The use of Hugin® to develop Bayesian networks as an aid to integrated water resource planning[1]

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Abstract: Integrated management is the key to the sustainable development of Europe's water resources. This means that decisions need to be taken in the light of not only environmental considerations, but also their economic, social, and political impacts; it also requires the active participation of stakeholders in the decision-making process. The problem is to find a practical way to achieve these aims. One approach is to use Bayesian networks (Bns): networks allow a range of different factors to be linked together, based on probabilistic dependencies, and at the same time provide a framework within which the contributions of stakeholders can be taken into account. A further strength is that Bns explicitly include the element of uncertainty related to any strategy or decision. The links are based on whatever data are available. This may be an extensive data set, output from a model or, in the absence of data, can be based on expert opinion. Networks are being developed for four catchments in Europe as part of the MERIT project; these are in the UK, Denmark, Italy and Spain. In each case stakeholder groups are contributing to the design of the networks that are used as a focus for the consultation process. As an example, the application to water management of a UK basin is discussed.

Keywords: Integrated water resource management; stakeholder participation; Bayesian network; uncertainty

INTEGRATED WATER RESOURCE MANAGEMENT: ESSENTIAL FEATURES

It is now widely recognised that sustainable, equitable and efficient management of water resources, particularly at the catchment scale can best be achieved through an Integrated Water Resource Management (IWRM) approach (Mariño and Simonavic, 2001). The European Union has adopted the concept as an integral part of their Water Framework Directive (WFD), which came into force in October 2000. The concept has been discussed at length in many publications and a number of definitions are available; whatever definition is adopted, however, two characteristics are invariably included:

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[1] *This work is being carried out as part of MERIT (Management of the Environment and Resources using Integrated Techniques), an EU Framework V funded project No. EVK1-CT-2000-00085. Web site: http://www.merit-eu.net*

- Firstly, the approach must recognise that the impact of management decisions will not be restricted to the water resource itself, but will inevitably affect a range of stakeholders with interests in the river basin. Furthermore, it must allow these impacts to be identified and evaluated under different scenarios. For instance, the decision to build a dam will have an immediate impact on the water resource of a region. But there will also be enormous social, economic, and political repercussions. Some sections of the population may benefit while others may suffer. To make a balanced and fair judgement a planner needs to be able to evaluate the effects of a decision based on a wide range of factors. Many of these impacts will conflict; a dam will provide more water but will result in the loss of land and housing; it may provide recreational facilities but deny water to communities further downstream. An integrated policy requires all these types of benefits and drawbacks to be taken into account and evaluated.

- A second essential element of integrated management is that it must actively involve the community in any decisions that are to be made; failure to do this will, ultimately, lead to poor implementation. Involvement does not mean consulting the community only after decisions have been made, but actively involving a representative cross section of organisations and individuals in the decision making process itself. This gives the opportunity for people with different points of view to express their opinion. Conflict may result, but part of the integrated approach is to incorporate techniques of achieving consensus. In this way, conflict resolution is more likely to be achieved, the process becomes more transparent, and the final decision is more likely to be widely accepted due to a sense of ownership of the result.

Although the principles are straightforward, successful implementation of IWRM is anything but straightforward. In the first place linking together all the factors affected by a particular decision in a quantitative way is complex; some of these factors may be environmental, others social or economic, each having different units of measurement. Some factors may well be qualitative in nature, with no recognised units of measurement. There is also the problem that when one factor is affected this may impact on another, which in turn may affect something else. This 'knock-on' process can be far reaching. A water resource planner needs to consider the effect of a range of potential actions on a large number of factors that are linked together and from this analysis implement strategies that are equitable, sustainable and efficient. All of this needs to be done while at the same time ensuring that effective stakeholder participation in the process is achieved. The problem is to find a technique to realize these goals. One way is to use Bayesian networks (Bns)[2], a type of model-based decision support system already used routinely in the fields of medicine and artificial intelligence.

What are Bayesian networks?

