Cranfield University

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The use of Bayesian networks to facilitate implementation of water demand management strategies

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ABBREVIATIONS

AM	Adaptive Management
ANOVA	Analysis of Variance
BAS	Bulgarian Academy of Sciences
Bns	Bayesian Networks
CCC	Canadian Centre for Climate
CPT	Conditional Probability Table
DMA	District Metering Area
DSS	Decision Support System
DST	Decision Support Tool
EBRD	European Bank for Reconstruction and Development
EDC	Every Drop Counts
EU-ISPA	European Union Instrument for Structural Policies for Pre-Accession
HadCM2	Hadley Climate Model (2)
HEP	Hydro-Electric Plant
HWCP	Hop Water Circulation Pump
ID	Influence Diagram
IS	Information System
IWRM	Integrated Water Resources Management
l/c/d	litres per capita per day
l/hh/d	litres per household
LAC	Lifetime Avoided Costs
LCP	Least Cost Planning
LGAs	Local government areas
M&E	Monitoring and Evaluation
MEU	Maximum Expected Utility
MoE	Ministry of Energy
MoEW	Ministry of Environment and Water
MoRD	Ministry of Regional Development
NPC	Necessary Path Conditions
O&M	Operation and Maintenance
OED	Oxford English Dictionary
OR	Operational Research
SD	System Dynamics
SOPs	Standard Operating Procedures
SV	Sofiyska Voda

UfW	Unaccounted for Water
UU	United Utilities
VOI	Value of Information
WDM	Water Demand Management
WFD	Water Framework Directive
WSAs	Water Saving Appliances

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PUBLICATIONS ARISING FROM THIS THESIS

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ABSTRACT

Bayesian networks have received increasing recognition in recent years as a potentially effective tool in supporting water management decisions. Despite a number of reports of their use, no formal evaluation of the effectiveness of Bayesian networks in facilitating water resources management exists. This study improves understanding of the strengths and weaknesses of Bayesian networks through their application in a water-stressed region in Europe where domestic sector water demand management is considered as a mitigation measure. The fieldwork results provide a comprehensive technical and end-user evaluation of the use of Bayesian networks in water demand management implementation which, to our knowledge, is the first of its kind to be reported in the academic literature. For the technical evaluation, expert knowledge was first used to generate the structure of Bayesian network models which were then populated with data collected in the case study region. The model development supported the examination of several research questions regarding the technical suitability of Bayesian network modelling to facilitate implementation of water demand management strategies. For the end-user evaluation a survey was used to record the experiences of practitioners who applied Bayesian network models to a number of water demand management problems during a one-day workshop. Evaluation indicators included the effectiveness of Bayesian networks in facilitating strategic planning, technical support, transparency of data, learning among and between stakeholders, organisational receptivity, reliance on decision, and a comparison of experiences of decision conflict, effort and decision confidence. Results from the end-user evaluation provide evidence that Bayesian networks are particularly effective in terms of technical suitability and transparency, and policy-makers perceived effectiveness scores were significantly higher than individuals from other professions. Conclusions from the technical evaluation found that Bayesian networks can provide support in achieving cost-effectiveness in terms of sampling and data collection by focusing resources on collecting relevant data to reduce uncertainty. Conclusions from the end-user evaluation found that, for cross-sectoral planning in the context of managing water scarcity, their transparent representation of strengths of causes and effects between variables makes Bayesian networks an effective tool for facilitating dialogue and collaboration across science-policy interfaces.

Chapter 1

Problem domain: Water demand management

1.1 Background

Each decade during the second half of the 20th Century, the number of people on our planet grew by almost 1 billion (United Nations Population Database, 2006). The high growth rate of the human population on planet Earth has led to increasing exploitation of natural resources, including water. This has led to escalating pressure on water resources, particularly in regions where the water supply is sporadic or uncertain, and has inevitably increased the requirement for governments, water utilities and the public to become engaged in programs to mitigate water scarcity through both supply augmentation (i.e. transfers, exploitation increasingly inaccessible resources) and demand reduction. In regions where the threshold of supply is regularly exceeded and all accessible water resources are already accounted for there is, inevitably, a more pressing need to look to demand-side approaches as a means to reduce pressure on water resources.

