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Integrated water resources management of overexploited hydrogeological systems using Object-Oriented Bayesian Networks

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ABSTRACT

Object-Oriented Bayesian Networks (OOBNs) have been used increasingly over the past few decades in fields as diverse as medicine, transport and aeronautics. In this paper, OOBNs are applied to the domain of integrated water management and used as a Decision Support System (DSS). This pioneering study, set in the Altiplano region of Murcia in Southern Spain, describes a method for the integrated analysis of a complex water system supplied by groundwater from four aquifers. This method is based on the development of a multivariable integrated technique based on Bayes' theorem. After identifying all relevant factors related to water management in the area these were then translated to variables within a Bayesian Network (BN) and the relationships between them investigated. Each network represented one of the four aquifer units. These individual BNs were then linked to form an OOBN which was used to represent the complex real-world situation. In this way a DSS to simulate the entire water system was constructed using a group of conventional Bns, linked to produce an OOBN. The main stakeholders of the region contributed to network design and construction throughout the entire process. The paper shows how this type of DSS can be used to evaluate the impacts of a range of management strategies that are available to local planners.

1. Introduction

The ever increasing demand for water the world over presents water managers with a myriad of challenges on many fronts. In Europe, the Water Framework Directive (WFD – Directive 2000/60/EC) adopts the philosophy of sustainability (World Commission on Environment and Development, 1987), and obliges all Member States to prepare Water Basin Management Plans by late 2009, in accordance with the principles of Integrated Water Resource Management (IWRM), and with the express requirement of active stakeholder participation in the planning process.

The concept of IWRM has been promoted at numerous international conferences such as the United Nations Conference in Mar del Plata (UNDP, 1977), the International Conference on Water and Environment in Dublin (WMO, 1992), and the Earth Summit in Rio de Janeiro (UNDP, 1992). The theory of integrated management is generally well accepted, but its implementation is fraught with problems. To achieve genuine integration the management strategy needs to be multi-disciplinary and to be capable of taking into account all relevant aspects related to the question of water management. This means evaluating not only the technical and scientific dimensions of a water system, but the economic, political, legislative and organizational aspects, which are equally important. There are many definitions of IWRM, and each one takes a different approach (Heinz et al., 2007; DWAF, 2003; GWP, 2000; Prato and Fulcher, 1998). According to Heinz et al. (2007) "Effective water management combines economic concepts and methods with engineering and hydrologic expertise". In addition, when proceeding to management analysis, it is necessary to have participation by the stakeholders in the water situation, so that they can have the opportunity to identify the issues that are most important to them; even though this may give rise to conflicts and opposing opinions, the process is enriched by it and consensus solutions may be found. The concept of integration means that the impact produced by a given type of management or by a specific decision is not limited to water availability, but may also span related aspects of the resource and its medium. In this sense, it has been remarked that "Many watershed management problems require holistic, integrated solutions" (Prato and Fulcher, 1998).

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In the present study a model based on an Object-Oriented Bayesian Network (OOBN) has been applied as an integrating tool to a water system supplied from four different aquifers, in a region with a semiarid climate, where the water deficit is extreme and water abstraction considerably exceeds recharge. These networks, ultimately, forms a Decision Support System (DSS) that enables managers to identify water supply scenarios and policies that are appropriate to the area. The case study is taken from the Altiplano region of Murcia in south east Spain where large irrigation demands have caused massive overexploitation of local groundwater sources, leading to water level drawdowns of up to 200 m.

The aim of this paper is firstly to show an OOBN model which was developed to assess the impact of a range of management interventions identified during the study and secondly to present the results obtained through the application.

The paper is structured as follows: Section 2, a description of the IWRM approach; Section 3, a description of the OOBNs approach; Section 4, a description of the model building processing; Section 5, the results of the research; and finally Section 6, the main conclusions to be drawn from the study.

2. Integrated water management of overexploited aquifers systems

Water systems depending on groundwater sources are particularly vulnerable to the overexploitation of the aquifers on which they depend. This problem is particularly prevalent in arid and semiarid regions where precipitation is low but where other conditions make it favourable to human settlement and economic development. The use of groundwater in such areas to supply extensive areas of irrigated land has been the foundation of agricultural and economic development in many countries over the past few decades (Martín de Santa Olalla et al., 2006). Groundwater for irrigation has transformed large areas of land with limited agricultural potential into regions of high productivity leading to unprecedented economic development. As a result agricultural income and the rural population has both increased. Good examples of this type of development are the central and south west areas of the USA and Mexico. In these cases, however, development has come at a cost; overexploitation of the aquifers supplying irrigation demand has led to an unsustainable situation manifested by long-term groundwater level drawdown. In California overexploitation had risen to about 5000 $Mm^3\,yr^{-1}$ by the mid 1950s, and was still 2500 $Mm^3\,yr^{-1}$ by the late 1980s and early 1990s (UNESCO, 2006; Schlager, 2006). In Spain, intensive exploitation currently amounts to some 700 $Mm^3\,yr^{-1}$ (Custodio, 2002). Most of these cases are in south east Spain, where numerous aquifers have been affected by intensive exploitation of groundwater for several decades. For example, in the Alto and Medio Vinalopó regions in Alicante, and in the Altiplano of Murcia, various aquifers (Jumilla-Villena, Ascoy-Sopalmo, Serral-Salinas, among others) have been severely affected. In some, piezometric levels have fallen by over 200 m during a period of 30 years. This has raised the cost of water extraction, and damaged the environment as springs have dried up and related wetlands have become desiccated. On the other hand, intensive groundwater use has had a positive impact by increasing agricultural income leading to population growth and allied socio-economic benefits.

The water management challenge in these areas is to develop strategies that are able to strike a balance between water resource sustainability and agricultural sector profit. According to the WFD at least two conditions are necessary for the development of effective strategies. The first is the active participation of stakeholders in the management and decision-making process; the second is the application of tools that enable the problem to be tackled in an integrated way using multi-disciplinary skills. Only by ensuring these conditions acceptable, sustainable strategies and policies can be formulated and more importantly implemented.

Tools used to support the implemention of IWRM can be divided into two main groups, models and Decision Support Systems (DSSs) (Barthel et al., 2008). Models are descriptions of a real-world system that simplify calculation and prediction. However, although these models are highly useful for studying water resources and impacts on the environment, in most cases they are not designed to address and integrate widely-varying aspects such as the socio-economic, legal and cultural issues related to water management (Henriksen et al., 2006). DSSs are considered the best tool for approaching an integrated analysis of water management. Such systems apply reason similar to that of a human being, who is the expert in the subject (Stevens, 1984). These systems are provided with data from many diverse sources of information, including experimental results, field survey data, and even those obtained from traditional models. There are many types of DSSs such as mathematical models, influence diagrams, decision trees, multi-criteria analysis or multiobjective optimization. In addition, there are also several commercial software packages, specifically designed for each type of DSS, (Cain, 2001). DSSs can be either stochastic or deterministic, depending on whether or not; they deal with processes containing a degree of uncertainty. Stochastic DSSs are further sub-divided depending on how uncertainty is dealt with, and include methods such as certainty factors (Buchanan and Shortlife, 1984), evidence theory (Sapher, 1976) and probabilistic methods. In this study, the selected technique is a probabilistic method: Object-Oriented Bayesian Networks (OOBNs).

3. Object-Oriented Bayesian Networks (OOBNs)

A Bayesian Network (BN) is a type of Decision Support System (DSS) based on a probability theory which implements Bayes' rule (Pearl, 1988; Jensen, 1996; Jensen, 2001; Bayes, 1991). The multilateral properties of belief networks appear to allow their use in multiple ways in resource and environmental modelling (Varis and Kuikka, 1999). According to Cain (2001), a BN can also be defined as follows: "Some nodes that represent random variables that interact with others. These interactions are expressed like connections between variables". The use of BNs presents a series of advantages over that of other Environmental DSSs, as mentioned in previous studies (Bromley, 2003, 2005; Castelletti and Soncini-Sessa, 2007). For instance, according to Borsuk et al. (2004), the graphical structure explicitly represents a cause–effect relationship between system variables that may be obscured under other approaches. BNs have been used as decision support systems for many years in many fields such as medicine, road safety and artificial intelligence; however, they have not been widely applied to environmental systems until more recently (Ordóñez Galán et al., 2009). Increasingly, BNs are being used to model diverse problems of high complexity for water management applications (Borsuk et al., 2004; Bromley et al., 2005; Castelletti and Soncini-Sessa, 2007; Domínguez, 2004; Farmani et al., 2009; Henriksen and Barlebo, 2007; Little et al., 2004; Malekmohammadi et al., 2009; Martín de Santa Olalla et al., 2006; Morteza Mesbah et al., 2009; Ticehurst et al., 2007; Varis and Fraboulet-Jussila, 2002).

As an example we can take the case of rainfall and river flow. Past information will provide prior knowledge of what the river flow is likely to be under the existing rainfall regime. However, if we know that rainfall is forecast to decrease as a result of climate change, we could use this new 'evidence' to revise and update our estimate of river flows in the future using Bayes' rule (Henriksen and Barlebo, 2007).

