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INTEGRATED WATER RESOURCE MANAGEMENT OF THE EASTERN MANCHA SYSTEM USING BAYESIAN NETWORKS

Domínguez Padilla A., Martín de Santa Olalla F.J., Artigao Ramírez A., Ortega Álvarez T.F., Brasa Ramos A., and Fabeiro Cortés C.

C.U. Dpto. Producción Vegetal y Tecnología Agraria, ETSI Agrónomos de Albacete
Universidad de Castilla-La Mancha, Campus Universitario s/n 02071 Albacete
Tel. and Fax: 967 59 92 90, email: alfonso.dominguez@uclm.es ,
francisco.santaolalla@uclm.es

ABSTRACT

Water demand is increasing on a general basis all over the world, a fact which is being aggravated by decreased water quality. Faced with this situation, the European Union regards it as a top priority that efficiency in the management and use of water resources should be improved. For this reason, since 1997, national and regional government authorities have been encouraged to develop fully comprehensive and integrated water policies, namely by taking into account all the factors involved.

Bayesian networks, mathematical models based on the probability theory, have been used recently to solve environmental problems. This methodology meets the relevant requirements to the effect that it is fully comprehensive and integrated, as it deals with the water resource as a whole and encourages the participation of all those people and groups who are somehow involved in its use or management.

The University of Castilla-La Mancha, through the MERIT Project, is developing a Bayesian network which is intended to be useful in the decision-making process related to water resource management in the Eastern Mancha System 08.29. The main problem here is the risk of overexploitation of the local aquifer, brought about by a considerable increase, over the last 30 years, in the surface area of irrigated arable land.

The tool is currently at the testing stage and expected to be fully operative by early-2004, the first results being available before the end of the Project in June of the same year.

Key words: irrigated land, overexploitation, bayesian networks, stakeholders.

1. INTRODUCTION

The use of groundwater to supply large surfaces of irrigated land has been the key to agricultural development in a large number of countries over the past few years. In arid and semiarid zones, irrigation using groundwater has transformed good quality land with low productivity (caused by drought) into areas of high productivity. Consequently, the income level of the farmers has increased and the rural population base has been maintained.

This use of groundwater should be kept sustainable by balancing abstractions with the replenishment of the aquifer. Overexploitation of the system has often been normal practice in the past, leading to serious environmental damage and contributing to the desertification process. Moreover, the exploitation of this land will eventually prove to be uneconomical in the future (Martin de Santa Olalla *et al*., 2001).

It is therefore imperative that strategies should be adopted to regulate the actual volume of water abstraction in order to sustain the level of groundwater adequately.

At least two conditions are necessary for this purpose:

- The participation of the stakeholders in the process. They need to accept that water is a limited resource. A permanent effort needs to be made to foster a greater degree of solidarity and co-operation among present and future users.

- The use of suitable tools which may ensure that the decisions made on the use of water resources will be the most adequate in each individual case. For this purpose, the use of state-of-the-art technology, particularly that based on models representing the existing relationship between the various variables which affect the hydrological System, may well prove to be of considerable assistance.

This paper discusses a case of study in the aquifer 08.29 Mancha Oriental (Spain). This case study is part of a Project known as 'Management of the Environment and Resources using Integrated Techniques', Ref. EVK1-CT-2000-00085 (MERIT), funded by the European Union, which is currently being developed and due to end in June 2004. In addition to the Eastern Mancha System, which is being studied by the University of Castilla-La Mancha, a further three hydrologic systems situated in the United Kingdom, Denmark and Italy are being addressed by research teams from these countries.

The Hydro-geological System 08.29 is located in the Southeast of the Iberian Peninsula, on the eastern side of the La Mancha plains, with a total surface area of 8.500 km^2 (IGME, 1980), as shown in Figure 1.

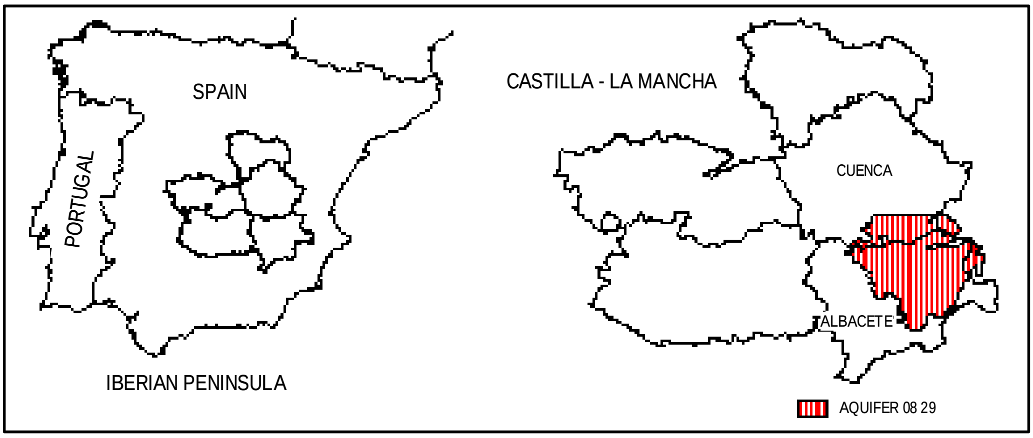

Fig. 1. Location of the 08.29 aquifer in Castilla-La Mancha (Spain).