Bayesian networks are based on an approach to probability theory developed by Thomas Bayes, an 18th Century English clergyman. The technique has been successfully applied for many years in fields such as medicine and artificial intelligence (Charniak, 1991; Heckerman, et al., 1995; Jensen, 1996; Pearl, 1988). However, it is only relatively recently that the technique has been applied to environmental issues (Kuikka and Varis, 1997; Varis, 1995; Varis, 1998; Varis and Kuikka, 1997) and to watershed management in particular (Ames and Neilson, 2001; Borsuk, et al., 2001).

So far, environmental case studies have not generally involved a wide range and number of variables, but have been restricted to specific issues. Part of the reason for this previously limited approach is the restriction imposed by computer speed and memory. Bayesian networks deal with large amounts of inter-linked data and it is only with the advent in the last few years of high speed, large memory, desktop personal computers that it has become feasible to set up and operate sufficiently large networks to cope with complex environments.

Bayesian networks are used to simulate domains containing some degree of uncertainty caused by imperfect understanding or incomplete knowledge of the state of the domain, randomness in the

[2] *A number of commercially available Bn software packages such as Hugin (http://www.hugin.dk/) and Netica (http://www.norsys.com/), enable networks to be constructed using standard desk top PCs.*

mechanisms governing the behaviour of the domain, or a combination of these. They can be used to assist decision making based on the best information available and are especially useful in situations where a large number of interlinked factors need to be taken into consideration. This makes them ideally suited as a tool to aid decision–making in the field of natural resource management, where problems are complex and data often scarce and uncertain.

A Bayesian network consists of a series of nodes, representing variables which interact with each other. These interactions are expressed as links between variables; the links, however, are not permitted to form a closed loop. A node representing variable 'A' will be linked to a number of 'parent' nodes, B_1, B_2, ... B_n, on which it is dependent. The links or 'edges' are expressed as probabilistic dependencies, which are quantified through a set of conditional probability tables (CPTs). For each variable the tables express the probability of that variable being in a particular state, given the states of its parents. As more data or knowledge becomes available it may be necessary to revise these tables to reflect the improved data set. For variables without parents, an unconditional distribution is defined.

A simple Bn is shown in Fig 1. The boxes are network *variables*, which represent the most important factors relating to a particular decision or action. They are linked together so that a change in one will result in a chain reaction of impacts on all the linked variables in the direction of the links. The design of the network, deciding which factors link to which, is based on a conceptualisation of the problem and the outcome of discussions with stakeholder groups.

In Figure 1, the links between 'Number of new houses' → 'Water use (2)' → 'Borehole abstraction' → 'River Flow (2)' indicate that the construction of new houses in the region can ultimately have an impact on low river flows. This follows because new houses need to have water which, in the example, is provided from groundwater sources contributing base flow to the river; more new houses means increased groundwater abstraction, leading to a decline in groundwater levels which in turn causes a reduction in base flow to the river. But the impacts go further; a severe reduction in low flows during the summer, for example, could adversely affect the price of property along its banks as well as devaluing the river as a public amenity; it may also reduce fish stocks, with adverse consequences for local angling clubs and for the river ecology in general.

In the example shown, however, it is not only the construction of new houses that can impact on river flow, there are other activities such as reducing 'Pipe leakage' and changing the 'Price of water' that may exert an impact. The example also demonstrates that networks can incorporate variables of any kind, be they economic, social, physical, or indeed any other type. The ability to link diverse types of information is a key characteristic of Bns and one which makes them particularly suited for the problems of integrated water management.