A BN consists of three main elements: (1) a set of variables that represent the factors relevant to a particular environmental system or problem; (2) the relationships between these variables that quantify the links between variables and (3) the set of conditional probability tables (CPTs) that quantify the links between variables and are used to calculate the state of nodes. The first two elements form a Bayesian Diagram and the addition of the third forms a full network.

A BN can be run as a stand alone network. But it is possible to link together a number of networks to produce an Object-Oriented Bayesian Network (OOBN) model (Koller and Pfeffer, 1997). OOBNs are based on the Object-Oriented Programming paradigm (OOP) and thus adopt the same attributes used in OOP languages (Koller and Pfeffer, 1997; Weidl et al., 2005). OOP techniques and languages include features such as encapsulation, modularity, polymorphism, and inheritance (defined below) (Armstrong, 2006). The traditional programming approach tends to separate data from behaviour, whereas in OOP this separation is not necessary; the result is that real-world phenomena can be represented in a much more realistic way (Booch, 1996). As Wirth (2006) states "*this paradigm closely reflects the structure of systems in the real-world, and it is, therefore, well suited to model complex systems with complex behaviour*".

A conventional BN is a single system that is unable to receive or transmit information from outside the network. In contrast an OOBN represents a number of networks that can be linked together such that it is possible to transfer information from one to the other. The transfer of information is accomplished through the creation of output and input nodes in each network. These types of node are able to import and export information outside individual networks; these linking nodes are called interface nodes. Together the interface nodes form what in Object-Oriented programming terminology is known as an 'instance node', which in effect represents an 'instance' of another network (Fig. 1). In object-oriented terms each network becomes equivalent to a class.

Object-oriented networks are a hierarchical description (or model) of real-world problems that mirror the way in which humans conceptualise complex systems. To cope with complexity humans think in terms of hierarchies of different classes. For instance, when considering the economic viability of an agricultural system, the human thought process might regard the problem in terms of three hierarchical classes: 'income source', 'crops', and 'vines'. In this scheme 'income source' is the most general class, which includes both crops and vines. At a lower level the class 'crops' will include a whole range of crop types, one of which might be vines. When considering this problem the human mind will abstract selectively from this hierarchy of class types. The use of instance nodes provides support for working with these different levels of abstraction in the construction of object-oriented network models.

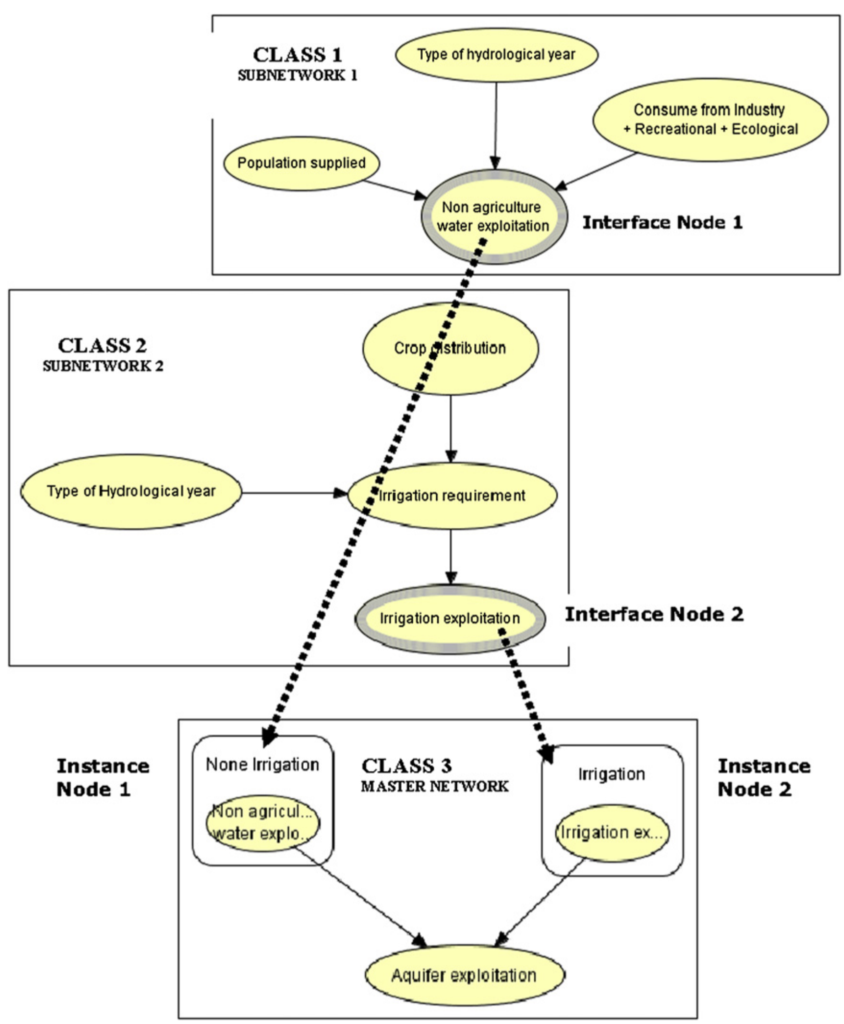

Fig. 1. Example of a simple OOBN application for integrated groundwater management.

There are three main programming features that characterize Object-Oriented programming and consequently OOBNs:

(1) *Encapsulation*: the encapsulation of the internal details of a class means that some objects can be hidden; only those objects required for interfacing with other classes need to be exposed.
(2) *Inheritance*: inheritance allows a class to inherit the attributes and methods of another class. This type of hierarchy allows the creation of brand new classes by abstracting common attributes and behaviours. This property means that attributes from a class (network) can simply be inherited by a sub-class (sub-network); it is not necessary to duplicate the attributes in both. For example if we have a class ‘crops’ then the classes ‘vine’ and ‘olives’ will automatically inherit the common attributes of the parent class ‘crop’. This function simply allows parts of the OOBN code to be re-used; because they don’t need to be repeated this leads to more efficient program execution.
(3) *Polymorphism*: finally, the feature of polymorphism allows objects to be of different types or nature, thus allowing an accurate representation of the real-world. This means for instance that economic, physical, social and other variables can all be represented together within a network, something which is essential if real-world environmental problems are to be realistically represented. A further advantage of OOBNs is that systems are often composed of collections of identical or almost identical components, models of many systems contain repetitive patterns (i.e., commonly occurring solutions or problem types). To stay with the crop analogy, the process by which income is earned through the class ‘vine’ will be repeated for a host of other crops. In Bayesian networks and influence diagrams, such patterns are manifested as network fragments. The notion of instance nodes makes it very easy to construct multiple identical instances of a network fragment. Finally, describing a network in a hierarchical fashion makes the network much less cluttered, and provides a better means to communicate ideas among users.

OOBNs can be utilized in two ways. First, they can be used for “time slicing”. This is useful for problems in which processes take place over multiple time periods. Because BNs are not intended for transient analysis, time slicing provides one way to generate predictive simulations. An example of this is given in Fig. 2 which shows how the future spread of a disease can be simulated over three time slices (Kjærulff, 2004). The second way in which OOBNs can be used is to form Sub- and Master-Networks, referred to here as an “organizational” application (Fig. 1). A sub-network is a network that forms part of a larger model, itself made up of other networks. A Master Network is a network that is used to describe the overall behaviour of a system; it receives and integrates information from multiple sub-networks. This is the approach that has been adopted for the current study where networks representing different spatial domains are linked to a central integrated network; this has been done for a single time step (1 year). Care was taken to develop a structure to accurately represent the real world and reflect the true nature of the relationships between the different elements of the model. The hierarchy and inheritance between objects has been properly represented and the model represents an accurate configuration of the real-world problem.

To summarize, an OOBN is a network that in addition to the usual network nodes, contains instance nodes. Instance nodes represent an instance of another network, and provide the means by which networks are linked. The links are made via interface (input and output) nodes that are embedded within the instance nodes. Note that instance nodes should be viewed as a copy of the network of which it is an instance. Instance nodes only comprise a subset of the nodes (interface nodes) in the master network, while nodes that are not directly connected to other networks are said to be hidden.

4. Model building

4.1. Study area

This study is set mainly in Murcia province that makes up 60% of the Segura Basin. It is focused on the Altiplano region, which has a total population of about 58,000 and includes the towns of Jumilla and Yecla (Fig. 3). Although centred on the Altiplano, the investigation also extends to the surrounding areas to which groundwater from the Altiplano is exported. The Altiplano is bounded to the east by the river Vinalopó, to the south by the sub-regions of Oriental and Vega Alta de Segura, and to the north and west by the province of Albacete. Agriculture is the main economic activity, which is characterized by high profitability.

