity that they present (especially for birds). Some of these wetlands are currently protected by RAMSAR convention (de la Hera, 2002); among these, the main are Tablas de Daimiel and Lagunas de Ruidera.

2.2. The problem

In the Upper Guadiana, two of the six hydro-geological units are over-exploited (Western Mancha and Campo de Montiel). In Western Mancha, the piezometric level has suffered a descent of 50m in the last 30 years (Coleto et al, 2003; Martínez-Cortina and Cruces, 2005). The declaration of over-exploitation means, according to the 1985 Water Law, an obligation to constitute irrigators' associations and the prohibition of drilling new wells or deepen the existing ones, as well as limiting the annual abstractions volume.

Since the 1970's, a great development of irrigation has been produced as a consequence of the European agricultural policy, which has long encouraged, through the subsidies coupled to production, the cultivation of crops with high added value and high water consumption (Varela-Ortega et al, 2003; Varela-Ortega, 2007). This has had several consequences: (1) important socio-economic development of the area, (2) serious over-exploitation of the aquifer Western Mancha

[3] Over-exploited perimeters are: Mancha Occidental, Sierra de Altomira and Campo de Montiel

(declared as over-exploited in 1989) and serious damages of natural sites (wetlands, especially Tablas de Daimiel)

After the promulgation of the National Water Law in 1985, which supposed a change from a model of private waters to public waters management, and as a consequence of the declaration of over-exploitation of the aquifer, water exploitation plans (Water Abstraction Plan = WAP) started to be implemented. These plans established a limitation in the water volume abstracted by farm. WAP has had high social opposition and farmers had continued abstracting over the permitted volumes. Only the European Agro-environmental programs implemented during the period 1993-1998, which offered subsidies to farmers in exchange for reducing water consumption, have succeeded to induce a certain recovery of ground water levels, but they supposed a high public expenditure. After the Luxemburg reform (2003), the new agricultural policy, based in the partial decoupling of subsidies and the inclusion of cross compliance, is expected to have as a consequence a change towards less intensive crops.

At present, farmers must adjust their water consumption to the quotas established by the water authority. But farmers present a low degree of compliance with these regulations: many of them abstract higher volumes than permitted, many others drill wells without permission, exceeding the capacity of enforcement of the water administration, which has to face high social and administrative costs. As a consequence of this situation, there are several sources of conflict among different groups involved in water management in the area: (I) A great number of illegal wells abstract water from the aquifer without any control. Consequently, although all the irrigated farms are consuming the resource, only the legal ones suffer from the restrictions imposed by the water authority. The number of illegal wells is such high that the social cost of their closure has stopped the authority from closing them up. (II) After several years of continuous damage in natural spaces, where most abstractions have had its origin in agriculture, environmentalists blame farmers for their responsibility in the ecosystem alteration. (III) The third source of conflict is the relationship between irrigators-administration. On the purpose of recovering the aquifer level, the Water Authority tries to apply restrictive measures in water use, which highly affect farm income. There is high social opposition to such policies and a lack of compliance that leads to high social costs for the River Basin Authority.

In addition, an aspect that makes the resolution of the conflict more difficult is the lack of transparency, which is deduced from the interviews held with the stakeholders, as well as from the disagreement of data coming from different sources. We deal with uncertainties: about the real volume of abstractions (estimations are made from the surface of crops declared by farmers and observed by satellite plus estimations about water use per crop), about the number of illegal wells. For the farmer, there is also the uncertainty about the evolution of policies, which is the main reason to make him free-ride.

In the last years, since the WFD came into effect, European legislation produces a synergy with national legislation, serving to legitimate the Water Abstraction Plan (WAP), which allows a decrease in the social cost (Varela-Ortega, 2007). In this context, the new exploitation plan for the basin (Plan Especial de Alto Guadiana = PEAG) is being developed, with the aim to find a solution for the water management conflict in the area. But it is important to keep in mind that the design of an efficient policy is not enough to solve the problem, but it is essential to attain the compliance with the law. When evaluating the efficiency of the policies, we will need to use some indicators of the degree of compliance (i.e. number of wells closed/total illegal wells) in order to see to what extent a high degree of compliance of the farmer supposes an increase of his vulnerability.

2.3. Methodologies involving stakeholder participation

The need to take stakeholders into negotiation and to involve them in decision making demands the use of decision support tools which must be simple, transparent and flexible (Henriksen et al, in press). There are several kinds of tools that can be used in the context of the IWRM. Among the ones used in catchment's management, there is the multicriteria analysis. The participation of stakeholders in this process is required for defining the management options and the related indicators that will permit the choice of the best management option. This system has been used by FEEM (Giupponi et al, 2004; Mysiak, Giupponi and Rosato, 2005), who have developed on this purpose, within MULINO European project, a software called mDSS.