The ability of Bns to integrate information lies with the nature of the 'links', the behaviour of which is defined by the construction of conditional probability tables (CPTs) for each variable. A CPT simply quantifies the probability of a variable being in any particular state, given the states of the variables linked to it (i.e. the 'parent' variables). An example CPT, based on the network shown in Fig 1, is given in Table 1. Here the variable we are dealing with is '*WaterUse (1)*', which is defined to be in one of three 3 states, 'increase', 'no change', and 'decrease'. The variables, that have a direct impact on '*Water Use (1)*', are '*Pipe Leakage*', for which 3 states are defined; a reduction of 0%, 5% or 10%, and '*Price Change*', which is also given 3 states; 'up' (+10%), 'no change', or 'down' (-10%). The selection of states is the decision of the user. Whether verbal descriptions are used, or quantitative states (either numbers or intervals), or even a simple true or false statement depends upon the objectives of the network.

The example CPT shown in Table 1 tells us that with no reduction in leakage, but a 10% increase in price, there is a 5% probability of water use increasing, a 65% chance it remains unchanged and a 30% chance of a decrease. Selecting different combinations of states for '*Pipe Leakage*' and '*Price of Water*' will change the probability of '*Water Use (1)*' being in any particular state. This is the mechanism by which the links are made between variables.

The conditional probability tables constructed for each variable, such as that shown in Table 1, are based on the best information available. This may be in the form of a *set of data.* For instance, in the case of the example, the information linking price change to water use may come from historical data relating consumption to price change, or perhaps from the results of studies in other areas.

Tables may also be constructed using the *output from models* in the place of observed data. Again in our example the data for the CPT linking '*Borehole abstraction*' and '*River Flow (2)*' could come from the output of a groundwater model.

In some instances the data available for a particular link will be limited or even non-existent. In these cases it may be necessary to fall back on *'expert opinion'*. Reducing low flows in the river for example will tend to affect the price of properties along its banks. This is represented by the link between '*River Flow (2)*' and '*Property Prices*' in Figure 1. But there is likely to be little data and no model to indicate the extent to which prices are affected. In this case expert opinion from, for instance, local estate agents may be introduced, which though not rigorous, still represents the best estimate available.

Bayesian networks thus allow the joint use of objective and subjective information. It should be stressed that networks do not replace existing environmental, economic or social models; instead it is able to take the output from these models and convert it into a format suitable for inclusion within a CPT.

An integral feature of Bns is that when the networks are compiled results are presented in the form of probability distributions rather than single values. An example of output for the network shown in Figure 1 is presented in Figure 2. In this network the impacts of house building, pipe leakage and changes in the price of water on factors such as river flow, property prices and angling, among others are included. In the particular example shown, only the impact of house building has been considered; the variables for price change and pipe leakage have been set at 'no change'. The network has been run to assess the impact of building 10,000 new houses in the region. The state of the variable affected by the construction of houses, '*Water use (2)',* is given as a probability distribution, rather than a single figure. In each box the column of figures on the left represents the percentage probability that the variable is in the state described in the right hand column. The percentage figure is also given as a bar graph. Thus given the construction of 10,000 houses '*Water use (2)*' is shown to have a 66.7% probability of being between 0.06 - 0.08 million m^3 day^{-1}. But because of the uncertainty of the data there is also a chance the variable might be in other states, as shown by the distribution. Likewise property values adjacent to the river are shown to have a 31.2% chance of falling in value by between 8-10%; but the wide distribution reveals considerable uncertainty about the result. The explicit representation of uncertainty provides a transparent means of representing the impact of different management options without concealing the considerable element of uncertainty that invariably exists with water resource planning.

At this point some explanation is necessary of the way in which the nodes representing actions or decisions such as 'new houses', 'pipe leakage' or 'price of water', shown in Figures 1 and 2, are used. In some types of network known as influence diagrams, decisions are represented as distinctive 'decision nodes' (Howard and Matheson, 1984). These types of node are used to help determine the best decision to make; however this is not what we are aiming for in the network shown in figures 1 and 2. Instead the network is being used to describe a number of possible scenarios (1000 or 10000 houses?). These nodes represent decisions that may be made in the future, but it is misleading to call them decision nodes. To distinguish them from decision nodes we shall call them *scenario defining nodes* or sdns. An sdn has no parents and when a scenario is to be analysed all sdns must be instantiated, in other words they must be given a state.