The system supplies water to about 100,000 ha of irrigated land provided with modern irrigation facilities. The aquifer also supplies domestic and industrial water to a population of over 275,000. The annual water draft for these purposes is about 450 hm^3 (425 hm^3 for irrigation and 25 hm^3 for urban supply) (Martín de Santa Olalla *et al*., 2003 and 1999a).

The considerable development of irrigation systems during the 1975-2000 period has caused a significant decrease in the piezometric levels of this aquifer, which have been decreasing continuously since 1975 (IGME, 1980; ITAP, 2001). As a result, the aquifer is close to overexploitation (Calera *et al.,* 1999; Martín de Santa Olalla *et al.*, 1999a and 1999b). Moreover, a deterioration is being detected in the quality of groundwater, particularly as a result of an increase in the concentration of nitrates caused by agriculture (ITAP, 2001).

An Irrigation Users' Association of Eastern Mancha (IUAMO) was founded in 1994 by users of aquifer 08.29. This institution groups farmers who manage over 90,000 ha of irrigated lands, with the main aim of achieving a sustainable level of water use.

To achieve this aim, various research and technology transfer projects have been developed in this area since 1995, with the participation of teams from universities, especially from Castilla-La Mancha University, and from technology transfer institutions, such as the Instituto Técnico Agronómico Provincial (ITAP). The participation of the UIAMO has been the key to the updating of technology leading to the solution of several practical problems.

This paper seeks to attach greater importance to those contributions which utilise the stakeholders' knowledge and experience in the design of management tools. In our case, this applies to the construction and setting up of a Bayesian Network which may prove to be of assistance in the decision-making process leading to proper water resource management.

It may therefore be worth analysing briefly, at this stage, the most significant uses in the Eastern Mancha System 08.29 and, consequently, the stakeholders who should ideally take part in the work involved.

In our case, the main use is for agricultural irrigation, which accounts for about 90% of the total water consumed. Irrigators are therefore the first element to be taken into account in the management of water resources. They are represented by the Irrigation Users' Association of Eastern Mancha (IUAMO).

Urban and industrial use accounts for only 10% of the total resources involved. It is managed on a joint basis, as industrial consumers are connected to the urban network. The bodies acting as representatives in this respect are the city councils and, by delegation, the companies responsible for the supply of drinking water to municipal districts.

The third type of use to be considered, though not of a consuming nature, is the environment, when it is geared towards environmental protection of the System, as well as when it is also intended for sport or recreation. In this respect all the citizens of the community involved have the right, as well as the duty, to express their views. In practice, official representation does exist, for instance, in the form of the Ministry of Environment and various private organizations which may act as NGO's.

Along with the users as such, we believe that experts in the knowledge and management of the System's resources should also be included in the development of the Network. In our case, there are various bodies or persons ideally qualified for this task.

The opinion of users and experts is relevant for various reasons:

- Users should be really interested in the decisions to be made and it is therefore advisable to include them in the management process so that decisions are agreed on by all the parties involved. This will enable us to ease the tension between groups with conflicting interests.

- Users can contribute to the process with on-site information which may be unknown to resource managers.

- Their point of view does not have to be the same as that of experts, technicians or politicians, which increases the diversity of criteria during the development of the Project.

- Experts are essential because of their wide knowledge of the subject, which enables them to assess the likely consequences of the solutions adopted or how the system will respond to the various courses of action suggested.

The first step is to identify managers, experts and users as well as their representatives. Once they have been identified, they should be contacted and familiarized with the aim of the Project and what they will be expected to do if they are interested in participating.

2. OBJECTIVES

The aim of the MERIT Project is to construct four bayesian networks for four European basins which pose different problems in terms of water use. These networks, regardless of the way in which they may be used in the management of each Hydro-graphic Basin, are intended to act as a pilot experience for the construction of any bayesian network geared towards water resource management within the framework of the European Union or even elsewhere.

For the purpose of our study, the scientific aim is to construct a Bayesian network corresponding to the Eastern Mancha System 08.29.

As mentioned earlier, the main problem this system has to face is the overexploitation of the aquifer.

This aim cannot be achieved without the participation of users and experts willing to help the research team to design the network, establish the relationship between its variables and define the conditions of the latter, as well as to test the results generated by the model.

3. MATERIALS AND METHODS

3.1 Description of the system and its relationship with uses in other areas

The exact location of the Eastern Mancha System 08.29 is given in the introduction and can be seen in figure 1.

This System is part of a wider area known as the Jucar System. The latter includes the Hydrographic Confederation of the River Jucar, its main tributary, i.e. the Cabriel, and a number of minor rivers, most of which do not flow directly into the main river, but through infiltration into the aquifer and, through the latter, into the river.

The whole Jucar System is regulated by three major reservoirs: Alarcón, Contreras and Tous, as well as by minor dams intended for hydro-electric power generating purposes.