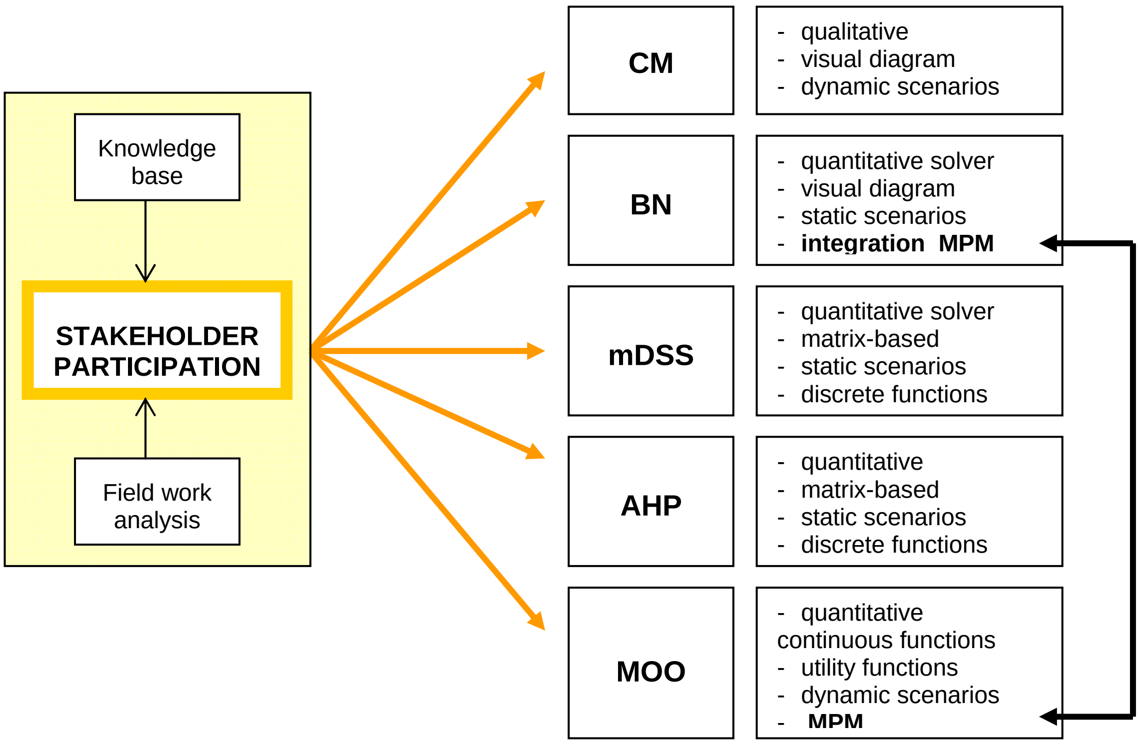
The Analytical Hierarchy Process (AHP) is one of the most widely used multicriteria analysis method to address complex situations. It allows the resolution of problems with different factors and stakeholders involved, in a context of uncertainty (Saaty, 1990; Moreno-Jiménez, 2002). The stakeholders participate in the process by quantifying preferences for the different criteria. The two main advantages of this method are: its transparency and the quantification of qualitative issues. This methodology has been already used in Spain for the evaluation of different techniques in growing olive trees (Parra-López and Calatrava-Requena, 2005)

Another methodology based on stakeholders' knowledge is the elaboration of cognitive maps (CM). Cognitive maps are qualitative models of a system which show the variables involved in such system and the casual links existing between them (Özesmi and Özesmi, 2004). Cognitive mapping is very useful for making explicit hidden information from stakeholders (Cole and Persichitte, 2000) and it has been used for facilitating the development of participatory environmental management applications in complex situations involving uncertainty. Cognitive mapping techniques are currently being used in the Guadiana basin in the framework of the European project SCENES[4], and has already been used for river basin management in another basin in Spain (Kok and van Delden, 2004).

Bayesian networks (BN) are Decision Support Systems which are also built with the participation of stakeholders, and they are based on Bayes probability theory. They have been long applied in different fields such as medicine or computers, and more recently in natural resources management (Varis, 1997; Cain, 2001; Cain et al, 2003). It is a good tool, which is able to simulate a system in which uncertainty is present due to imperfect or incomplete knowledge of such system. The ability to link different types of information is a key feature of Bayesian networks (Bromley, 2005), as well as the possibility of coupling BN with other types of models.