STAKEHOLDER PARTICIPATION

Stakeholder participation is central to an integrated management approach; the opinions of people affected by decisions have to be taken into account. Without this grass roots involvement, the successful implementation of any strategy faces difficulty for the reason that people may perceive it to be irrelevant.

Bns offer one way to introduce the contribution of stakeholders to the decision making process. Networks provide a framework within which the opinions of stakeholders can be fed. It is recommended that following initial stakeholder consultations a preliminary network is constructed; this network should then be modified in the light of feedback from subsequent stakeholder meetings. Only when a final structure is agreed should data collection for the CPTs begin. Once the network is running it becomes relatively easy to explain to stakeholders the reason for the adoption of any particular decision; this is because of the speed with which the impacts of a large number of possible options can be demonstrated, the graphical nature of the output, and the explicit representation of uncertainty. While many, if not all stakeholders will appreciate the importance of uncertainty in the world around them, the quantification of this uncertainty is something that is beyond most of them, but is where graphical representations of causal relationships can prove their usefulness. The process is shown diagrammatically in Figure 3. It should be stressed that used in this way, Bns do not make the decisions. They simply show the impact of any particular action on all factors linked to it, with all the attendant uncertainties; it is left to the planner or manager to make the final choice. But with the network the whole process of decision making is made to be much more inclusive and transparent.

The precise format of the stakeholder consultation will vary according to circumstances; in some cases finance may provide a constraint in others it may be time or the nature of the problem. Across the four study catchments within the MERIT project a range of techniques are being employed. These include:

Leaflets + brochures for stakeholders	*(UK, Spain)*	Project start
Public meetings	*(Denmark)*	↓
Surveys, interviews, questionnaires	*(UK, Denmark, Spain)*	↓
Focus groups and forums	*(Denmark, UK)*	↓
Site meetings (stakeholders + decision-makers)	*(UK, Denmark, Spain, Italy)*	Project end

The process of consultation and network construction is still underway, so it is too early to comment on the effectiveness of the different approaches at this stage. However, some observations can be made. Firstly, when the issue being dealt with is particularly contentious, the presence of a skilled and independent facilitator is essential. Without the guidance of such a person opinions can quickly polarise and the meeting degenerate into conflict. Secondly, although public meetings may be useful as an initial or occasional contact, experience has shown that it is more practical to work in the longer term with small groups (less than 10) of stakeholder representatives; this is particularly the case when networks are being developed. Finally, when collecting data for the CPTs visits to individual stakeholders may be necessary, and sometimes essential, particularly where very few data exist.

More can be found about recent developments in public participation techniques and stakeholder analysis in Petts (1997), European Union (2002) and Gray and Luscombe (2002).

EXAMPLES OF NETWORK DEVELOPMENT

MERIT is developing networks in four countries; the UK, Demark, Italy and Spain. In each case they are being constructed in consultation with relevant stakeholder groups, using a range of consultation techniques. The issues being addressed vary from country to country.

- <u>UK, Loddon Catchment and Portsmouth area:</u> Two networks are focused on;
  - the management of domestic water demand
  - the impact of abstraction from a spring on the bird population of coastal flats .

- <u>Denmark, Havelse Catchment</u>: a network is being constructed to investigate potential actions to deal with pesticide pollution of the groundwater supply to Copenhagen.

- <u>Italy, Vomano Catchment</u>: a network is being developed which looks at the increasing water requirements for irrigation in the Vomano catchment in the face of competing demands for hydropower. The network will be linked to an operational reservoir management model.

- <u>Spain, Jucar Catchment</u>: a network will focus on the intense competition for water between domestic, environmental and agricultural sector requirements, examining the likely impact of various management interventions on the different stakeholder groups.

To illustrate some of the advantages and problems encountered in the application of networks thus far encountered we can examine one of those being developed in the UK, which is reasonably well advanced, though by no means complete. The demand management network is being developed for the Loddon catchment, South East England.