The main consumer sectors of water in the area are agriculture and tourism. Demand for both activities is at its height during the summer months, when availability is inconveniently at its lowest. This problem has led to strict regulation of surface water use and to the increasing exploitation of groundwater to make up deficiencies in supply. At present the demand in Segura Basin (SE Spain) from all sectors exceeds available supplies, and has led to a looming crisis in the whole region.

Every aquifer in the area supplies an irrigated area, officially defined by the Basin Water Agency and form the natural basis for any agro-economic study. There are four aquifers in the Altiplano: the (1) Ascoy-Sopalmo, (2) Cingla, (3) Jumilla-Villena and (4) Serral-Salinas aquifers. The only water available for irrigation is supplied by these four aquifers. The boundaries of each of the aquifers extend beyond the boundaries of the Altiplano and of the hydrographic region. Administratively, the first two aquifers belong exclusively to the Segura River Basin Authority (CHS, 1997). The others are shared with the Júcar River Basin Authority (CHJ, 1997), and the Alicante regions of Alto and Medio Vinalopó, which belong to the Valencia Autonomous Community (Fig. 3). In the past the Altiplano has been specifically excluded from all major water supply projects that have been carried out in south east Spain, such as the Tajo-Segura water-transfer scheme and the “Mancomunidad de Canales del Taibilla”, the latter being dedicated exclusively to providing water supply for human consumption. Furthermore no

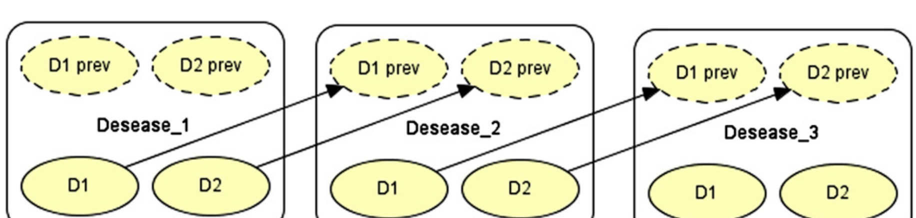

Fig. 2. Example of “time slicing” application for a disease problem. Taken from Kjærulff (2004).

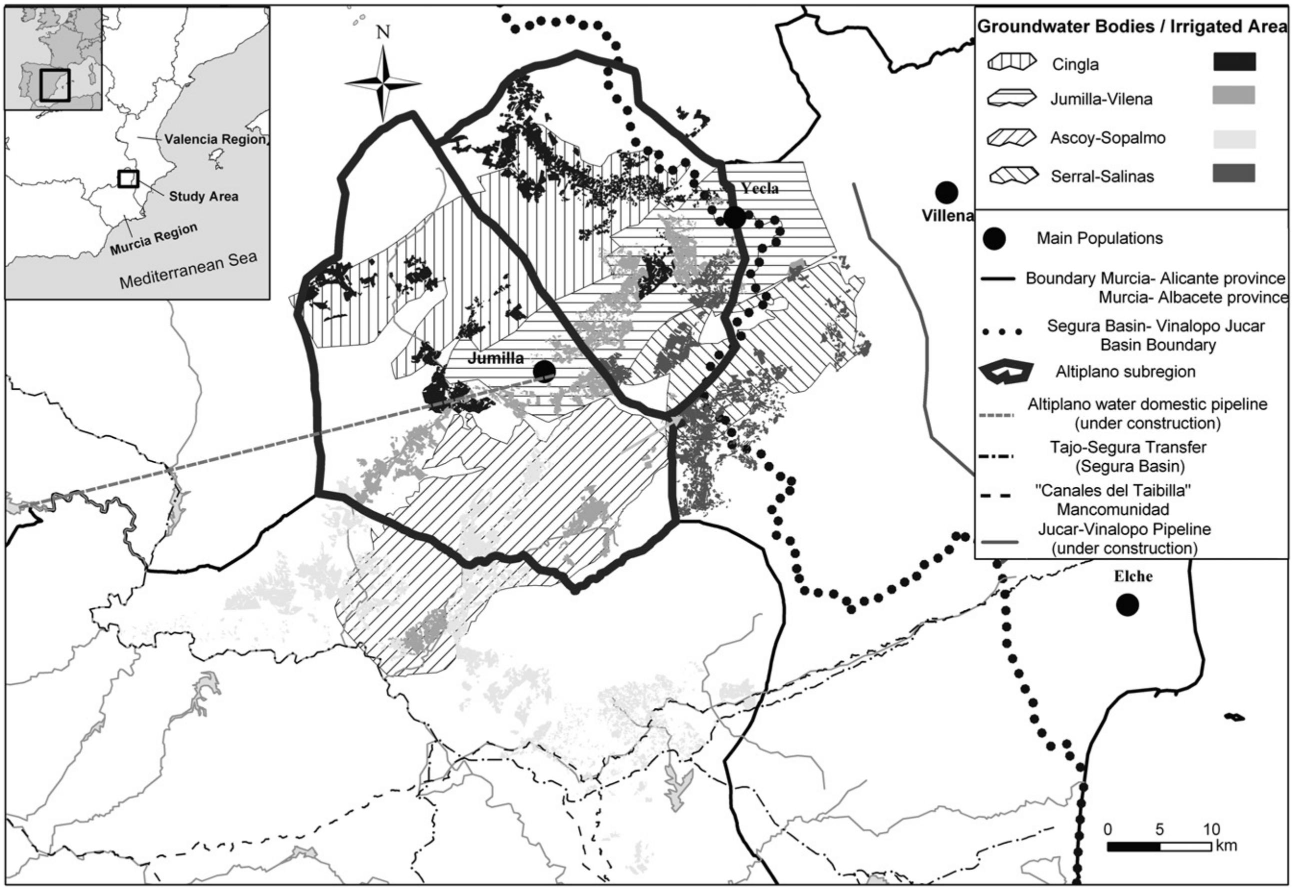

Fig. 3. Main groundwater bodies and their related irrigated areas estimated by Remote Sensing.

water management interventions have been carried out in the region by any administration. Recently, however, some measures have been implemented in an attempt to alleviate the water problems faced in the region. The main measure has been the connection of the public water supply systems of Jumilla and Yecla to the "Mancomunidad de Canales del Taibilla", via a conduit through the Talave-Cenajo system, thus providing access to water from the Tajo-Segura water-transfer network. Recently, within the framework of the hydrological planning process, different scenarios aimed to reduce the degree of overexploitation, have been preliminarily evaluated in economic terms (Esquema de Temas Importantes, 2008; CHS, 2008).

4.2. Hydrogeological study

With regard to the study of the hydrologic and hydrogeologic aspects of the area, the investigation was focused, for every aquifer, on the hydrometeorologic analysis needed to assess aquifer recharge, on quantifying pumped abstraction and on calculating the consumption of water reserves. The average precipitation in the region is about 300 mm/year, with a marked interannual variation (in some cases over 100%), and occasionally intense rainfall that can exceed 100 mm d^{-1}, but very low spatial variation within the study area. Recharge was evaluated from a daily 30 year hydro-meteorological record using the Visual Balance (Samper et al., 1999) water balance code. The renewable water resources for the four aquifers is 35 $Mm^3\,yr^{-1}$, this being derived exclusively from the infiltration of precipitation onto permeable outcrops (Table 1). The application of these methods revealed a scarcity of existing data for models calibration, It also highlighted problems and uncertainties concerning the evaluation of the recharge, due among other reasons to our lack of knowledge about the natural regime of the aquifers. Pumped abstraction can only be estimated indirectly, as very few boreholes are fitted with volumetric control meters. In this study, the volume and rate of water abstraction is estimated by studying bibliographic records and from field surveys of the main water users. At present, there are about 125 active boreholes and their average rate of exploitation over the last 10 years amounts to some 147 $Mm^3\,yr^{-1}$. However, the number of boreholes actually drilled in the area may be up to four times higher, not counting those that have been replaced

Table 1
Annual water budget of the groundwater masses and drawdown rates.

Groundwater mass	Cingla	Jumilla-villena	Ascoy-sopalmo	Serral-salinas	Total
Recharge (mill m^3/year)	13	15	2	5	35
Actual pumping (mill m^3/year)	30	46	52	18	147
Storage variation (mill m^3/year)	-17	−31	−50	−13	−111
Total drawdown since natural regime (m)	25	115	187	130 (Occidental sector) 290 (Oriental sector)	
Average water table depletion rate during the last ten years (m/year)	1.3	3.5	4.5	4.9 (Occidental sector) 10.5 (Oriental sector)	

or deepened; thus, the total financial investment made has been very significant. The water balances calculated from the above data are clearly negative (Table 1), which points to a notable consumption of water reserves (-111 $Mm^3 yr^{-1}$ and an accumulated drawdown exceeding 3000 $Mm^3 yr^{-1}$). The rates of drawdown of the piezometric levels have exceeded 10 $m\,yr^{-1}$ in some sectors of the aquifers, these figures being amongst the highest in Spain.

From these hydrogeological studies a groundwater flux model using MODFLOW (McDonald and Harbaugh, 1988) was constructed for each aquifer. The output of these models regarding to aquifer water balances was the input information introduced in the DSS (Table 1).