Water demand management (WDM) aims to reduce the volume of water taken from the environment for human needs. The focus of the research reported in this thesis was demand management in the domestic sector. Human drivers of increasing domestic demand include population growth (EEA, 2001; Ofwat 2000a), lower household occupancy (Mitchell, 2001; Ofwat, 2000a), and lifestyle changes related to technology, personal habits and affluence (Princen, 1999; EEA, 2001). In recent years, to address issues of water scarcity and water stress, researchers (e.g Michelson *et al*., 1999; Renwick and Archibald, 1998; Maddaus, 2001; Howarth and Butler, 2004) and environmental organisations (UK Environment Agency, 1997; USEPA, 2002; Read, 2005) have recommended that municipal and private water utilities adopt an Integrated Water Resource Management (IWRM) approach in which demand-side alternatives are employed, in conjunction with conventional supply-side activities. Though there is wide recognition of the need to implement WDM, reports (Howarth, 1999; Gumbo and Zaag, 2002; Read, 2005; Jeffrey, 2006) indicate that creating the necessary conditions for successful implementation, which include commitment from local water utilities and customers and the required political-will and leadership from governments to provide supporting legislation, remains a challenge faced in realising successful implementation of integrated water resources management's (IWRM's) demand-side approaches.

The objective of the case study fieldwork reported in this thesis was to develop, apply, and evaluate, a computer-based decision support tool (DST) for facilitating water demand management (WDM) implementation. The fieldwork was carried out in a water-stressed region in Europe, the Upper Iskar sub-catchment in south-west Bulgaria, which includes the capital city of Sofia.

The critical nature of design science research for developing computer-based DSTs lies in "the identification of as yet undeveloped capabilities needed to expand the use of DSTs into new realms not previously believed amendable to IT support. Such a result is significant design science research only if there is a serious question about the ability to construct such an artefact, there is uncertainty about its ability to perform appropriately, and the task is important to the IT support community" (Markus *et al*., 2002, p180). As described in Chapter 2 of this thesis, research into the use of Bayesian network (Bn) modelling to facilitate integrated water resources management (IWRM) has increased in recent years and although reports have been positive, prior to the research presented in this thesis, no formal evaluation had been carried out. The case study field work presented in Chapters 3 to 7 which involved: (i) a technical evaluation of Bns (Chapters 5 to 6) where a number of 'artefacts' of the WDM implementation process are presented and (ii) an end-user evaluation (Chapter 7) where practitioners perceptions of the effectiveness of Bns in facilitating WDM implementation were collected, composes the first formal evaluation of the use of Bn modelling in water resources management.

Design science is inherently a problem solving process (Hevner *et al*., 2004). Varis and Kuikka's (1999) informed opinion following nearly a decade of developing computer-based tools to support natural resources management is that the application of computer-based support tools "should be in the service of problem solving and, therefore, the <u>method</u> and the <u>problem domain</u> must be deeply comprehended, not just one of them. This introduces a challenge and incentive to move towards inter-disciplinarity: domain experts, methodology people, and decision makers should understand each other and be able to work together" (Varis & Kuikka, 1999, p189).

Following Varis and Kuikka's observation about how research into the application of computer-based DST should be carried out, Chapter 1 below is devoted to examining the problem domain of water demand management (WDM), whilst Chapter 2 is concerned with the method, i.e. Bayesian network (Bn) modelling, that was tested and evaluated during the case study fieldwork. To develop in-depth understanding and provide evidence for the study objectives literature reviews of the problem domain and the method were completed. The literature reviews are not presented as stand-alone sections but instead, they have been integrated into the main text to support discussions, in Chapters 1 & 2.