The Eastern Mancha aquifer 08.29 has, as its natural drainage, the river Jucar in the stretch between the two reservoirs of Alarcón and El Molinar, whose length is approximately 80 km.

In the model designed, we consider as inputs to the river Jucar the outputs from the Alarcón dam and as outputs the inputs to the El Molinar reservoir, close to the boundaries of the Regional District of Castilla-La Mancha.

Downstream of the latter reservoir, the river Jucar has to satisfy the urban, agricultural and hydro-electric demand of a significant part of the Valencian Region.

The main economic activity in the Eastern Mancha System is agriculture. Rain-fed dry-land crops prevailed until 1975 but, from then onwards, the use of irrigation became increasingly more widespread and the crops with higher water requirements acquired greater importance. The reason for this is that the gross profit margin obtained with these crops is estimated to be from five to ten times as high as that achieved with rain-fed crops (PNR, 2001). Table 1 shows the surface area occupied by irrigated crops in the System during 2002.

Table 1. Distribution of Crops in the eastern Mancha System 08.29 in 2002 (ITAP, 2003).

Crop	Surface Area (hectares)	Crop	Surface Area (hectares)
Barley	17.219	Beet	4.388
Wheat	14.613	Sunflower	1.591
Oats	729	Lucerne	10.446
Rape	157	Corn	20.631
Opium Poppy	3.339	Onion	5.869
Pea	988	Sweet Corn	1.601
Garlic	4.666	Potato	1.173
Forage Vetch	1.062	Kenaf	339
Green Pea	897	Olive, Vine and Almond	4.758
		Bean	535
Set-aside	9.754	Other	744

The size of irrigation land exploitations is also an important factor. As it can be seen in Table 2, the surface area of irrigated land above 100 ha accounts for 32% of the total. This figure shows that a significant part of the total water consumed corresponds to major exploitations which are usually provided with efficient state-of-the-art irrigation facilities. It should be pointed out that, within this group of exploitations with a surface area above 100 ha, we have included collective irrigated plots created by public initiative and organized into Agricultural Transformation Societies (SAT).

Table 2. Surface area ranges of irrigated plots related to the total surface area of irrigated land in the Hydro-geological Eastern Macha System 08.29 (JCRMO, 1999).

Surface Area Range (ha)	% of total surface area of irrigated land in the System
≤ 10	21
10 – 50	29
50 – 100	18
100 – 250	16
250 – 500	11
> 500	5

The type of irrigation system used is shown in table 3. The University of Castilla-La Mancha has made various assessments of the existing irrigation systems in the area. From the results obtained it can be discerned that, in general, pivoting systems work with average uniformity, measured through the Christiansen Coefficient of Uniformity (CU) of approximately 87% (Montero *et al*, 1998) which may be regarded as high. The current trend is a gradual decrease in the size of surface irrigated areas and an increase in that of spot irrigated land.

Table 3. Percentage Distribution of Irrigated Surface Area related to each type of Irrigation Facilities in the Eastern Mancha System 08.29 (JCRMO, 1999)

Irrigation System	Irrigated Surface Area %
Pivot	39
Sprinkling	33
Semi-fixed Sprinkling	4
Spot Irrigation	1
Surface Irrigation	12
Eventual Irrigation	11

3.2 Techniques to involve users and experts

Establishing an integrated management implies taking into account the opinions of all those who are interested, for financial, political, social, cultural, etc. reasons, in the decisions which may be made. If this stage is not covered, the implementation of the model required is less likely to be successful, as these people will regard themselves as far removed from the decision-making process and may no longer feel involved in the implementation of the decisions adopted.

In the MERIT Project, active involvement is being encouraged, particularly at the design, development and testing stages of bayesian networks, on the part of representative groups of each social sector related to the use of the water resource, as well as on the part of experts fully acquainted with the subject. The former play an essential role in the design of the network as they contribute with their own on-site information which may prove to be unavailable through alternative procedures. In addition, they are given the opportunity to make comments and suggestions throughout the development of the Project at workshops and meetings held on a regular basis.

The following method has been adopted to involve users and experts:

The first step will be to identify, by means of recognised techniques (Environment Agency, 1998) all the relevant stakeholders' groups and invite their representatives to attend meetings and workshops. Each representative, in order to be regarded as likely to provide information relevant to the development of the Project, will have to meet a number of requirements, such as, for instance, living, working or being somehow related to the area involved, being interested in participating in meetings and workshops, having some authority within the group represented, as well as being well acquainted with the problems to be analysed and the results of the decisions which may be made.

In our particular case, after identifying the users, their representatives and the experts, we explained the aims of the project, the method to be followed and what was expected from those who might decide to participate. Prospective participants were then sent a questionnaire whose aim was to identify the user, his decision-making capacity, the information made available to him on the System and to collect the data related to his activity and the opinions which he might consider to be most relevant to improve the water resource management.