4.3. Socio-economic study

The socio-economic study included an analysis of the uses and demands for water, and their repercussions on the local society and economy. Total water demand was estimated using the data contained in the Segura (CHS, 1997) and Júcar (CHJ, 1997) catchment hydrologic plans, augmented by other information collected during this research.. In the case of the Segura catchment area, the gross water demand for irrigation from the 30,000 ha area supplied by the four aquifers is 135 $Mm^3 yr^{-1}$.

Concerning agro-economic issues, to examine the relationship between agro-economy and groundwater availability a model of 22

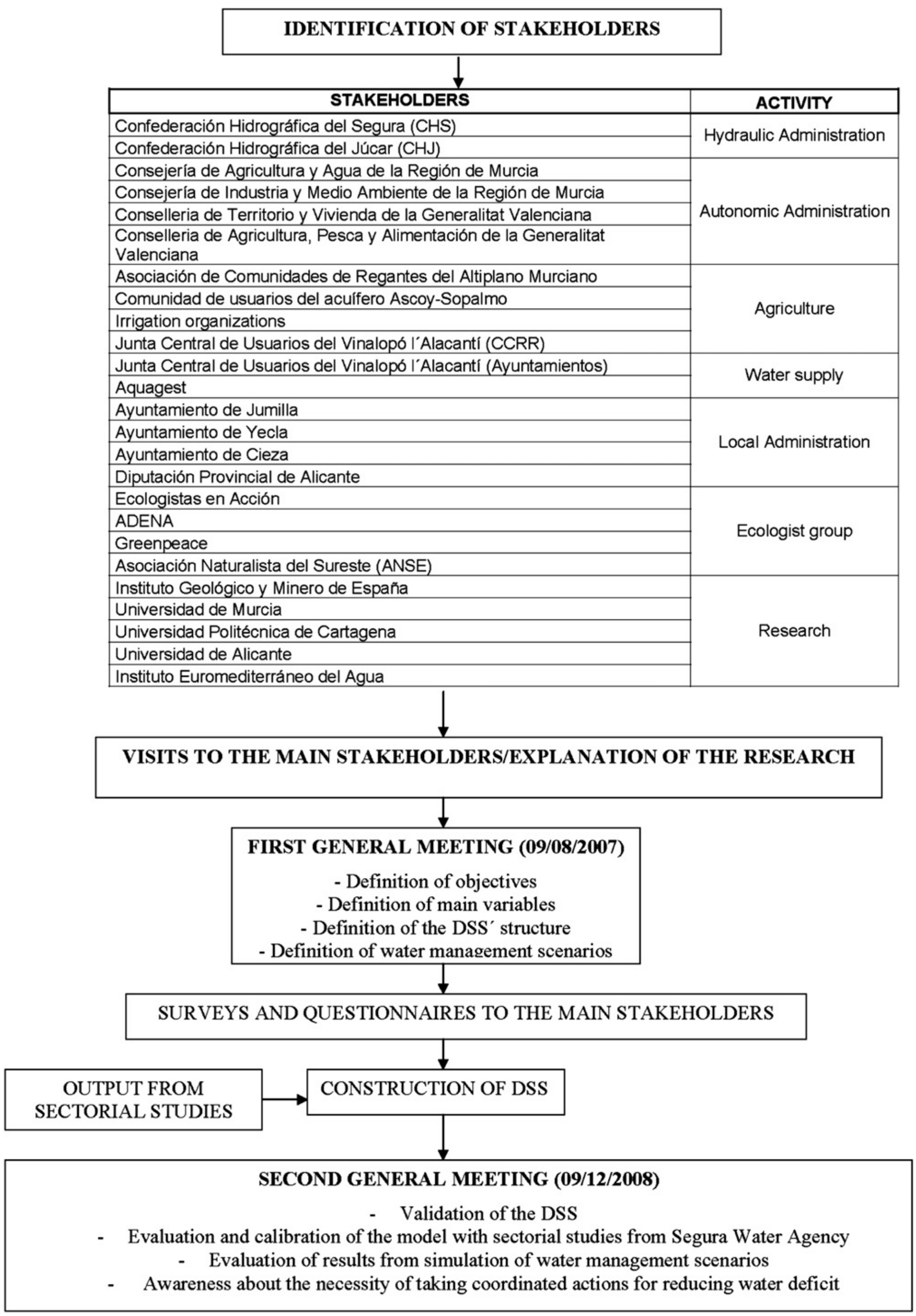

Fig. 4. Stakeholderś engagement process.

different types of crop was developed The crops irrigated are non-citric fruits (apricots, peaches, pears), which occupy 35% of the surface area but represent 58% of water requirements. In contrast wine grapes occupy 25% of the surface area but account for only 7% of water demand. The Júcar catchment area, on the other hand, contains large areas of irrigated crops in the Alto and Medio Vinalopó, and in Campo de Alicante (over 40,000 ha, in all), with a total water requirements of some 155 $Mm^3 yr^{-1}$; this demand is partly met from the groundwater of Jumilla-Villena and Serral-Salinas aquifers. Most of these crops are outside the boundaries of the Altiplano area, which has a total irrigated surface area of about 18,000 ha (55% in Yecla and 45% in Jumilla).

Despite the great depth at which the groundwater is located, extraction costs do not exceed 15% of total agricultural costs. The average abstraction cost is currently 0.18 €/m^3, including investment in infrastructures. These values rise slightly with increased drawdown of piezometric levels, but it is difficult to establish a precise relationship, since it is strongly influenced by electricity consumption, the price of which is established by direct negotiation between each user and the electricity company (approximately 0.06–0.10 €/kwh). Thus, cost of groundwater is not a major limiting factor to agricultural profitability in the zone; the real problem is the scarcity of water and in the potential exhaustion of reserves.

Fruit crops are the most profitable in the area, because their productivity is very high (30–35 tonnes/ha year); despite high relative costs, recent years have been good in this respect. The average net margin for fruit crops in the area has been estimated at 8000 € ha^{-1}. The yield of table grapes is comparable to that of the fruit crops, and grapes are currently profitable due to high market prices. In the case of wine grapes, yields are much lower (7 tonnes $ha^{-1} yr^{-1}$) and these crops are currently loss-making.

Urban and industrial demand met from the water supply system totals some 5 $Mm^3 yr^{-1}$, satisfying the needs of over 60,000 inhabitants of the Altiplano area. In addition, about 13 $Mm^3 yr^{-1}$ is currently extracted to partially meet the urban and industrial demands of urban areas in the Vinalopó-Alacantí system, which belongs to the Júcar catchment area. The fact that groundwater represents the unique source of supply has obvious socio-economic repercussions and is a factor in urban development.

4.4. Stakeholders involvement

The Water Framework Directive (WFD) encourages the active involvement of stakeholders in environmental decision making; the earlier in the decision-making process this involvement takes place, the better (Bromley, 2005). The degree of involvement cannot be prescribed, but will depend on a number of factors: local circumstances, the time and money available for the procedure and the type of decision being made. Involvement of stakeholders ensures that decision making is better grounded and more consensual, and that all relevant socio-economic implications are taken into account (Andreu et al., 2006; López-Gunn and Martínez-Cortina, 2006). The process of building models supported by multiple sources of expertise and constituency has been studied by several transdisciplinary approaches such as Adaptive Environmental Assessment and Management (AEAM) and Integrated Assessment and Modelling (IAM) (Videira et al., 2003). There are also plenty of methodologies for tackling the collaboration of stakeholders in water management studies. Thus, in Antunes et al. (2006) Mediated Modelling (MM) is described as the process whereby stakeholders, not just clients, collaborate together in the development of a simulation model about a specific problem, usually in a series of modelling workshops supported by a facilitator (Van den Belt et al., 2000; Van den Belt, 2004). Furthermore, according to Henriksen et al. (2006), public participatory modelling (PP modelling) is a modelling process that concerns reasoning and decision making about whole systems using computer based modelling and analysis technology, and with active involvement of stakeholders. According to Voinov and Brown (2008), PP modelling is the process of incorporating stakeholders, often including the public, and decision-makers into a modelling process to support decisions involving complex natural resources questions.

In the present study a mixture of the two previous methodologies is used. Thus, public participation was secured through interviews, surveys, questionnaires and organization of general meetings where the main stakeholders had the opportunity to discuss about this research and the DSS. The stakeholder groups consulted included the regional and local water boards, agricultural organizations, research bodies and ecological groups. (Fig. 4). Data obtained from these stakeholders were included in the decision support system, and proved to be highly useful, providing genuine information input to the problem. In general, the design of the network is a conceptualisation of the problem based on the outcome of discussions with stakeholders. From discussions with stakeholders a network representing their perception of the system was constructed and in some cases they provided information for use in the Conditional Probability Tables (CPTs). By working closely with stakeholders it proved possible to construct a model that was a representation of reality acceptable to all groups.