Finally, another line of decision support systems that has included recently the participation of stakeholders in their construction is the multi-objective optimisation (MOO) (van Calker et al, 2006; Marchamalo and Romero, 2007). The contribution of stakeholders consists on the elicitation of utility functions and the assignation of weights to the different attributes involved in the system. Although the participative process has to be further developed, this contribution makes this line a very promising tool for decision making.

Figure 2: *Decision Support Systems built with stakeholder participation. Main features.*



CM= Cognitive Mapping; BN= Bayesian Networks; mDSS= FEMM multi-criteria methodology; AHP= Analytical Hierarchy Process; MOO= multi-objective optimization

SOURCE: Own elaboration

[4] SCENES project: "Water Scenarios for Europe and for Neighbouring States" – FP6-2005-GLOBAL-4(OJ 2005 C 177/15), DG Research. European Commission.

Figure 2 shows the main characteristics of the different Decision Support Systems considered, which are built with the participation of the stakeholders.

The choice of each of these methods depends of the kind of problem and the context in which the DSS is going to be developed. Table 3 shows the main advantages of the different methods explained before, that make them suitable for our specific case study:

Table 3: *Main advantages of some Decision Support methods*

ATTRIBUTES	**METHODOLOGIES FOR DSS ELABORATION**			
	mDSS (FEEM)	AHP	CM	BN
Participatory level	++	++	+++	+++
Capacity to address complex situations	++	++	++	++
Integrated approach	++	++	++	++
Includes uncertainty	+	+	+	+++
Includes dynamic aspects	+	+	+++	+
Allows quantification of qualitative issues	++	+++	+	+++
Transparency	++	++	+++	+++
Simplicity	++	+	++	++

(+) Level of compliance of the methodology with the attribute considered

SOURCE: Own elaboration

Both the multicriteria analysis and Bayesian networks allow the integration of different aspects involved in water management. However, Bayesian networks present some advantages compared to other tools: first, the graphical nature and the visual simplicity, which facilitates interaction with stakeholders who have different backgrounds (Batchelor, 1999; Cain et al, 1999; Bacon, 2002), as it has been the case in the various stakeholder meetings held in the Upper Guadiana within NeWater project (Varela-Ortega et al, 2006). But the main advantage of Bayesian networks is that they explicitly consider uncertainty in decision making, as well as the possibility of coupling the network with a formal economic model.

Compared to Cognitive mapping, BN present the disadvantage of a difficult interface for representing dynamic aspects. However, other characteristics, mainly the possibility of quantifying qualitative issues of the system, have made us prefer to adopt BN for our research.

Moreover, BN have already been used in Castilla La Mancha region in the framework of MERIT project (Domínguez-Padilla et al, 2003; Martin de Santa Olalla et al, in press) for ground water management (Eastern Mancha aquifer). Our research in the same line as this last one, but our main contribution to the methodology used in Eastern Mancha is the coupling with an economic model, which had not been fully developed or not clearly specified in Eastern Mancha model.

3. OBJECTIVE OF THE RESEARCH

The objective of this research is building, with the active involvement of stakeholders, a Bayesian Network (BN) that will serve as a decision support system for water management in Upper Guadiana Basin, aiming at the double objective of socio-economic and environmental sustainability. The main advantages of BNs are its participatory approach, the explicit consideration of uncertainties and the possibility to integrate different disciplines, characteristics that make BNs a powerful tool which is able to respond to the Water Framework Directive guidelines.

The Common Agricultural Policy has encouraged since the 1970s an important development of irrigation in the Upper Guadiana area. This has motivated a considerable socio-economic development of the area, but also the serious over-exploitation of groundwater resources and critical environmental damages, especially for the internationally reputed wetlands 'Tablas de Daimiel'. At present, the Water Authority establishes water quotas for irrigation farming, which face strong social opposition by the irrigators and high costs of enforcement to the River Basin Authority. In this context, stakeholder participation is crucial so that management decisions are accepted by all of those involved in the use of the resource.