Eliciting stakeholder concerns in the Loddon Catchment

The first step was to determine the interests of stakeholders involved in the abstraction, distribution and use of water supplies within the catchment. The agency responsible for licensing abstraction in the area posted 400 leaflets explaining the nature of a new licensing strategy to potential stakeholders and stakeholder groups, asking for comments and feedback. Responses were received from a number of different types of stakeholder, including wildlife trusts, a golf club, both industrial and agricultural abstractors, six local or parish councils, two water companies, four fisheries and angling associations, three canal/waterways groups, and a cross-section of residents within the Loddon catchment. Based on the responses, a number of representative individuals were selected to form the stakeholder group.

It is important to note that while the same stakeholders were involved in both the abstraction management strategy process and the UK component of the MERIT project, the degree of stakeholder participation was very different. In the development of the abstraction management strategy, the stakeholders were involved primarily to inform a process being driven by the agency with whom the final decision on abstraction rested. In contrast, the development of the Bayesian networks involved the stakeholders at each stage of designing and developing the networks. The networks were constructed to reflect stakeholder concerns, and as such they demonstrated a greater enthusiasm for the final output, and a sense of ownership of the result.

An initial stakeholder meeting was held in December 2001, at which a number of stakeholder concerns were raised. Among others, these included:

- the probable expansion of housing in the area, and the effects on the adjacent rural and greenbelt areas. Water management plans have to identify local sources of extra water for new housing, or consider long-distance water transport to meet the extra demand.
- the water companies have a statutory duty to supply domestic water users, but are often constrained by restrictions on abstraction from local sources to meet these requirements.
- most of the stakeholders present raised concerns about the abstraction management strategy process being non-predictive. For example, the water companies frequently operate on a 25 year planning period, and need to be able to consider aspects such as increases in population, and matching high demand during periods of low supply. There was generally an optimistic response to the idea of using a Bayesian network to complement the abstraction management strategy process, if this could lead to some extra degree of forecasting.

A number of the stakeholders were familiar with both ecological and hydrological modelling techniques and it was necessary to draw a distinction between these and the use of Bayesian networks. Some difficulty was encountered in getting the stakeholders to understand the basis of conditional probabilities used in the networks, but the use of a demonstration network to illustrate the ‘cause-and-effect’ nature helped overcome this.

From the larger group, several key stakeholders were identified to help construct a network to represent current and future domestic water supplies in the Loddon catchment. These included the agency responsible for abstraction management, the water company responsible for local service provision, and one of the local council planning departments.

Demand management network, UK

Water resources in the Loddon are under increasing stress and the plan to build a large number of houses in the region over the next 15 years will only add to the pressure. The water supply companies operating in the area are legally obliged to provide a safe and reliable water supply to all houses, so more water will be needed to meet this extra demand. An obvious solution is to increase the supply by installing more boreholes or increasing reservoir capacity, but this is expensive and encounters environmental concerns. An alternative option is to concentrate on reducing domestic demand, which accounts for the bulk of consumption in the region. The question is how best to achieve such a reduction.

Development

We conducted several in-depth, individual interviews with the selected stakeholders, each taking from one to two hours, which provided an opportunity to clarify the stakeholder's specific concerns. Each of them had already seen the demonstration Bayesian network, but it was at this point that we were able to determine the various constraints on water use and distribution within the catchment, and how the different stakeholders viewed the issues. As the issue to be represented by the network was domestic water demand, much of the stakeholder discussion centred on water quantity and likely increased future demand. However, both the discussion at the meeting at which all stakeholders were present, and from the one-to-one interviews, it was clear that the stakeholders were concerned not just about the problem of water supply and demand, but also cared about how they would be involved in the decision-making process, and wanted to feel that their participation mattered and would actually be used, *i.e.* a sense of ownership of the final outcome.