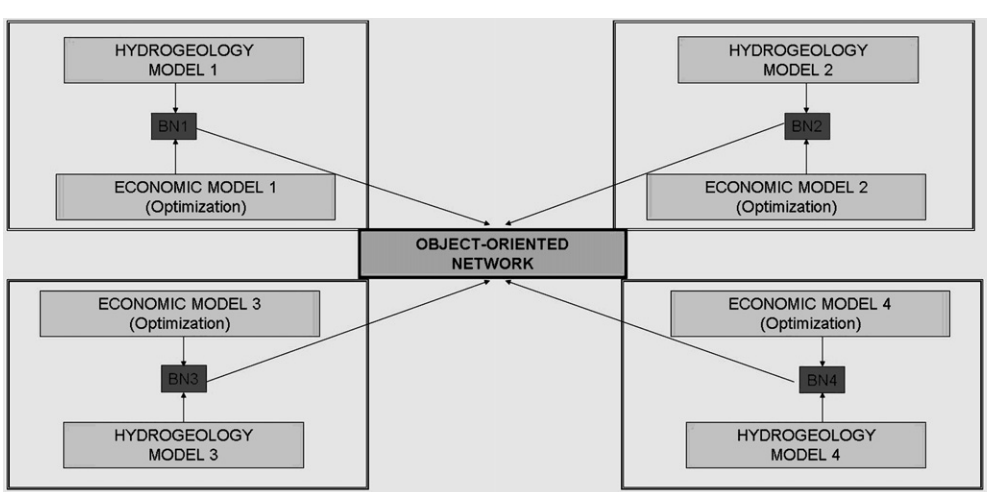

Fig. 5. Scheme of the whole model.

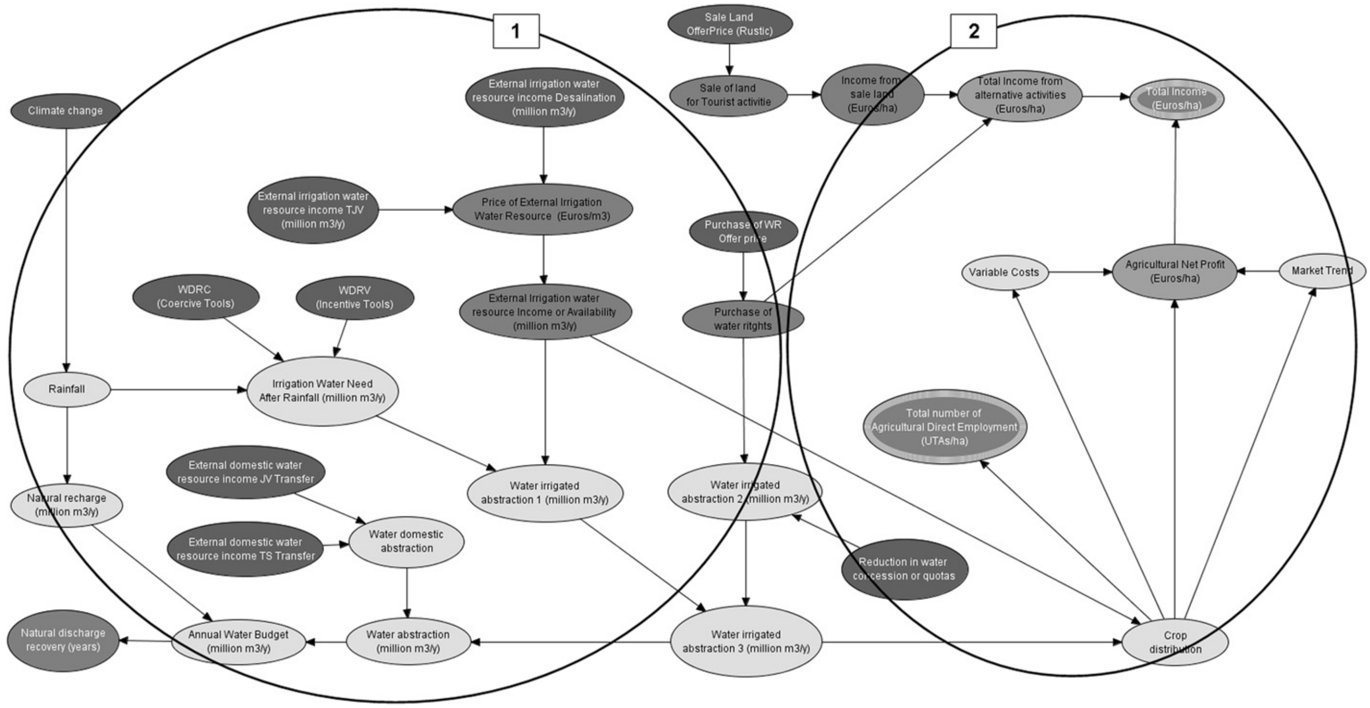

Fig. 6. Bayesian network structure for every aquifer (full version). Hydrogeological part (1), Socio-economic part (2).

4.5. Structure of the OOBNs model

The software used for building the DSS was Hugin (2007). This software utilizes the well known Bayeś theorem for calculating the conditional probability of a variable depending on a previous one by the propagation of the probability. The HUGIN software allows working with OOBNs as well as coupling with different programming codes by Application Programming Interface (API).

The system under study comprises four independent groundwater bodies and consequently it would be excessively complex, if not impractical, to incorporate all aquifers within one network. Moreover, the possibility of representing all aquifers as one system, with averaged hydrological variables, would not be realistic. For this reason, a BN has been designed specifically for each aquifer (Fig. 6). Every aquifer also has a related and specific irrigated area that does not necessarily coincide with the area of that particular aquifer. This means that water from one aquifer may be used in an area underlain by another. Although each aquifer differs hydrogeologically, they all possess the same socio-economic characteristics (variables). Because they are common to each aquifer these socio-economic variables can be identified in each network as an interface (output) node and connected to a master network where the same nodes appear and where they can be analysed jointly. This master network is used to assess the impact of the social and economic conditions in all four aquifers combined. In effect it describes the average social and economic behaviour of the whole system (Fig. 5). One of the primary benefits provided by the OOBN is that the final network inherits the socio-economic information of the four previous aquifer networks. Thus, any change in the probability distributions of the socio-economic variables in the aquifer networks will change the final network and vice versa.

BN construction follows a set procedure. Firstly the variables that describe and impact upon the system are identified; secondly the relationships between these variables are defined; and finally the CPT tables are completed based on the best data available. The timescale of the network is one year, so that all variables and data are defined accordingly. However, the system allows the possibility to step the system through time using a network for each time slice; this type of model is currently being developed.

4.6. Variables description

The BN used to describe each aquifer is divided into two main sections; one deals with the hydrogeology, the other with social and economic conditions (Fig. 6). Of course, the aquifers are not identical, which means that the configuration of each one is slightly different to reflect the specific circumstances of each aquifer. Fig. 6 and Table 2 reveal all 32 variables that appear in the aquifer networks, though not all 32 appear in each and every aquifer; the variables of the fifth network are also shown.

The hydrogeological variables were defined using the hydrogeological models developed for this research. The CPTs for hydrogeological variables were entered automatically via the Learning Wizard module,[1] using data obtained from the output of groundwater models constructed for each aquifer. This module automatically discretizes data by transforming continuous distributions into discrete counterparts (i.e. get into groups or intervals with its resultant probability). Automatically entered variables included ‘‘Rainfall’’, ‘‘Recharge’’, ‘‘Water abstraction’’ and ‘‘Annual Water Budget’’. The relationship among these variables was established within the groundwater flux models.

The socio-economic variables were defined from two ways with the agreement by the stakeholders obtained in the two general meetings: firstly from an agro-economic simulation model in which the main variables were defined; these variables are: *‘‘Crop distribution’’, ‘‘Market Trend’’, ‘‘Variable Costs’’ ‘‘Agricultural Net Profit’’, ‘‘Total number of Agricultural Direct Employment’’;* secondly, from the economic study about non-agricultural activities in which the market price of the land is the key factor (Sale of land) *‘‘Total Income from alternative activities’’,‘‘Sale of land for Tourist activities’’,’’*

[1] This module is included into the Hugin Expert System, the software used for building the OOBN model.

Table 2
Extended list of variables and their states for the four aquifer BNs.