A further important point to be stressed is that at each of the four sites involved a skilled facilitator will be hired to chair each of the meetings held. A team of experts in the field who belong to the University of Birmingham (United Kingdom) participate in the MERIT Project. They are responsible for monitoring meetings and achieving agreements between participants, whether users, managers or researchers. It is important to hold separate meetings by gathering first of all those who are most likely to come to an agreement and make a joint proposal. Once this aim has been achieved, we can then move on to the organization of meetings to be attended by all the parties involved. The main aim of these meetings is to identify the problems and their causes and find potential solutions for each of the study zones. These factors will eventually lead to a number of variables in the bayesian network.

3.3 Bayesian networks: System Variables

A bayesian network consists of a series of nodes representing random variables which interact with each other. These interactions are expressed as connections between variables, which should result in a cyclical structures (Cain y Abel 2001)

One node representing a variable B will be connected to a number of 'parent' nodes A_1, A_2, ..., A_n on which it depends. In this case, variable B will be a 'child' variable. These connections are expressed as probability dependences, which are quantified by means of a set of conditional probability tables (Jensen 2001). For each variable, the table shows the likelihood of a variable being in a particular condition, once its parents' conditions are known. The more information is included in these tables, the lower will be the degree of uncertainty as to the likelihood of a variable being in a particular condition. For variables with no parents, i.e. independent variables, an unconditional distribution is defined (Jensen 2001).

In order to simplify the above paragraph, a straight-forward explanatory example is given as follows. As a simplified version of what happens in reality, it can be said that starting a car at the first attempt will depend on the car having enough petrol and on the spark plugs not failing to work. This system is made up of three variables. Petrol, 'spark plugs' and starting. Both 'petrol' and 'spark plugs' are independent variables, as neither of them depends on the other's condition, whereas 'starting' depends on the remaining two variables. As explained earlier, the independent variables will be 'parent' variables and 'starting will be a 'child' variable. Figure 2 shows a diagram of this model.

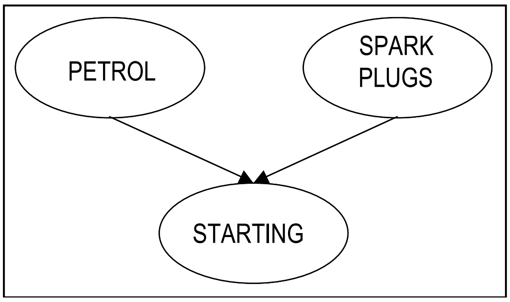

Fig. 2. Variables taking part in a car engine ignition process.

Once the relevant variables have been identified, they will have to be assigned certain conditions and the probability of the variable involved being in one of these conditions. These conditions should include all the various situations in which the variable may be, though the sensibility of the model used will ultimately depend on the number of conditions finally considered. Table 4 shows the conditions and the probabilities assigned to each of them.

Table 4. Conditions and Probabilities of the Model Variables.

PETROL		SPARK PLUGS	
Yes	0.75	Good condition	0.60
No	0.25	Fair condition	0.35
		Poor condition	0.05

STARTING						
Petrol	Yes			No		
Spark Plugs	Good condition	Fair condition	Poor condition	Good condition	Fair condition	Poor condition
Yes	0.95	0.65	0.20	0	0	0
No	0.05	0.35	0.80	1	1	1

As shown in the above table, the 'starting' variable is given, for its two conditions, a large number of situations which coincide with the combination of the conditions corresponding to its 'parent' variables. As to the value of the probabilities assigned to the latter, the probability of a given car having petrol and the likely condition of its spark plugs, this could be obtained by random sampling with the vehicles parked in a public street. In a similar manner, a test can be carried out in a garage to assess the probability of a car starting at the first attempt by combining the above situations.

In general, the probability of a variable being in a given condition can be obtained from sampling and testing, though other methods may also be used. One of the most widely used methods is the statistical processing of historical series. These probabilities can be estimated through the analysis of historical series by using custom-made tools or software (Hugin Expert S/A, 2003). In those situations in which no reliable information is available, bayesian networks enable experts on the subject to be those who assign probabilities to the condition of each variable.

It is relatively easy to identify most of the variables of any system, or even establish which variables are independent and which of them are influenced by others. The identification of variables in our System has been based on the knowledge of the research team, experts in water resource management for agricultural purposes, and on the opinions, gathered in the questionnaires, of users and experts.

The network corresponding to the eastern Mancha system is made up of a total of 49 variables arranged into 5 large groups. These groups are the water inputs to the System, environmental consumption, urban consumption, agricultural consumption and the volume of water at the output from the System. Agricultural consumption is, in turn, made up of five sub-groups. The reason for this configuration is that the largest consumer is agriculture, which makes it necessary to study in further detail each of the factors likely to affect final water consumption for irrigation purposes. Taking into account the historical series of water volumes entering the System, we can confirm that, under the present conditions, there would never be a shortage of water to meet environmental and urban requirements, which also include industrial consumption. Moreover, the low significance of these uses, and the fact that environmental users as such are not consumptive i.e. that this volume becomes available once again at the output from the system, obviates the need for any further discussion on these groups of variables for the purpose of our study.

Numbering and explaining each individual variable would be time-consuming, which is the reason why we have decided to discuss briefly the significance of each group. Regardless of this simplification, the chapter on results shows the network with all its variables and the name assigned to each of them. In some cases, to achieve full understanding of certain variables, some background knowledge may be required on the reader's part.