With a better understanding of individual stakeholder concerns, we were then in a position to develop a network that links these concerns to the need for improved demand management. A number of potential strategies for managing domestic water demand are available. These strategies have been included within a demand management network, which examines the effectiveness of each strategy to reduce consumption, either individually or in combination. The overall structure of the draft network is shown in Figure 4 (although the detailed design cannot easily be seen at this scale). Nodes are drawn as ellipses, which denote different factors, and the arrows show the links between them.

The network identifies 4 potential types of action for controlling domestic water consumption: pricing, awareness-education campaigns, grey water reuse, and leak reduction. These actions have been included following discussions with the company responsible for supplying water to most of the catchment. Further refinements to the network have been made at the suggestion of the other two stakeholder groups involved in the network construction.

Within the network the effect of the above strategies on consumption is given for three types of housing:

- Metered, where water is charged according to the amount used,
- Un-metered, where a flat rate is charged, irrespective of the amount used, and
- Future housing planned for the next 15 years; it is assumed that all this will be metered.

One of the stakeholders, the water company, suggested a further sub-division of housing based on income levels, which will be introduced, particularly in that part of the network concerned with pricing. Some of the main features of Bns and the advantages and limitations of their application to water resources planning can best be explained by examining specific elements of the network.

Overall design

Demand management is a complex issue; any single factor is likely to be affected by a large number of others. For instance, in the water demand network the total metered water use will be affected by all four strategies being considered (i.e. household water meters, unit price for water, grey water re-use, and leakage repair). However, if one node were to represent total metered water use it would have four parents, which would cause the resulting conditional probability table to be excessively complex, and practically impossible to construct. It is, therefore, advisable to construct the network so that any node does not have more than two parents; in this way the CPTs become much more manageable. The network design shown in Figure 4 illustrates the way in which a modular construction can be used to avoid the problem of multiple parents and complex conditional probability tables.

House numbers and type

The section of the network relating to the determination of house numbers in the catchment can be used to illustrate the way in which uncertainty is included as an explicit element of the Bn approach. To estimate total house numbers a GIS survey based on post code areas was undertaken from which a figure of 280,000 dwellings was obtained. Although confident the result was reasonably accurate it was recognised that because of a slight mismatch between post code and catchment boundaries, an error of up to +/- 10% might be involved. Given this uncertainty the network was used to convert the estimated number to a probability distribution, based on our knowledge of the possible scale of error. The result is shown in Figure 5. From the single figure of 280,000 entered into the node '*NumExHouses*', and assuming a normal distribution, the '*GISestimate*' node generates a probability distribution based on the information entered into the conditional probability table linking the two factors (Figure 5). From the distribution, the probability of there being 280,000 houses is 40%, but there is a 1.4% chance it might be as high as 305,000 or as low as 255,000. This distribution is subsequently used as the basis to calculate the number of metered and un-metered houses (Figure 5), and ultimately the total water consumption for the catchment. The explicit recognition and display of uncertainty with available data is one of the strengths of Bns, making them a particularly open and transparent tool with which to work.

Impact of Pricing

Links between nodes can be based on whatever data are available; the pricing section of the Loddon network is a good example of a link being made with data that are at least partly subjective. The nodes relating to price as a potential mechanism to control demand are highlighted in Figure 6. Price is an 'intervention' used to control water demand in many parts of the world, but the effect of price changes on water use is difficult to predict, because there are so many factors that play a part. Some data from historical studies are available, but there is always the problem of transferring the results to another region. However, the strength of Bns is that this type of less rigorous data can be accommodated, although the attached uncertainty is inevitably increased. An example of the effect of increasing price in the Loddon catchment is shown in Figures 6(a) and 6(b). The data for this section of the network has been drawn from a number of published sources including Pezzey (1998), Nauges (1998) and Lyman (1992). The node labelled '*pricing policy*' is a scenario defining node (sdn); this means it has no parents, and the state of the node needs to be input by the user. This is akin to setting a scenario. The states for this node represent price increases which are given in intervals of 5%, ranging from 0 to 30%. In reality strict control by the regulatory body OFWAT means that annual increases of little more than the current rate of inflation would be permitted; however, we have included much higher rates in this network to illustrate the potential impact of much larger increases.