Group	Name	Explanation	States			
			Ascoy-sopalmo	Serral-salinas	Jumilla-villena	Cingla
1. Parents	Climate change	% Annual rainfall reduction	No; medium; strong	No; medium; strong	No; medium; strong	No; medium; strong
	HDRC (coercive tools)[a]	% Reduction of agriculture water demand applying coercive tools	No reduction; 0–25; 25–50; >50	No reduction; 0–25; 25–50; >50	No reduction; 0–25; 25–50; >50	No reduction; 0–25; 25–50; >50
	HDRV (incentive tools)[a]	% Reduction of agriculture water demand applying incentive tools	No reduction; 0–25; 25–50; >50 reduction	No reduction; 0–25; 25–50; >50	No reduction; 0–25; 25–50; >50	No reduction; 0–25; 25–50; >50
	External irrigation water resource income TJV[a]	million $m^3\,y^{-1}$		0; 0–5; 5–10	0; 0–15; 15–30; 30–45	
	External irrigation water resource income desalinitation[a]	million $m^3\,y^{-1}$	0; 0–20; 20–40; 40-60	0; 0–5; 5–10	0; 0–15; 15–30; 30-45	0; 0–20; 20–40; 40–60
	Purchase of WR offer price[a]	Euros ha^{-1}	3000–6000; 6000–9000; 9000–12,000	3000–6000; 6000–9000; 9000–12,000	3000–6000; 6000–9000; 9000–12,000	3000–6000; 6000–9000; 9000–12,000
	External domestic water resource income JV Transfer[a]	Boolean (False/True)		False; True	False; True	
	External domestic water resource income TS Transfer[a]	Boolean (Y/N)		False; True	False; True	False; True
	Reduction in water concession or quotas[a]	% Reduction in total water quotas assigned	0; 0–25; 25–50; 50–100	0; 0–25; 25–50; 50–100	0; 0–25; 25–50; 50-100	0; 0–25; 25–50; 50–100
	Sale land offer price (Rustic)	Euros ha^{-1}	10,000–20,000; 20,000–50,000; >50,000	10,000–20,000; 20,000–50,000; >50,000	10,000–20,000; 20,000–50,000; >50,000	10,000–20,000; 20,000–50,000; >50,000
2. Intervention action	Price of external irrigation water resource	Euros/m^3	0.2–0.4; 0.4–0.6; 0.6–0.8	0.2–0.4; 0.4–0.6; 0.6–0.8	0.2–0.4; 0.4–0.6; 0.6–0.8	0.2–0.4; 0.4–0.6; 0.6–0.8
	External irrigation water resource income or availability	million $m^3\,y^{-1}$	0; 0–20; 20–40; 40–60	0; 0–5: 5–10	0; 0–15; 15–30; 30-45	0; 0–20; 20–40; 40–60
	Purchase of water rights	% Water rights sold by the farmers	0; 0–25; 25–50; 50–100	0; 0–25; 25–50; 50–100	0; 0–25; 25–50; 50-100	0; 0–25; 25–50; 50–100
	Sale of land for tourist activities	% Irrigated crop area sold	0–33; 33–66; 66–100	0–33; 33–66; 66–100	0–33; 33–66; 66–100	0–33; 33–66; 66–100
	Income from sale land	Euros/ha	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000
3. Intermediate nodes	Rainfall	Annual average rainfall (mm/year)	100–250; 250–400; 400–550; 550–700	100–228.75; 228.75–357.5; 357.5–486.25; 486.25–615	100–250; 250–400; 400–550; 550–700	100–250; 250–400; 400–550; 550–700
	Natural recharge	million $m^3\,y^{-1}$	0–2; 2–5	0–3.5; 3.5–7; 7–10.5; 10.5–14	0–4; 4–8; 8–12; 12–16	0–4; 4–8; 8–12; 12–16
	Irrigation water need after rainfall	million $m^3\,y^{-1}$	0–20; 20–40; 40–60; 60-80	<7.5; 7.5–10; >10	0–15; 15–30; 30–45; 45–60; 60–75	0–10; 10–20; 20–30; 30–40; >40
	Water irrigated abstraction 1	million $m^3\,y^{-1}$	0–20; 20–40; 40–60; 60–80	0–5; 5–10; 10–15; 15–20	0–15; 15–30; 30–45; 45–60; 60-75	0–10; 10–20; 20–30; 30–40; 40–60
	Water irrigated abstraction 2	million $m^3\,y^{-1}$	0–20; 20–40; 40–60; 60–80	0–5; 5–10; 10–15; 15–20	0–15; 15–30; 30–45; 45–60; 60-75	0–10; 10–20; 20–30; 30–40; 40–60
	Water irrigated abstraction 3	million $m^3\,y^{-1}$	0–20; 20–40; 40–60; 60-80	0–5; 5–10; 10–15; 15–20	0–15; 15–30; 30–45; 45–60; 60–75	0–10; 10–20; 20–30; 30–40; 40–60

(*continued on next page*)

Table 2 (*continued*)

Group	Name	Explanation	States			
			Ascoy-sopalmo	Serral-salinas	Jumilla-villena	Cingla
	Water domestic abstraction	Binary (current abstraction/none)		None; current abstraction	None; current abstraction	None; current abstraction
	Water abstraction	million $m^3 y^{-1}$		0–5; 5–10; 10–15; 15–20	0–15; 15–30; 30–45; 45–60; 60–75	0–10; 10–20; 20–30; 30–40; 40–60
	Annual water budget	million $m^3 y^{-1}$	<40; −20 to −40; 0–20; 0–2; 2–5	−11 to −19; −3 to −11; − 3–5; 5–13	−45 to −60; −30 to −45; −15 to −30; 0 to −15; 0–5; 5–0; 10–15	−20 to −40; −10 to −20; 0 to −10; 0–10; 10–20
	Crop distribution	% Crop surface	D1; D2; D3; D4	D1; D2; D3; D4	D1; D2; D3; D4	D1; D2; D3; D4
	Market trend	Trend of crops prices in the last 5 years	Strong decrease prices; light decrease prices; steady; light increase price; strong increase prices	Strong decrease prices; light decrease prices; steady; light increase price; strong increase prices	Strong decrease prices; light decrease prices; steady; light increase price; strong increase prices	Strong decrease prices; light decrease prices; steady; light increase price; strong increase prices
	Variable costs	% Increasing above Retail Price Index (RPI) RPI: 4.5%	No increasing; 5; 10	No increasing; 5; 10	No increasing; 5; 10	No increasing; 5; 10
4. Partial objectives	Total income from alternative activities	Euros ha^{-1}	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000
	Agricultural net profit	Euros ha^{-1}	0–1000; 1000–5000; 5000–10,000	0–1000; 1000–5000; 5000–10,000	0–1000; 1000–5000; 5000–10,000	0–1000; 1000–5000; 5000–10,000
5. Final objectives	Total income	Euros ha^{-1}	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000	0–1000; 1000–5000; 5000–10,000; 10,000–20,000
	Natural discharge recovery	years	Never; 300–500; 150–300; 0–150	Never; 100–200; 70–100	Never; 100–200; 50–100	Never; 25–50; 0–25
	Total number of agricultural direct employment	Number of employments/ha	0–0.1; 0.1–0.3; 0.3–0.4	0–0.1; 0.1–0.3; 0.3–0.4	0–0.1; 0.1–0.3; 0.3–0.4	0–0.1; 0.1–0.3; 0.3–0.4

[a] Parent and water management interventions.

"Income from sale land", "Sale Land Offer Price (Rustic)"and finally " Total Income" that is the sum of both ways.

For socio-economic variables the CPTs were also defined in two ways. Firstly, using an agro-economic simulation model constructed for each irrigated area. In addition, an evolutionary multiobjective optimization procedure (GANetXL, 2007) was linked to the OOBN, specifically into the economic model in order to provide a more accurate simulation of the current situation and the potential behaviour of planned crop distributions (Molina et al., submitted for publication). Secondly, CPTs for the aforementioned non-agricultural variables were defined by the economic study of land and properties.

Variables are divided into five groups according to their function in the network (Table 2). The groups are:

(1) *Parent nodes*: these are not subject to changes in the states of other nodes; in this study most parents represent proposed strategies that may or may not be implemented.
(2) *Intervention actions*: these are actions that follow from the strategies selected through the parent nodes.
(3) *Intermediate variables*: represent simulation of the intermediate processes that take place between action and objective.
(4) *Partial objectives*: intermediate objectives that contribute toward final objectives.
(5) *Final objectives*: represent the variables that are of key importance to the system; it is the states of these variables that are of most concern to stakeholders.

Finally, 'interface' variables in the system include "Total Income" and "Total Number of Agricultural Direct Employment". These variables connect to the fifth integrated ('master') network that describes the overall socio-economic conditions in the combined area of the region irrigated by all four aquifers (Table 3).

To summarize, states of the variables (Tables 2 and 3) were defined according to the outputs of the previous models made in the sectorial studies (groundwater flux models and agro-economic model), as well as according to the results from the questionnaires, surveys and the interaction in the general meetings. As in many previous studies (Borsuk et al., 2004; Bromley et al., 2005; Ticehurst et al., 2005), variables have been parameterised using either knowledge or data.

4.7. Validation of the DSS

Evaluation and validation of the DSS was conducted in collaboration with stakeholders and by using information from parallel studies being undertaken by the Segura Water Agency. Results obtained from the numerical part of the DSS based on OOBNs are in line with results of previous hydro-economic partial studies.