4. METHODOLOGY

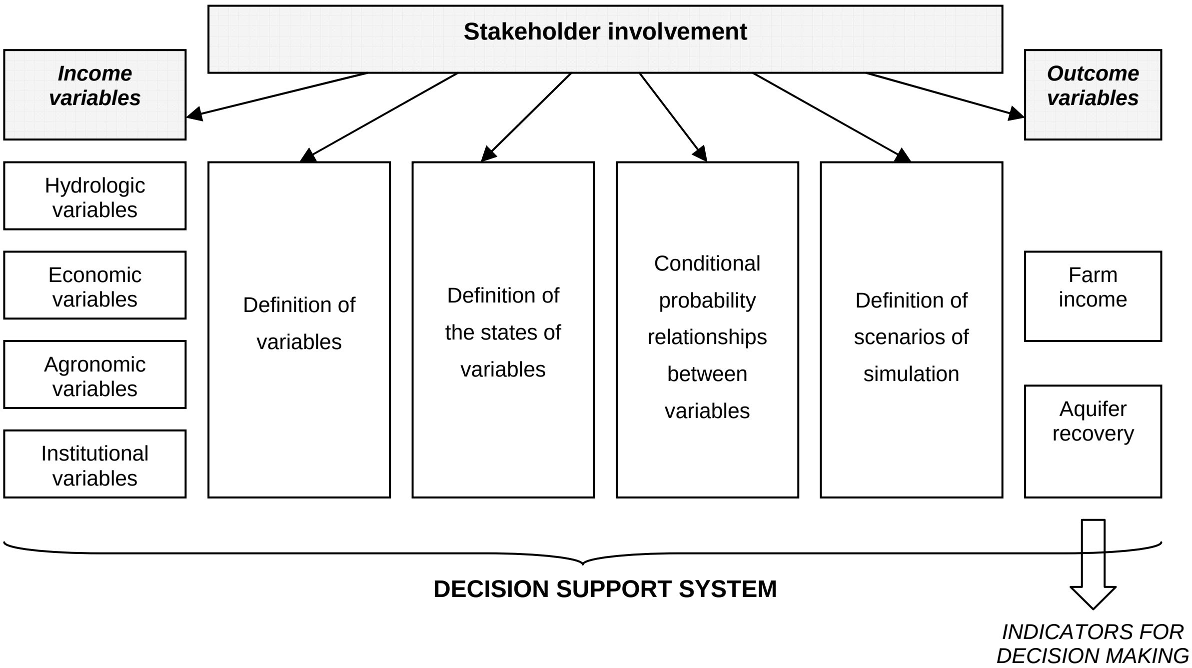
The methodology of the research consists on the construction of a Decision Support System (DSS) in a participatory way, which will be used in water management decision making and where the main components are:

- A Bayesian network, which represents the water management system and allows to test different management options
- An agro-economic model, which will be used to simulate the farmer's behaviour when different policies are applied. The outputs (farm income, cropping patterns) from this model will serve as an input for the Bayesian network.

Bayesian networks are a decision support tool suitable for the resolution of management problems including elements of very different nature (economic, social, physical…) and where uncertainty is present. A basic feature of this tool is that it is built with the participation of stakeholders, which makes it appropriate for the approach proposed by the WFD.

The figure 3 shows the participatory process of the network construction:

Figure 3. *Participatory process of elaboration of the Bayesian network*



Bayesian networks are based on Bayes probability theory, which demonstrates mathematically how existing beliefs can be modified by the acquisition of new evidence (Bromley, 2005; Henriksen et al, in press). Cognitive psychology is in the base of this theory, establishing the relationship between Bayesian statistics and cognitive theory (Anderson, 1998). The probability of one hypothesis is defined as the degree of confidence or belief that one observer has on it. This probability is updated with the acquisition of new evidence.

BNs are composed by a group of interrelated variables which define the system. Each variable is characterized by its states, which are the different values that it can adopt. Links between variables are expressed through conditional probability tables that express probability for one variable to adopt a certain state, given the possible states of its parent variables. The information about conditional probabilities can come from various sources: direct measures, mathematical models, experts' opinions. Once constructed, BNs can be used to find out the state of a sub-group of variables given the values of other variables on which the sub-group is dependant (parents), through the process called "probabilistic inference". The mathematical bases of this process, consisting of computing the distribution of variables given the evidence, are Bayes probability rules; when A depends on B, then:

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

$$P(a_i / b_j) \cdot P(b_j) = P(a_i, b_j)\ ;\ P(a_i) = \sum_{j=1}^{J} P(a_i, b_j)$$

Bayesian networks have been used in as a decision support tool in several fields, first in medicine and computing (Pearl, 1988), and more recently in natural resources (Varis, 1997; Bacon, 2002; Henriksen et al, 2006), including water management (Batchelor and Cain, 1999; Martín de Santa Olalla, in press; Bromley, 2005; Henriksen et al, in press). The European project MERIT ("The Management of the Environment and Resources using Integrated Techniques", EVK1-CT-2000-00085) developed between 2001 and 2004, under the Fifth Framework Programme, Bayesian networks for several examples of water management in different European countries. As a result of this project, a guideline document was elaborated for the use of Bayesian networks in water resources management (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 indicators adequate for evaluating the different management options.
3) Design of a preliminary network to be used as a basis for discussion
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