In Fig 6(a) the price increase is set at 0-5%. This is shown in the left hand window, headed '*Pricing Policy*', where the state 0-5% is shown to be at 100% probability. With this scale of price increase the household consumption, shown in the '*Metered Use1*' window, is between 140-150 litres per person per day; this compares with a pre-price-change figure of 157 litres person^{-1} day^{-1}, pointing to a saving of around 10 litres person^{-1} day^{-1}. The total consumption in million m^{3} year, for all metered houses before the price rise is shown in window '*Met Cons1*'; the consumption after the price rise is given in '*Met Cons2*'. In this case the price change has made very little difference. In contrast, Figure 6(b) shows the effect of a much larger price rise of 25-30%. With this larger price rise savings are increased to around 20-30 litres per day, but because of uncertainty in the data the probability distribution is correspondingly great. At this stage a point worth stressing is that when operating a network it is always important to remember that data and calculations should always be consistent for all factors; in other words they should be based on the same area (e.g. catchment) and the same time period (e.g. annually).

Grey water reuse

Links between nodes are not restricted to probability tables; they can also take the form of a simple calculation. Good examples are contained within the grey water reuse part of the network. This section of the network deals with the significant savings in domestic water use that can be achieved by the installation of grey water systems which allow waste water from the bath and wash basins to be used for flushing the toilet (Figure 7). A number of studies have investigated the scale of possible savings (Dixon, et al., 1999; Mikkelsen, et al., 1999). These sources and others provide data for the links in this part of the network, which simply calculates the savings to be made depending upon the size of storage tank used in the system. Much of this part of the network is based on calculation rather than using probability tables. For example, the link between the nodes '*PCent WC Save*' and '*Indiv Wc Save*' is a simple calculation. The first represents the percentage saving of water in the WC for a selected size of tank ('*Storage Capacity*'); the second is the revised amount of WC water used per person as a result of the saving. The link is simply the '*PCent WC save*' distribution of percentages multiplied by 38, which is the number of litres currently used daily in the WC by one person without a grey water system. Figure 7 shows that for a 40 litre tank there is an 80% probability that the saving will be 20%, which translates to a saving of 6-8 litres per person per day using the calculation described above.

Conclusion

The use of Bayesian networks as a focus for stakeholder consultation and as a tool to aid decision makers offers a number of advantages:

- The way in which the network can be built up with the involvement of stakeholder groups and the graphical nature of the presentation makes it a useful tool for decision makers keen to encourage transparency and stakeholder participation in the decision making process. Encouraging stakeholders to contribute to the design and development of the network fosters a real sense of ownership and participation.
- Networks allow very different types of data, economic, social, physical and so on, to be linked together in a way that allows integrated analysis.
- The impact of a number of potential actions, or combination of actions, can be simulated very quickly.
- Uncertainty is explicitly represented. This is particularly important in a field such as water resource management where the data is often uncertain and scarce.
- The use of networks encourages a holistic approach to planning; designing a network ensures that all aspects of a problem are taken into account, especially if the participation of stakeholders is encouraged.

It should be added that Bayesian networks are not the appropriate tool for all circumstances. There are some cases in which they may not be suitable:

- If the problem is restricted to one subject area, for example, hydrology then the most effective decision making tool might be a hydrological model rather than a Bn. Networks are most useful when data from different disciplines need to be taken into account.
- For day-to-day operational systems. In water resource planning Bns can be used most effectively when used as a strategic planning tool.

On completion MERIT will provide a set of guidelines for the use of Bayesian networks as a decision making tool for water resource management and the integral involvement of stakeholders.