The whole process cannot be carried out by the analyst alone, but should be done together with the stakeholders. These water actors indicated whether the results offered by the DSS, both partial and global, are acceptable or, on the contrary, the relationships between variables, their states or their probabilities should be changed in order to make them acceptable. In order to achieve this aim, two meetings were held before we arrived at the definitive version (Fig. 4). Thus, the stakeholders' participation is justified, apart from being a WFD objective, by the fact that the DSS cannot be entirely numerically validated because is being used in a "what if" analysis. So, a "user validation" has been performed. Once the model has been validated, we can be certain that the stakeholders will trust the BN further down the decision-making process.

5. Results from simulation of water management scenarios

To assess the impacts of potential water management actions a number of scenarios were simulated and compared to the "Business As Usual" scenario (BAU). The BAU is assumed to be the current condition as described by data available in the hydrological year 2007–2008 (Figs. 7 and 8). Proposed interventions in Section 5.2 have been based on actions carried out in neighbouring basins as well as on information obtained from stakeholders. All states and probability distributions for every intervention were, as far as possible, based on information obtained from stakeholders.

5.1. Results from simulation of Business As Usual (BAU) scenario

The results of simulations representing current conditions for each aquifer and for the overall system can be summarized as follows (Table 4).

The Ascoy-Sopalmo aquifer has a 0% probability of recovery to its natural state under current conditions. On the other hand, agricultural net profit for the related irrigated area is high. The network shows there is an 80% chance of net profit falling within the range 1000–5000 euros ha^{-1} and a 20% chance of it being even higher, from 5000 to 10000 euros ha^{-1}. Given this buoyant economic situation an employment rate of 0.40 employees per hectare per year is simulated for current conditions.

The Serral-Salinas aquifer has a 3.3% probability of recovering to its natural regimen under current conditions (Fig. 4). On the contrary, agriculture is very profitable. Income over the irrigated area supplied by the aquifer is 100% likely to fall within the range 1000–5000 euros ha^{-1}. When income from other activities is taken into account there is a 13% chance it will increase to between 5000 and 10,000 euros ha^{-1}. In this aquifer there is a 30% chance that the rate of employment rate will be less than 0.1 employees per hectare per year.

For the Jumilla-Villena aquifer the chance of total recovery within a period of 100 and 200 years is 8.8%. Agricultural net profit is 100% likely to fall within the range 1000 and 5000 euros ha^{-1}.

Finally, for the Cingla aquifer thelikelihood of recovery to its natural state under current conditions is only 0.74%. Meanwhile the agricultural net profit has a 90% chance of falling between 1000 and

Table 3
Extended list of variables and their states for the fifth OOBNs.

Fifth network	Variable	States				
Intermediate nodes	Total income 1	Euros ha^{-1}	0–1000	1000–5000	5000–10,000	10,000–20,000
	Total number of agricultural direct employment 1	Number of employments/ha	0–0.1	0.1–0.3	0.3–0.4	
	Total income 2	Euros ha^{-1}	0–1000	1000–5000	5000–10,000	10,000–20,000
	Total number of agricultural direct employment 2	Number of employments/ha	0–0.1	0.1–0.3	0.3–0.4	
Overall objectives	Total income	Euros ha^{-1}	0–1000	1000–5000	5000–10000	10000–20000
	Total number of agricultural direct employment	Number of employments/ha	0–0.1	0.1–0.3	0.3–0.4	

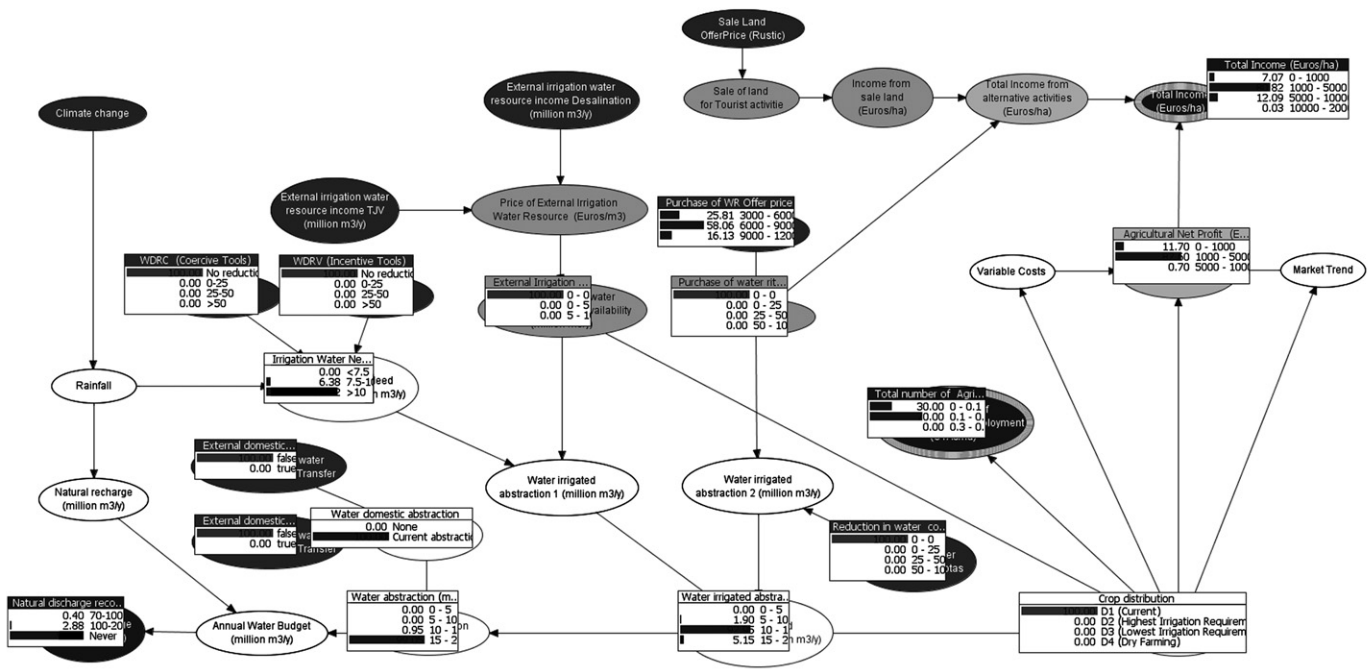

Fig. 7. Example of a single Bn with the results under current conditions (Serral-Salinas aquifer and its related irrigated area).

5000 euros ha^{-1} year and a 10% chance of being in the range 0 and 1000 euros ha^{-1}.

The overall economic behaviour of the system under current conditions is shown in Fig. 8. As things stand total income is most likely to fall between 1000 and 5000 euros ha^{-1} (82.5%) with only a remote chance (0.08%) that it might exceed 10,000 euros ha^{-1}. Finally, there is a 94.4% possibility of obtaining between 0.1 and 0.3 agricultural employments per hectare and per year.

5.2. *Results from the simulation of individual water management interventions*

The existing hydrological unsustainability of these aquifers, (Fig. 7) means the only way to restore them to their natural state is through the application of water management interventions. At the moment no interventions are underway, so the implementation of any action will lead at least to some modification of the present situation. The probability distributions of the interventions, introduced into the BNs are the results of the stakeholders' contributions made through questionnaires, surveys and the organization of meetings. In this analysis, all variables other than the intervention nodes have been maintained in their current states, in order to evaluate the impact of each intervention. The following actions have been considered:

5.2.1. *External water resource income (EWRI)*

This scenario approaches the problem from the supply side, taking irrigation and domestic supply as separate issues. For irrigation concerns, there are two approaches. The first is by external water transfer from the Jucar-Vinalopo, with water being applied to aquifers that have some surface area in the Jucar Basin (Serral-Salinas and Jumilla-Villena). The second scenario is the application of desalinated water to all aquifers. The amount of water that can actually be transferred into the water system depends to a large extent on its price. But the price paid for the water also depends upon the amount being purchased; the more that is purchased the cheaper the unit rate. To cope with the problem of supplying domestic water, two strategies have been investigated. The first is to use water imported from the Jucar-Vinalopo Transfer and to use this in aquifers that lie partly in the Jucar Basin (Serral-Salinas and Jumilla-Villena). The second scenario is to bring in water from

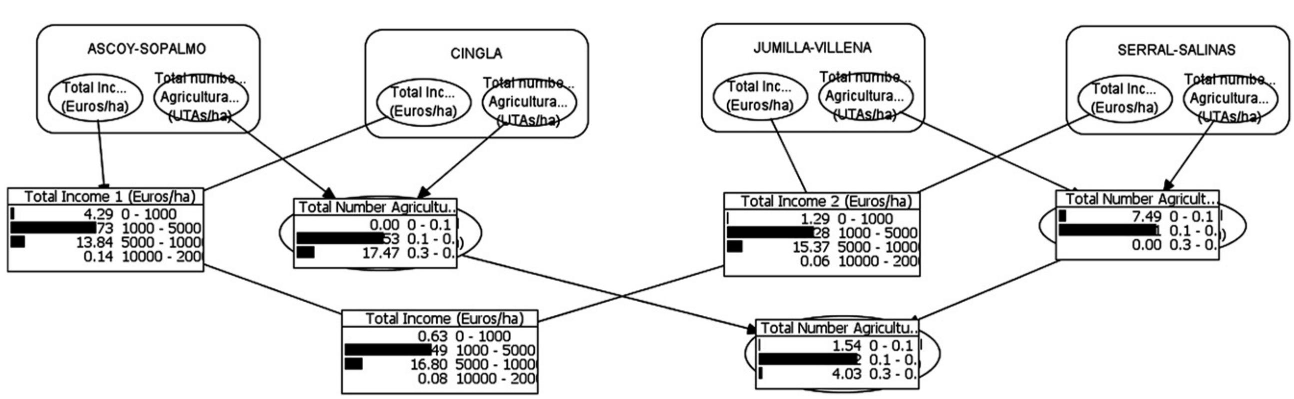

Fig. 8. Object-Oriented Network describing the overall economic behaviour of the whole system (current conditions).