Two distinct stages of WDM implementation: legislation (Section 1.1) & design (Section 1.2) are characterised in Chapter 1. Figure 1.1, below, shows research tasks and issues that need to be addressed at each stage.

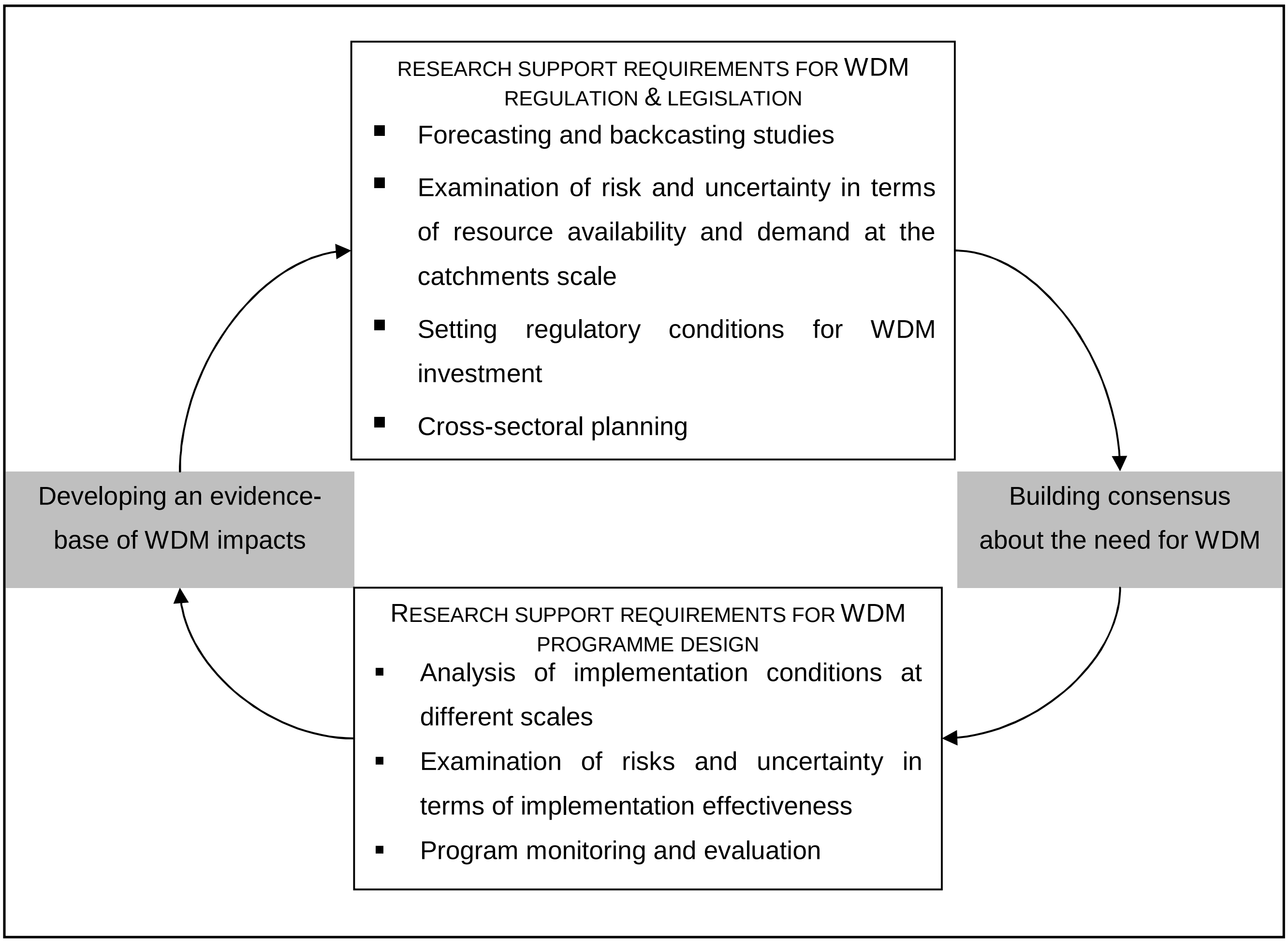


Figure 1.1. *Distinguishing research support requirements for iterative stages of WDM implementation*