Acknowledgements

We would like to thank the European Union for their financial contribution to the MERIT project and in particular Dr. Panos Balabanis who has provided much encouragement and support. Thanks also to our fellow participants from Birmingham, Aalborg, La Mancha and Milan Universities and from GEUS, CESI and the Regione Abruzzo. Without their invaluable contributions this paper would not have been possible. Finally special thanks to all those stakeholders, who have tolerated our consultations with such patience.

References

Ames, D. and Neilson, B., 2001. A Bayesian Decision Network Engine for Internet-Based Stakeholder Decision-Making. In: Phelps, D. and Shelke, G., (Eds.), ASCE World Water and Environmental Resources Congress Conference. Bridging the Gap: Meeting the World's Water and Environmental Resources Challenges. Orlando, Fla. ASCE (American Society of Civil Engineers).

Borsuk, M., Clemen, R., Maguire, L. and Reckhow, K., 2001. Stakeholder Values and Scientific Modeling in the Neuse River Watershed. Group Decision and Negotiation 10 355-373.

Charniak, E., 1991. Bayesian networks without tears. Artificial Intelligence Magazine 12 (4) 50-63.

Dixon, A., Butler, D. and Fewkes, A., 1999. Water saving potential of domestic water reuse systems using greywater and rainwater in combination. Water Science Technology 39 (5) 25-32.

European Union, 2002. Guidance on public participation in relation to the Water Framework Directive. Active involvement, Consultation, And public access to information. Draft 1.1 (27/08/2002). European Union, Brussels. 1-66

Gray, A. J. and Luscombe, D., 2002. Evaluating Methods for Public Participation. R&D Technical Summary E2-030/TS. ISBN No 1 85705 840 2. Environment Agency, Bristol, UK. E2-030/TS,

Heckerman, D., Mamdani, A. and Wellman, M. P., 1995. Real world applications of Bayesian networks. Communications of the ACM 38 (3) 24-26.

Howard, R. A. and Matheson, J. E., 1984. Influence diagrams. In: Howard, R. A. and Matheson, J. E., Readings on the Principles and Applications of Decision Analysis. Strategic Decisions Group: Menlo Park, CA. 719-762

Jensen, F. V., 1996. An introduction to Bayesian Networks. UCL Press: London

Kuikka, S. and Varis, O., 1997. Uncertainties of climatic change impacts in Finnish watersheds: a Bayesian network analysis of expert knowledge. Boreal Environment Research 2 109-128.

Lyman, R. A., 1992. Peak and Off-Peak Residential Water Demand. Water Resources Research 28 (9) 2159-2167.

Mariño, M. A. and Simonavic, S. P., 2001. Integrated Water Resource Management. International Association of Hydrological Sciences: Wallingford.

Mikkelsen, P. S., Adeler, O. F., Albrechtsen, H.-J. and Henze, M., 1999. Collected rainfall as a water source in Danish households - what is the potential and what are the costs? Water Science Technology 39 (5) 49-56.

Nauges, C. and Thomas, A., 1998. Efficient Estimation of Residential Water Demand with Panel Data. In: (Eds.), Paper presented at EAERE annual meeting: Série D ; 97-08D. Venice. Universite des Sciences Sociales de Toulouse. 34

Pearl, J., 1988. Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. Morgan Kaufmann Publishers: San Francisco, CA, USA

Petts, J., 1997. The public-expert interface in local waste management decisions: expertise, credibility and process. Public Understanding of Science 6 (3) 359-381.

Pezzey.J. and Mill, G. A., 1998. A Review of Tariffs for Public Water Supply. Water Demand Management Centre of the Environment Agency, Worthing.

Varis, O., 1995. Belief networks for modelling and assessment of environmental change. Environmetrics 6 439-444.

Varis, O., 1998. A Belief network approach to optimisation and parameter estimation: Application to resource and environmental management. Artificial Intelligence Magazine 101 (1-2) 135-163.

Varis, O. and Kuikka, S., 1997. BeNe-EIA: A Bayesian approach to expert judgement elicitation with case studies on Climate Change impacts on surface waters. Climatic Change 37 539-563.

Figure captions