As mentioned earlier, the aim of this bayesian network is to construct a management model which may be used as a support tool during the decision-making process. Because the main problem faced by the System is the over-exploitation of aquifer 08.29, the network is geared towards quantifying the annual water abstractions made and assessing the extent to which this abstraction volume makes the aquifer sustainable with time. This is done by balancing consumption for the various purposes against the volume of water with which the System is replenished on a yearly basis. This balance deducts, from the initial volume available, the consumption needed to maintain the beds of the rivers flowing through the system, urban consumption and agricultural consumption. As explained earlier, environmental restrictions cannot be regarded as consumptive, but they do limit the actual availability of water. This volume becomes available once again at the output from the system.

- Group 1: 'Input volume'. This is the volume of water stored in the System in the year prior to that of the simulation.
- Group 2: 'Volume available after environmental restrictions'. This is the quantity of water after deducting from the input to the System the annual volume required to maintain the river beds at a constantly environmental level.
- Group 3: 'Volume available after urban consumption'. This is the quantity of water available after deducting the volume required to cover urban consumption.
- Group 4: 'Agricultural consumption'. This group is made up of five subgroups which are analysed below. The combination of all these subgroups is intended to estimate the volume of water abstracted from the System to be consumed by irrigated crops.
- Group 4.1: 'Technical limitations of the irrigation systems used'. The purpose of this set of variables is to estimate the efficiency of the irrigation systems fitted and the conditioning elements derived from the latter.
- Group 4.2: 'Maximum availability of irrigation water'. This group of variables represents the volume of water which is made available to irrigators every year

according to the political decisions made. These decisions are based on both physical aspects, mainly the quantity of water available in the relevant year, and legal aspects, namely the rights on the subject of irrigation water corresponding to the zone.

- Group 4.3: 'Agrarian Income'. In our case, agrarian income is clearly linked to the quantity of water used for irrigation purposes. It can be said that, in general, though this does not apply to all crops, the higher are the water requirements of a crop, the higher is its gross profit margin. If farmers do not obtain a sufficiently high level of income, they will switch to more water-consuming crops, which will entail increasing water abstractions for the whole system thus moving away from sustainability.
- Group 4.4: 'Exploitation Plan Control Capacity'. Every year, each farmer is assigned a volume of water for irrigation which is determined according to the rights to which he is entitled and to the availability of water for the year involved. With this volume, each farmer has to develop his Exploitation Plan and submit it to the JCRMO for approval. An Exploitation Plan is a document listing all the crops, as well as the surface areas allocated to each of them, which a farmer is going to cultivate during the corresponding year in his exploitation. In order to be approved, an Exploitation Plan should never exceed the volume of water originally assigned. To prevent a farmer from failing to adhere to his Exploitation Plan, i.e. to ensure that the actual surface areas or crops cultivated do correspond to those described in the Plan, the JCRMO can rely on a number of technical and legal tools to enforce compliance as well as to detect and punish any offenders. This set of variables is intended to assess the actual degree of control which is being exerted over exploitation plans. The less strict is this control, the larger will be the number of potential offenders and, as a result, the volumes of water illegally abstracted from the System.
- Group 4.5: 'Consumption for irrigated crops'. The four sets of variables described above act on this group by determining the actual quantity of water which is expected to be abstracted from the System for arable land consumption.
- Group 5: 'Volume at the output from the System'. The sum of urban and agricultural consumption should be lower than the input volume so that the volume at the output from the System may be positive. This will ensure its sustainability. Environmental consumption does not really affect the balance, as the flowing water which is infiltrated replenishes the System and that which reaches the end becomes available to the managers of the following hydrological system. It should be remembered that the surface waters of this system do not flow into the sea, but they reach the El Molinar reservoir before entering the Valencia Region.

3.4 Construction of the bayesian network

The construction of any bayesian network follows a well defined procedure. As mentioned earlier, a bayesian network is a set of interconnected variables which are assigned a number of conditions and a probability for each of the latter. A software programme processes all this information and gives the relevant results. The stages to be completed and the work carried out throughout the Project are described below.

- Identification of the variables which affect the System.

  The first step consists of the elaboration of a list of variables which affect the process to be modelled. The variables do not necessarily have to represent one element of the process. They can identify a group of factors which may be related. This technique simplifies those situations in which it is difficult to obtain information from certain parameters or where their separate individual influence may be unknown.

In the case of Eastern Mancha, the research team elaborated, in subsequent meetings, an initial document on the variables likely to have a relevant influence on the system. The identification of these variables was essentially based on the experience of each member of the team and on the information contained in the questionnaires completed by users and experts.

- Establishment of relationships between these variables.

  Once the variables have been identified, it becomes necessary to create the links which connect them and to distinguish dependent and independent variables. This process ends with the construction of a diagram showing all the variables related to each other by means of arrows, as represented in the software programme.

  As in the previous stage, during several meetings, relationships were established between the variables selected. It should be stressed that both this and the previous step were devised on a combined basis as time went by, the reason for this being that the interpretation of the significance of some variables had to be modified as the construction of the diagram progressed.