The tasks and issues in Figure 1.1 are reflected in the model development presented in the technical evaluation chapters concerning WDM legislation (Chapter 5) and WDM program design (Chapter 6). As implied in Figure 1.1, there is a link between legislation and design in the need to develop an evidence-base of the potential impacts of WDM before legislation can be justified. The following section, which is supported by references to literature reporting experiences of how WDM programs have been implemented in different parts of the world, describes tasks and issues that need to be addressed so that economic regulation and supporting legislation can be introduced, and allow investment in WDM programs to proceed.

1.2 Regulation and legislation requirements for water demand management implementation

Among the regulatory requirements for water demand management are setting of the economic conditions to incentivise major water suppliers to reduce their bulk water demands. Important roles exist for water utilities and the research community to aid policy-makers, regulators and environmental agencies in understanding how legislation and economic regulation can be used to facilitate the process of change in organisations that is required if WDM is to be adopted as a strategy to mitigate water stress and achieve sustainability.

At the beginning of the WDM planning process policy-makers, water suppliers and environmental agencies are faced with the challenge of determining what level of demand management, if any, should be aimed for? The question faced may also be framed as: how much investment in water conservation measures is justified? All those involved in the collaborative process are required to consider a range of issues and Baumann *et al.,* (1998) have suggested that these should include: conservation goals, potential water savings, potential benefits and costs, applicability and technical feasibility, understanding of social acceptability and implementation conditions. Planning for such a wide range of interconnected issues, with numerous organisational perspectives, increases the requirement for an interface to integrate the issues in a way that is easy to understand, so as to facilitate dialogue and negotiation between different parties. The first task in the WDM planning process usually takes the form of some kind of forecasting and backcasting studies.

1.2.1 Forecasting and backcasting

Comparing the inherent value of forecasting and backcasting studies, Mitchell and White (2003) observe that forecasting and backcasting are complementary in planning for the future of water systems. Forecasting can tells us important information about the near future. This allows us to optimise the existing system in the short term. Backcasting is in contrast much more powerful as a means of reflecting on the medium to long-term. This is because it allows assumptions about how systems might be configured in the future to be challenged and reconsidered.

Forecasting involves projecting into the future based on what are perceived as the current dominant trends. Forecasting conceives of the future as immutable and a derivative of the present and the past while backcasting addresses the potential for people to change significant aspects of the future as it occurs. Fane *et al*. (2004, p3) observe that - “the future is of course both of these things, being in part derived from the present and in part the result of deliberate shaping”.

Backcasting, in comparison to forecasting, involves describing a desired future end-point and then working back from that point, to determine the feasibility, and what would be required to reach that goal (Fane *et al*., 2004). Researchers at the Institute of Sustainable Futures in Sydney, Australia, where a comprehensive body of detailed case studies have been developed and made available in the service of public knowledge, highlight the importance of backcasting combined with detailed forecasting studies (e.g. Fane *et al*., 2004; Turner *et al.,* 2006). Backcasting is useful when problems are complex, there is need for major change, and/or dominant trends are part of the problem (Dreborg, 1996). It is an approach for exploring means by which specified future states might be attained (Robinson, 1982).

Fane *et al*. (2004, p4) conclude that any study of water conservation needs should include both forecasting and backcasting and that “detailed forecasting is the basis of insightful backcasting.” They recommend that forecasting should be based on understanding the underlying trends driving the demand for water (demographic change and the need for water-related services) rather than crude predictions based on the past volumes supplied; this opens the potential for backcasting.