As a basic input of the Bayesian network, we have used the results of a mathematical programming model that has been developed in the area of study within NeWater project (Varela-Ortega et al, 2006a). The model is a farm-level non-linear mathematical programming model that represents farmer's behaviour confronted to different water and agricultural policies. Following previous work in the area of study (Varela-Ortega et al 1998), 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 climate (affecting crop yields) as well as market (affecting crop prices) uncertainties. The utility function is defined by a gross margin (Z) and a risk vector (R) that takes into account climate as well as market prices 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 carried out during 2006 and 2007 (Varela et al., 2007) in the study area, consisting of surveys and interviews with farmers, irrigation community representatives, technical experts, river basin managers, and regional government officials. The model was duly calibrated and validated, using the risk aversion coefficient as calibration parameter and the comparative data on crop distribution, land and labor parameters in the study area (Varela-Ortega, 2007).

Results from the agro-economic model (income, crop alternative and water consumption for the different farm types and policy options) have been introduced in the BN. As well, several thematic stakeholder meetings that have taken place[5] and data obtained has also been used for BN's construction. Once elaborated, the following step is the validation of the network. This preliminary version of the BN will be discussed and validated with the participation of the stakeholders during the coming months.

Figure 4. *Methodological scheme of the research.*

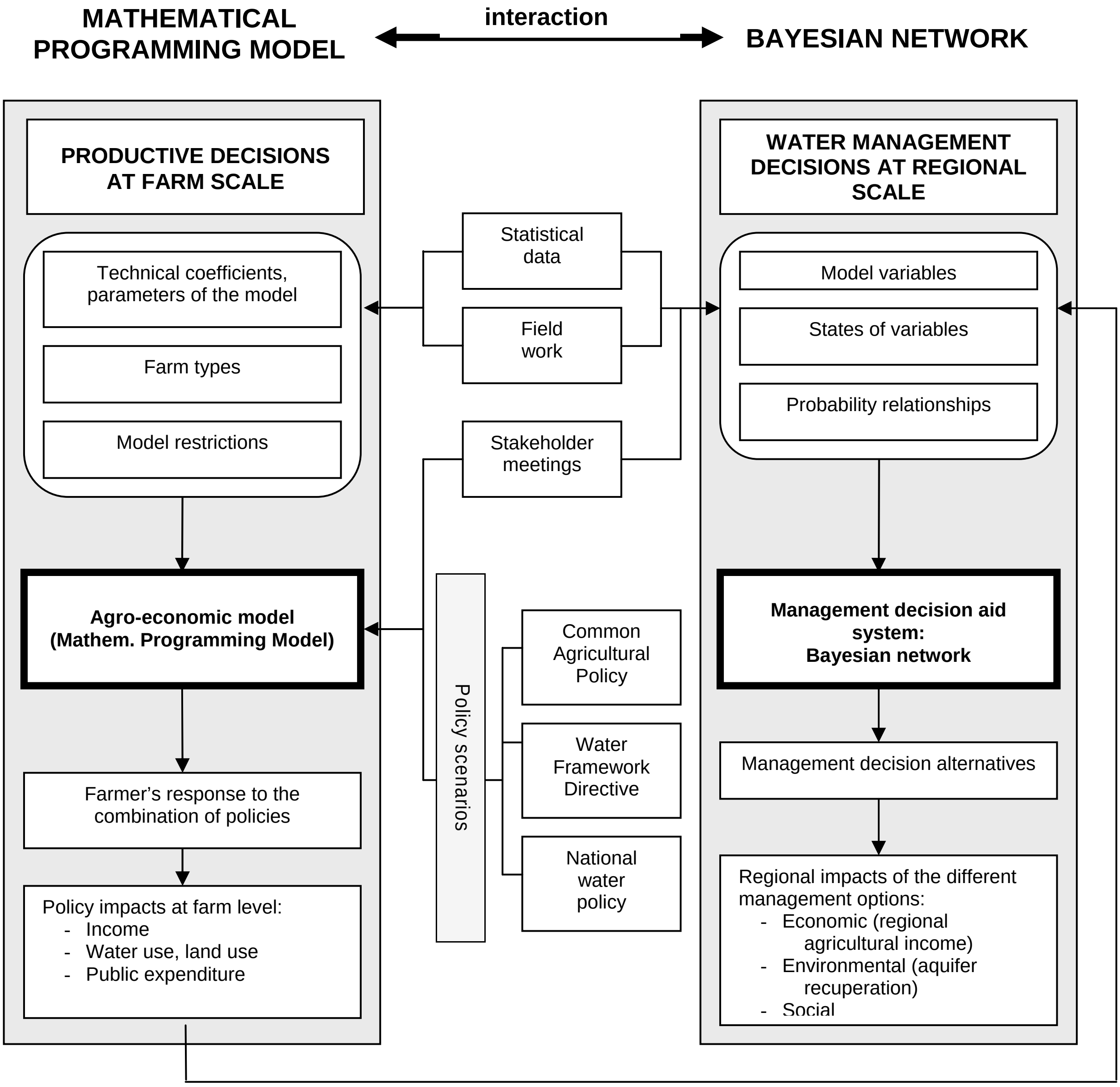


Figure 4 shows the methodological framework adopted in this research. It illustrates the relationship between the Bayesian network elaborated for water management decision making at a regional level, and the different information sources used for its construction: mathematical

[5] Within stakeholder groups, the following are included: representatives of the Irrigation Communities, Farmers' Associations, environmentalists, Guadiana River Basin authority, Castilla la Mancha Agricultural Council, as well as other independent groups related to water use in the Upper Guadiana basin.

programming model for the economic variables, statistical sources and knowledge/opinions of the stakeholder groups.

4.1. Participation of stakeholders.

Several thematic meetings have been held with stakeholders in the framework of NeWater project. These meetings have been co-organized by the UCM team, coordinators of the Guadiana case study, the UPM and the IGME (Geological Survey of Spain). The objective of these thematic meetings was explaining our activities in NeWater project and discussing about the different points of view of stakeholders regarding the situation of the basin (Varela-Ortega et al, 2006). The format of the meetings was based on discussions guided by questionnaires that were previously distributed to stakeholders, who were divided into heterogeneous groups. When the selection of stakeholders was made, we tried to include all groups involved in water management: Ministry of Environment, Water Management Administration, Agricultural and Environmental Regional Government, water users' associations, farmers' unions, environmentalist groups, scientific experts…