- Assignment of conditions and probabilities to each variable.

  This is the last step before entering the data into the software programme. At this stage, it is necessary to define the conditions for each of the variables, i.e. the potential values the latter are likely to acquire and the probability of their being in each of them. Conditions can be one numerical value, an interval, a probability distribution or simply a definition. The probabilities assigned are obtained from various sources: sampling, testing, databases, historical series, or even users and experts' opinions.

  The information gathered from the questionnaires proved to be of valuable assistance throughout this stage, particularly in the definition of conditions of a subjective type, as this is where the personal views of users and experts were recorded. This stage will be the most widely discussed part during the result testing period, as both the conditions assigned to each variable and the degree of accuracy in the probability assessed have considerable influence on the final result.

Once these stages have been completed, we should only need to enter this data into the software programme and test its results.

3.5 Software Tools

To construct a bayesian network, in addition to obtaining the relevant information, identifying the variables involved, relating them to each other and assigning to each of them its conditions and probabilities, we will need to have a tool available and capable of processing all this data and producing some results.

Recent advances in computer science over the past few years, particularly those related to the increase in data processing speed, along with a decrease in the price of hardware components, have made it possible to develop custom-made software needed for the construction and handling of complex bayesian networks. There are several programmes of this type currently available on the market, one of them being known as the 'Hugin Researcher' (Hugin Researcher A/S, 2003). This programme, in its version 6.1, is the one used for the construction of the various networks of the Project and has been developed by the Danish company Hugin Expert, linked to the University of Aalborg (Denmark).

One of the groups taking part in the MERIT Project is a team of experts in bayesian networks who are precisely the authors of this software. This has enabled us to rely on their continuous advice, even since the beginning of the project, both on the correct use of the programme and interpretation of its results and on the theoretical and practical principles needed for the construction of a bayesian network, regardless of the programme being used. Although the use of this programme at the operating level is fairly straight-forward, it is also true that there are a number of state-of-the art options available which require a high degree of specialization on the part of those who handle the software.

At the University of Castilla-La Mancha and, more specifically, at the School of Computer Science of the Albacete Campus, there is also a research team of experts in bayesian networks. The assistance of this team has been invaluable in the design of the Network. The fact that this is a network whose aim is to be used as a tool for the decision-making process in the management of the local water resources raises special interest on the part of this group, as their work had previously been based on theoretical networks with less practical application. They have been actively co-operating with us since the beginning of 2002, thus complementing the advice we obtain from the Aalborg group.

3.6 Testing of the network

The result given by the software programme, once all the data has been entered, is to calculate for each variable the probability distribution of its conditions as a result of its interaction with the remaining variables making up the network. Initially, probabilities are assigned to each of the conditions in which a variable may be found to be. The result given by the network does not therefore consider any particular situations, as no variables are found to be in one condition. The programme does, however, make it possible to simulate concrete situations, i.e. if certainty exists to the effect that a variable is in a certain condition, it can be assigned a 100% probability for this condition.

This concept can be clarified with an example. The variable 'Present year rainfall' is made up of three conditions, each of them representing the range of water volumes measured on the surface of the System in a year. Each of these conditions has been assigned a probability calculated as a function of the relevant historical series. This is a 'parent' variable as it does not depend on any other variables.

Similarly, we may have sufficient information available to know the particular condition of each of the remaining 'parent' variables of the network in a given year and how the System responded in this situation.

In this case, we would proceed to the validation of the System fixing at 100% the condition which includes the known value of each of the 'parent' variables. As the response of the System to this situation is known, the result given by the network should coincide with this response.

The programme offers interesting management options. It is possible fix a given result and ask the programme to assess the most likely condition in which all the variables have to be for this result to be obtained. This option, by fixing the aim to be achieved, enables the programme to show in which condition the ‘parent’ variables should be. Managers can act directly on some of these variables, such as price of water, price of inputs or funds allocated to the improvement and updating of irrigation facilities, etc. Once they know the current situation, by comparing it to the result given by the model, managers are in a better position to know where changes should be made in order to achieve their aim.

Regardless of the above, a testing process is necessary to validate the results offered by the model. In addition to a final result which may seem to be logical or coincide with a known situation, we also need to analyse, on a one-by-one basis, all the variations experienced by each variable and the results produced by a given group of intermediate variables in various conditions. The whole process should be carried out not only by the creators of the network but also by the whole group of users, experts and resource managers. They are those who should decide whether the results offered by the model, both partial and global, are acceptable or, on the contrary, the relationships between variables, their conditions or their probabilities should be changed in order to make them acceptable.

Once the model has been tested with this method, we can at least be certain that all those who are somehow involved in the use and management of the water resource can accept the tool, which should prove to be helpful in the decision-making process. This is of paramount importance, as it increases the users’ confidence in their managers and, therefore, in their decisions.

4. RESULTS

Figure 3 shows the network in its current state which, with very little variation will be its final condition.