Forecasting and backcasting studies are required when making water management plans in regions of water scarcity to understand potential risks to future water availability and uncertainty about the potential effectiveness of WDM options. The need to address risks and uncertainties in the context of legislation is discussed in the following section with reference to examples.

1.2.2 Risk and uncertainty

In regions of water scarcity practitioners and researchers have observed a mentality that has been described as the 'hydro-illogical' or 'awareness-apathy' cycle. Speaking of experiences in western USA, Thomsen (1994) describes how "…during a crisis such as a drought, there is much motivation to communicate, and unlimited funds are available to evaluate and solve drought problems. Awareness is peaked and action is prompted by the event. The crisis would be much more effectively handled if investments in data, analysis, communication, and relationships were made in advance. However, once the event has passed, the tendency is to move on to other priorities created by other crises." Sharing his experience of economic barriers to better drought planning, Thomsen goes on to say that, "… it becomes very difficult to compete for funds and personnel when crisis is not imminent. Drought issues do not capture public interest and media attention during non-drought periods … the tendency is to save the funds and hope (or believe) the reservoir will not recede."

Uncertainty about hydrological conditions and the dominant trends in water management influence the timing of implementation of water stress mitigation strategies. A number of authors (e.g. Wilhite, 2005; Ituarte and Giasante, 2000) have recognised a need for change in thinking about local and national water drought management policy away from crisis management to risk management. Risk management emphasizes the need to address risk through the use of long-term planning to mitigate water deficits. Wilhite (2005) points out that, where the crisis management paradigm is used in policy-making, it can result in a relief-reliant culture where managers are only rewarded for acting once the crisis is looming, thereby rewarding the poor resource manager. At the same time the crisis management paradigm gives no incentive for good stewardship of natural resources.

Quantitative uses of the terms uncertainty and risk are fairly consistent from fields such as probability theory, actuarial science, and information theory (Hubbard, 2007). Outside of the more mathematical uses of the term, however, usage may vary widely. In cognitive psychology for example, uncertainty can be real, or just a matter of perception, such as expectations, threats, etc. Tannert et al (2007) have produced a taxonomy of uncertainties and decisions, represented in Figure 1.2, that include a more broad sense of uncertainty and how it should be approached from an ethics perspective.