Table 4
Comparison of the impacts on the objectives caused by the water management implementation, for each aquifer and for the overall system.

Aquifer	Intervention	Objective likelihood											
		Natural discharge recovery (%)		Agricultural net profit (%)			Total income (%)				Number of agricultural employment (%) (emp/ha)		
	STATES	Yes	No	0–1000	1000–5000	5000–10000	0–1000	1000–5000	5000–10,000	10,000–20,000	0–0.1	0.1–0.3	0.3–0.4
Ascoy-sopalmo	BAU	0	100	7.3	77.30	15.4	4.96	72.62	21.87	0.55	0	0	100
	EIWRI (irrigation)	0	100	7.47	72.76	19.76	5.00	69.26	25.03	0.70	0.69	0	99.31
	PWR	0	100	8.46	73.82	17.72	4.97	69.81	24.52	0.70	1.55	0	98.45
	RWR	0	100	10.04	72.96	17.01	6.42	70.25	22.73	0.61	3.21	0	96.79
	WDR	0	100	17.04	68.83	14.13	10.23	69.44	19.83	0.5	10.63	0	89.37
Serral-salinas	BAU	3.28	96.72	11.70	87.6	0.7	7.07	80.82	12.09	0.03	30	70	0
	EIWRI (irrigation)	3.86	96.14	13.46	82.16	4.38	7.92	77.42	14.48	0.18	30.29	64.57	5.14
	EDWRI (domestic)	11.63	88.37	11.52	84.45	4.03	6.94	78.41	14.48	0.17	28.85	66.52	4.63
	PWR	3.65	96.35	13.8	83.26	2.94	7.28	78.02	14.57	0.13	30.99	65.86	3.15
	RWR	3.74	96.26	14.48	82.78	2.74	8.46	78.25	13.18	0.11	31.6	65.53	2.87
	WDR	4.22	95.78	17.22	80.98	1.80	9.86	77.92	12.15	0.07	34.07	64.34	1.59
Jumilla-villena	BAU	8.78	91.22	4.4	91.9	3.70	3.32	81.34	15.19	0.15	0	100	0
	EIWRI (irrigation)	8.61	91.39	5.28	82.45	12.26	3.67	74.64	21.18	0.51	1.41	84.85	13.74
	EDWRI (domestic)	14.99	85.01	4.5	89.5	5.99	3.35	79.6	16.81	0.25	0.24	96.09	3.67
	PWR	8.52	91.48	6.77	87.73	5.51	3.95	78.41	17.39	0.25	2.58	94.38	3.03
	RWR	8.6	91.4	9.04	85.85	5.1	5.66	78.54	15.58	0.21	4.94	92.52	2.53
	WDR	8.78	91.22	14.04	82.49	3.47	8.22	77.87	13.76	0.14	10.09	89.68	0.24
Cingla	BAU	0.74	99.26	52.20	47.80	0	27.68	66.05	6.27	0	30	70	0
	EIWRI (irrigation)	4.37	95.63	44.7	44.42	10.88	23.74	60.78	15.02	0.45	26.36	58.66	14.98
	EDWRI (domestic)	0.65	99.35	47.45	46.14	6.41	25.19	63.07	11.47	0.27	27.36	63.81	8.82
	PWR	3.32	96.68	49.62	45.52	4.85	24.09	64.98	10.72	0.21	29.52	63.80	6.68
	RWR	4.28	95.72	50.25	45.22	4.53	26.64	63.41	9.76	0.19	30.23	63.54	6.23
	WDR	12.61	87.39	56.51	43.01	0.48	29.87	64.06	6.05	0.02	36.74	62.60	0.66
Overall system	BAU	Not applicable					0.63	82.49	16.8	0.08	1.54	94.42	4.04
	EIWRI (irrigation)						0.53	75.84	23.38	0.25	1.32	90.26	8.41
	EDWRI (domestic)						0.55	78.6	20.68	0.17	1.32	92.23	6.45
	PWR						0.56	78.6	20.68	0.16	1.86	92.58	5.56
	RWR						0.73	80.64	18.50	0.13	2.33	92.44	5.23
	WDR						1.10	83.73	15.10	0.07	4.44	92.26	3.30

the Tajo-Segura Transfer, for using in all the aquifers. In this case the variable states are binary (i.e. Yes or No).

5.2.2. *Purchase of water rights (PWR)*

This water management intervention has already been implemented in other Spanish basins. The success of the intervention depends on the offer price for the amount of water right (euro m^3) being acceptable to farmers. In reality, farmers are very reluctant to sell their water rights and thus need to be compensated by an extremely good offer price.

5.2.3. *Reduction in water rights (RWR)*

This tool provides an alternative to the purchase of water rights option. In this case, there is no economic compensation to farmers to reduce their water abstraction from the aquifers. Instead it is a compulsory measure that in practice is almost impossible to carry out legally. Nevertheless, it provides a target for water managers to aim at. This option has a direct and strong impact on agricultural net profit.

5.2.4. *Water demand reduction (WDR)*

This scenario approaches the problem from the demand, rather than the supply side. According to the Segura Basin Agency, the amount of water used by farmers for irrigation is close to the optimum, suggesting that a reduction in supply is not possible without causing a significant decrease in crop production. Nevertheless, despite this assertion, some scope for water demand reduction exists through improved agricultural management. Water demand measures can be implemented in one of two ways: first by coercive actions such as fines and taxes, and second through incentive means in the form of awareness raising campaigns. Reduction of demand through the second approach is likely to be much less than the first; this is reflected by the results of the network.

The results of all interventions for each aquifer are shown in Table 4. It is clear that under existing conditions the probability of any aquifer to recover to the natural state is extremely low. On the other hand, if the water management interventions are carried out to the extreme, recovery becomes more likely, but the practical problems of implementation would mount. For this evaluation, we have adopted the most realistic set of actions for each intervention, based on the results obtained from discussion with all key stakeholders.

The impact of interventions on socio-economic variables in the system, are not strong. There are two reasons for this: (1) extreme measures have not been considered, but only those that stakeholders consider reasonable, (2) most of the crops in the area are trees that cannot be changed on a year to year basis. Since the present networks only consider a time period of one year the impact of changing crops cannot be simulated. To effect a drastic change in socio-economic variables in the timescale being considered would require the implementation of extreme actions including the application of multiple interventions simultaneously. But of course these types of action are not practical in reality. This means that in the short term it is not possible to restore these aquifers to their natural state; even in the longer term full recovery is unlikely ever to be achieved. Moreover, under existing conditions it does not even seem possible to stabilise the water tables at their current levels to prevent further long-term drawdown.

6. Conclusions

This paper shows the way in which a multiple aquifer water system can be modelled and integration of hydrological, economic and social factors simulated using an Object-Oriented Bayesian Network (OOBN) approach. No water management interventions have so far been attempted in the study region so at present there is a high degree of uncertainty concerning the decision-making process. For this reason and because of the large number of variables and complex nature of the system the use of the OOBN technique is justified. To evaluate the possible impacts caused by future water management actions on the water system, some interventions have been selected and simulated by the model.

Results reveal that under current conditions there is a large negative water budget in all four aquifers. Using reasonable interventions it is not possible to recover aquifers to their natural state or in the short term to even stabilise water tables at their present day levels. Furthermore, results also reveal that any intervention to reduce drawdown will inevitably have a negative effect on agricultural income unless efficiency can be improved or other changes made to increase income (e.g. changing crops; increased market prices, etc). So far as agricultural income is concerned this varies according to the size of the irrigated area and the type of crop. The most profitable is the Ascoy-Sopalmo irrigated area and the least the Cinglás region, in this case mainly because of the type of crop.

This paper provides a practical demonstration of how an OOBN model may be used to support water resource management decision-making exemplified in the “Altiplano” region of south east Spain. It has also been demonstrated that OOBNs can be used to balance the socio-economic versus the hydrological sides of the equation. The results of the model application show the direction and the order to which the efforts should be directed. Stakeholder participation is the key to achieve the validation of this type of model, as well as strengthening collaboration and increasing confidence among stakeholders, managers and researchers.

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