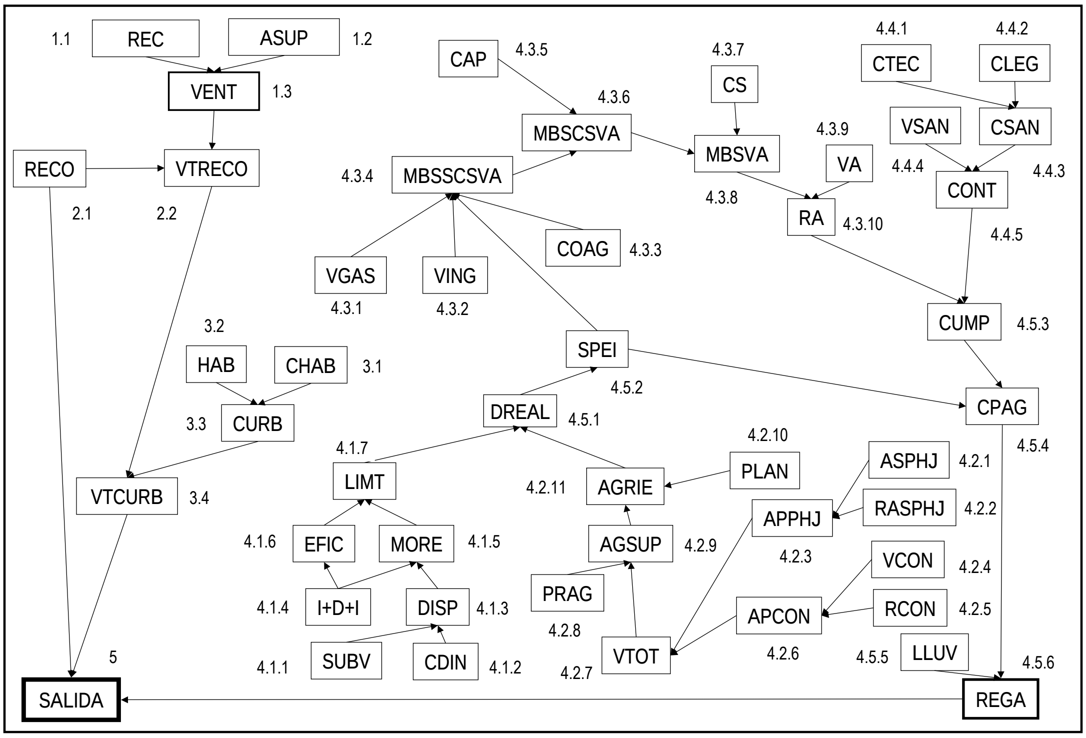

Fig. 3. Bayesian network applied to the Eastern Mancha System 08.29

Table 5 shows the meaning of the acronyms used in table 3 and their numbering.

Table 5. acronyms of the variables of the network applied to the Eastern Mancha System 08.29.

1. Water inputs		2. Volume available after environmental restrictions	
1.1 REC	Replenishment	2.1 RECO	Restrictions for ecological flows
1.2 ASUP	Annual inputs from surface water	2.2 VTRECO	Volume available after RECO
1.3 VENT	Water inputs		
3. Available volume after urban consumption		4.1 Technical limitations of irrigation systems	
3.1 CHAB	Consumption per capita	4.1.1 SUBV	Capital subsidies
3.2 HAB	Population	4.1.2 CDIN	Capital costs
3.3 CURB	Net urban consumption	4.1.3 DISP	Capital available
3.4 VTCURB	Volume available after CURB	4.1.4 I+D+i	R+D improving irrigation systems
		4.1.5 MORE	Update irrigation systems level
		4.1.6 EFIC	Efficiency
		4.1.7 LIMIT	Technical limitations of irrigation systems
4.2 Maximum volume available for irrigation		4.3 Agrarian income	
4.2.1 ASPHJ	PHJ assignations	4.3.1 VGAS	Gross inputs variation
4.2.2 RASPHJ	Technical availability to use water	4.3.2 VING	Gross income variation
4.2.3 VCON	Concessions volume	4.3.3 COAG	Water cost
4.2.4 RCON	Concessional water availability	4.3.4 MBSSCSVA	Gross margin without CAP, CS & VA
4.2.5 APPHJ	PHJ contributions	4.3.5 PAC	CAP subsidies
4.2.6 APCON	Concessions contributions	4.3.6 MBSCSVA	Gross margin without CS and VA
4.2.7 VTOT	Total volume without water price	4.3.7 CS	Social determinants
4.2.8 AGSUP	Available surface water	4.3.8 MBSVA	Gross margin without VA
4.2.9 PRAG	Surface water price	4.3.9 VA	Water sale
4.2.10 AGRIE	Maximum volume for irrigation	4.3.10 RA	Agrarian income
4.2.11 PLAN	Annual groundwater exploitation plan		
4.4 Exploitation water plan control		4.5 Irrigation consumption	
4.4.1 CTEC	Technical tools	4.5.1 DREAL	Actual volume available for irrigation
4.4.2 CLEG	Legal tools	4.5.2 SPEI	Σ individual exploitation water plans
4.4.3 CSAN	Possible sanctioning	4.5.3 CUMP	Level of fulfilment
4.4.4 VSAN	Opportunity to sanction	4.5.4 CPAG	Fitted potential consume
4.4.5 CONT	Exploitation water plan control	4.5.5 LLUV	Rainfall volume of the current year
		4.5.6 REGA	Irrigation consumption
		5. SALIDA (Water outputs)	

Figure 4 shows the result the model gives for a hypothetical year in which each parent variable is assigned the most probable of all its conditions as certain. This situation corresponds to what is likely to happen most frequently according to the data entered into the programme. As it can be seen, in this case, the System would be sustainable with an 80.03% probability. This value indicates that, in a series of five normal years, during one of them more resources would be consumed than those which the System can provide without resorting to its reserves.