The role of stakeholders is crucial in the BN construction. According to MERIT guidelines (Bromley, 2005), it is desirable to held a first set of meetings or consultations with stakeholders; from the output of these meetings, a preliminary network can be built, which will be modified and validated in later interviews. In our case, results obtained from NeWater thematic meetings have served as an input for the construction of the pilot network that we have built. As well, results from a linear programming model built within NeWater activities have been used (Varela-Ortega et al, 2006). Such model aimed at evaluating the impacts of the joint application of several agricultural and water policies in the Upper Guadiana basin. It provides results concerning farm income, copping patterns and water consumption for the different farm types when the alternative policy combinations are implemented. Among the agricultural policies, two CAP options have been tested: Agenda 2000 and the 2003 Luxemburg reform (with partial decoupling of subsidies). Each of these policies was combined with the following water scenarios: water availability equal to the initial concession, previous to the application of the current Water Abstraction Plan (WAP); water availability equal to the quota currently established by the WAP; water availability equal to quotas established by the Agri-environmental programs, with 50% and 100% reduction of volume compared to the WAP.

4.2. Construction of the BN

- Definition of variables

The identification of variables has been made based on the information obtained during the stakeholder meetings and on the knowledge of the scientific team. The set of variables selected (nodes) represent the relevant elements of the system, and they can be grouped into several blocks:

· Institutional block: it includes variables related to policies whose implementation affects water management in the Upper Guadiana basin. It includes CAP subsidies, Water Abstraction Plan, and the possibility of selling water rights.

· Agrarian block: it comprises variables related to the farm, mainly crop alternatives and income.

· Environmental block: variables related to water consumption derived from the agricultural activity and with water availability in the aquifer (as a function of consumption, irrigation techniques and rainfall)

- Definition of the states of variables

These states can be defined as discrete values, intervals, qualitative or boolean estimations. In our case, most variables have been defined by qualitative estimations. Firstly, statistical data have been considered. Secondly, the stakeholders' information reported during the meetings, as well as expert's opinions were used. In the third place, the data obtained during the field work developed under NeWater activities (Varela-Ortega et al, 2006) were used. Finally, the results from the linear programming model were also introduced in the network.

- Elaboration of the conditional probability tables

Data needed to fill the conditional probability tables may come from: direct measures, simulation models or experts' opinions. As we are in a preliminary phase in the process of the BN construction, the objective of this first version is the establishment of a basis for discussion for future stakeholder meetings. In this preliminary BN, probabilities have been estimated from stakeholders and experts' opinions. Furthermore, the results of simulations held with the linear programming model elaborated by the UPM team have been used. In future stages, these tables will be completed with the stakeholders' feedback, as well as with the results from new simulations with the agro-economic model.

4.3. Validation of the Bayesian network

The present work is the first phase of a Bayesian network participatory building process in the Upper Guadiana basin. This preliminary network has to be discussed and improved with the participation of stakeholders, which will be held in the following months.

4.4 Simulations

Once the network is elaborated, different possible <u>actions</u> on water management are selected and <u>simulations</u> are held. The network can be used in several ways:

- Giving fixed values to the input variables ("parents"), from which a certain distribution of probabilities will be obtained for the output variables.
- Fixing the values of the output variables that we are interested in, and calculating from these values the states needed for the input variables so as to get those expected results.

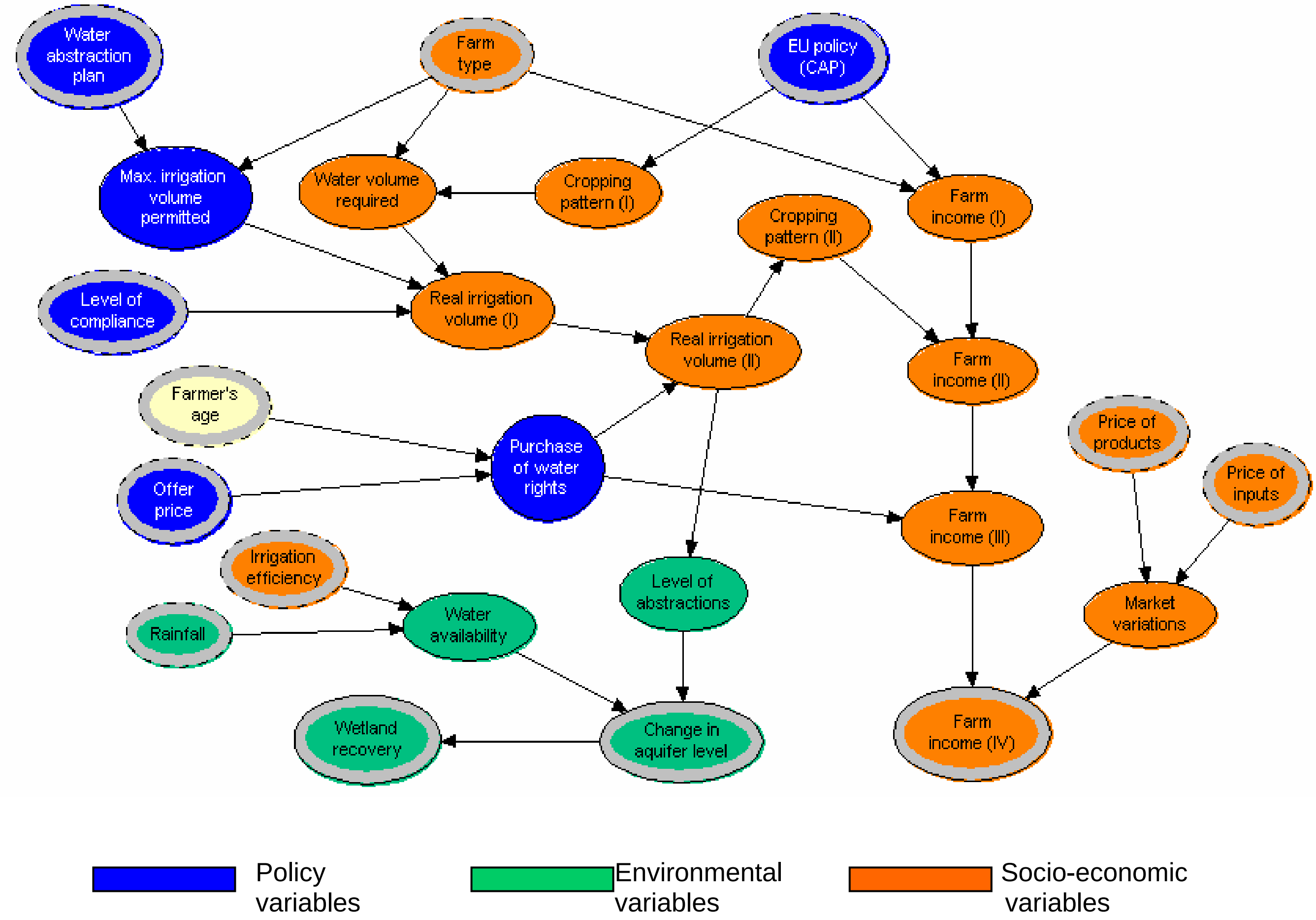
In our case, the alternative followed has been the first one. We are interested in evaluating the farm variations in farm income and the recovery of water levels as a function of the variables considered as the most significant in the over-exploitation of water resources in the area: the policies implemented and the degree of compliance of the farmers with those policies. Among the policies implemented, we have considered the possibility of the Water Authority purchasing water rights from irrigators at different price levels. Regarding the CAP, we have simulated partially decoupled subsidies, which is the currently implemented. For the water policies, simulations have been made considering the Water Abstraction Plan for the current year.