The same figure shows, in addition to the result, both the probabilities calculated for the conditions of some intermediate variables and the definite conditions of some parent variables.

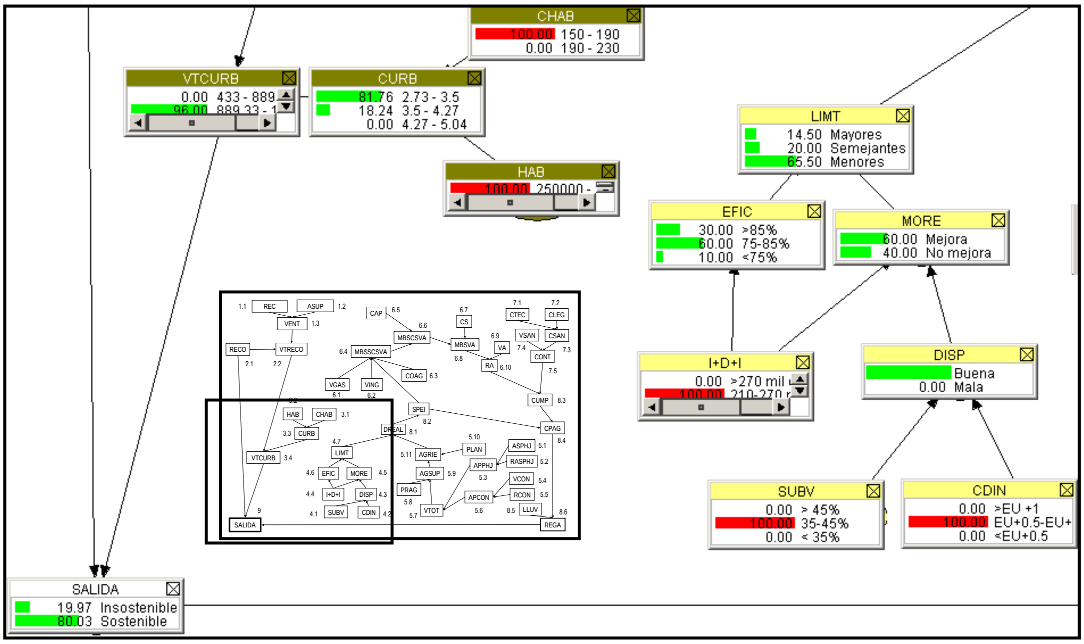

Fig. 4. Example for the most probable situation.

In the above case, the condition of parent variables was fixed in order to know the System's behaviour.

As mentioned elsewhere, the programme makes it possible to fix the result, for instance, that the System is 100% sustainable. For this situation, the programme would compute the condition in which each of the variables making up the network is to be found. Starting from the results, those who are involved in water resource management can compare the actual condition in which variables are found to be to that in which they should be in order to achieve the aim of 100% sustainability. In this manner, courses of action are devised more efficiently and, if it is not possible to modify the conditions of all the variables at the same time, we can start with those which require the least effort to achieve the most significant improvements.

Throughout the testing stage, users and experts should express their views on both the final results the programme offers and the values adopted by intermediate variables.

5. CONCLUSIONS

Modelling for a fully comprehensive and integrated management of hydro-geological resources by using bayesian networks offers highly promising prospects. As the scenarios involved are affected by a large number of variables, which are, in turn, marked by a high degree of uncertainty, we believe the use of this technique is justified.

This paper seeks to develop a tool which may prove to be a assistance to water resource managers of the Eastern Mancha System 08.29 in the decision making process. The advantage of this tool is that it can predict the behaviour of all the variables making up the model when we act on one or several of them. Similarly, it makes it possible to fix a result and compute the conditions in which the relevant variables should be in order to achieve this result.

The co-operation in the construction, testing and use of the model by all those who are somehow involved in the use or management of the water resource adds further, and in a way novel, value to this Project. It is to be expected that, under these circumstances, the results which the tool may offer will be regarded as more acceptable by all the users of the water resource.

At the moment, the model has been assigned those variables which are expected to be of vital importance to its functioning. Relationships have been established between these variables, their conditions have been defined and the relevant probabilities have been assigned. All this data has been entered into the software programme and is giving the first results. These results are being examined by our research team and the model can be said to offer acceptable values. Once this preliminary examination has been completed, meetings will begin to be held with users and experts for the final validation of the model.

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