The approach followed in the elaboration of scenarios have been to fix the values of the input variables, making the model calculate the values of the rest of the variables and observing the values adopted by the output variables: farm income and wetlands recovery (directly linked to the aquifer level). In these first simulations, the following variables have been selected as input variables:

(1) Policies implemented: <u>purchase of water rights</u> from farmers to the water authority has been considered, simulating several offer prices, and (2) The <u>degree of compliance</u> (defined qualitatively as *high*, *medium* and *low*) of farmers to water restrictions.

The figure 5 shows the Bayesian network built from the data and opinions provided by stakeholders, as well as from the economic model elaborated by UPM in NeWater.

Figure 5. *Bayesian network elaborated: variables of the system and relationships existing among them.*



5. MAIN RESULTS

Table 4 shows the results of the BN simulations. Results are presented as a set of probabilities taken by the output variables for the different states taken into account, as a function of the different states that the input variables will take.

Results show that the highest level of recovery of the aquifer and the wetlands happens when price of water rights are high and the level of compliance with water restrictions is also high. If this second condition is missing, even though farmers still sell water rights, the level of recovery of the aquifer is lower than when the first condition is missing. That is, the level of compliance by the farmers with water abstraction restrictions is more determinant for attaining the recovery of the aquifer than the price paid for the water rights.

Regarding farm income, the model shows reductions between 10 and 15% when the level of compliance with water restrictions is high, compared to the income with a medium-low level of compliance. Higher prices have a negative impact in the final income distribution. This happens because high prices attract a higher number of farmers to sell their rights, which in turn increases indirectly the level of compliance with restrictions.

Table 4. *Main results of simulations with preliminary Bayesian network in the Upper Guadiana Basin*

				States of input variables			
Input variables	**Price of water rights paid by the Water Authority (€/m3)**			*Low (3000 - 6000)*	*Low (3000 - 6000)*	*High (9000 – 12000)*	*High (9000 – 12000)*
	Level of compliance			*High*	*Low*	*High*	*Low*
Output variables	**Sell of water rights (% rights sold)**	*States*	*0%*	0,837	0,837	0,607	0,607
			50%	0,125	0,125	0,280	0,280
			100%	0,038	0,038	0,113	0,113
	Total farm income (€/ha)	*States*	*< 150*	0,250	0,160	0,325	0,280
			300 - 700	0,105	0,030	0,105	0,065
			700 - 1200	0,630	0,780	0,550	0,655
	Wetlands recovery	*States*	*Yes*	0,557	0,439	0,576	0,510
			No	0,443	0,561	0,424	0,400

6. CONCLUSIONS

- Bayesian networks have demonstrated to be a tool which is able to respond to the Water Framework Directive requirements in water management: (1) Taking into account the hydrological system, the socio-economic and the environmental dimensions, as well as all the aspects involved with the overall water use in the basin. (2) The need to involve users and stakeholders in the resource management and to increase public participation.

- The participatory construction of the Bayesian network implies the representation of a complex reality that, when analyzed as a whole by the stakeholders, may be enough simplified to facilitate its use, but at the same time we make sure that variables considered as important by stakeholders are taken into account.

- Regarding the results of simulations, although this is a preliminary model, we can conclude that the level of compliance with policies (Water Abstraction Plan) is a key element in the water level recovery. However, the compliance with water restrictions leads to important loses in farm income. That is the reason why irrigators show a strong opposition to water policies implemented by the River Basin Authority, which has had to face high social costs due to the enforcement of their policies. In this sense, a legitimation of the Water Abstraction Plan is expected thanks to the Water Framework Directive, allowing a reduction of social costs.

- It is not possible to get to a reduction in water abstractions such as to attain the water level recovery in the aquifer and the recovery of wetlands without a loss in socio-economic welfare in the agricultural sector. Water restrictions imply a decrease in farm income for many farmers, who would be pressed to abandon the agricultural activity. One possibility to reduce the effects of this phenomenon could be the purchase of water rights by water authority. This would lead to a reduction of water abstractions, while compensation would be provided to farmers who decide to sell their rights, although it may result in the abandonment of part of the farming activity.

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