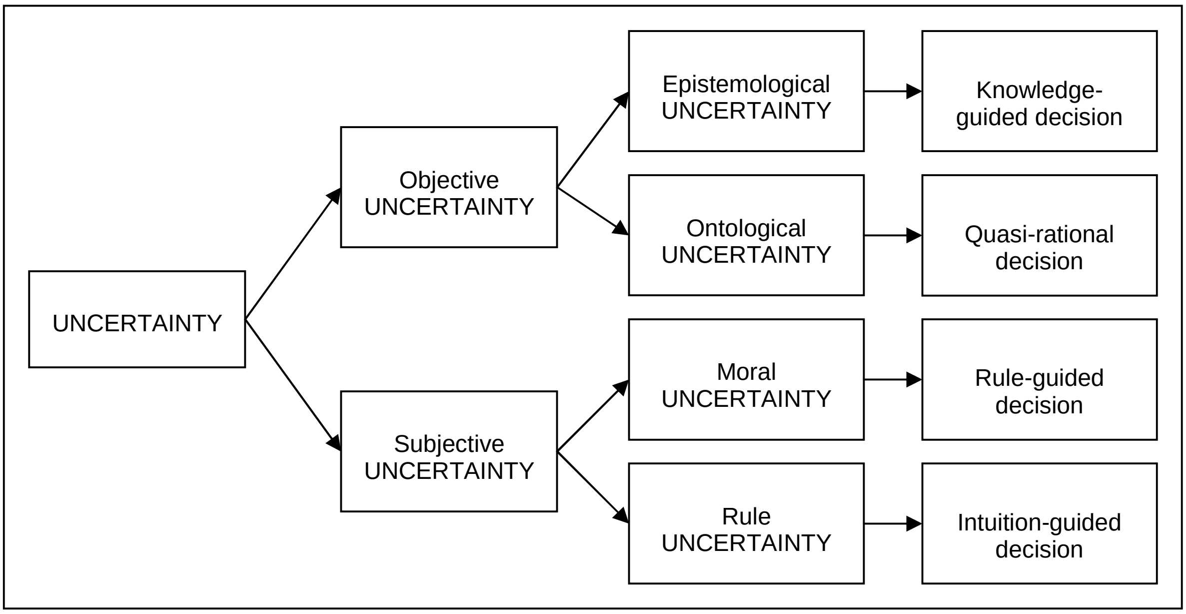


Figure 1.2. *Taxonomy of uncertainties and decisions*

Vagueness or ambiguities are sometimes described as "second order uncertainty" (Hubbard, 2007), where there is uncertainty even about the definitions of uncertain states or outcomes. The main difference that Hubbard distinguishes is that this type of uncertainty is about the human definitions and concepts, not an objective fact of nature. It has been argued that ambiguity, however, is always avoidable while uncertainty (of the "first order" kind) is not necessarily avoidable.

When used in the context of computer-based support tools “uncertainty” often refers to a lack of knowledge that the decision-maker (s) has about the state of certain variables or the causal relationships between variables (Hardekar, *et al*., 1997). “Risk” only arises when considering whether or not to intervene in a situation. Risk can also be defined as imperfect knowledge where the probabilities of the possible outcomes are known, and uncertainty exists when these probabilities are not known. Harwood *et al*. (1999) view risk management as choosing among alternatives to reduce the effects of risk. Decision support and DSTs should have a focus on risk that can be bound to a set of given sustainability criteria.

The experiences of drought management in Spain in the 1990s emphasize how methods used for forecasting and planning can influence the dominant water management trend. During that period Spain experienced the most severe water crises of any European country. Commenting on the crisis that resulted from the drought, Ituarte and Giasante (2000) highlight a number of factors that, in combination, led to the Spanish system being vulnerable to drought. One of their main conclusions is that the hydraulic model, which is based on the systematic increase of water regulation capacity, expressed in deterministic values, discouraged the perception of residual risk, leading to reactive, as opposed to pro-active, drought policy. The model promoted the expansion of water demands, leading to the subsequent reproduction and even enhancement of vulnerability. Economic, technological, demographic or climatic uncertainty scenarios were almost completely absent in this context, and drought risk and uncertainty were disguised in average figures presented in a deterministic manner which, they suggest, was misleading. The Spanish case highlights the way that representation in models used in decision-making can influence the way that policy-makers incorporate uncertainty and elements of risk into their decisions.

1.2.3 The importance of prior- and post- WDM program evaluation

Prior to setting the necessary legislation to support investment in demand management, policy-makers require information about the potential social, economic and environmental impacts of WDM. Prior- evaluation involves data collection to describe implementation conditions so that potential costs and benefits of WDM can be forecasted. Post- evaluation on the other hand involves an assessment of the effectiveness of a program after implementation to learn lessons so that future programs can be implemented more effectively.

Prior- evaluations often make use of information gathered from post-evaluations of other studies, either in other cities or from pilot studies carried out in the same region. Pilot studies can be expensive in themselves and the challenge for the water conservation manager is finding the balance between too much / too little and relevant / irrelevant information to support prior- evaluations. Securing the initial investment that is required to develop the evidence-base to justify the introduction of legislation to provide the financial resources to invest in comprehensive WDM, creates a potential constraint within the policy-making process. For example, the quotes below, Box 1.1, are comments from individuals involved in a recent study of

WDM policy requirements in the England (Inman, 2007), and emphasize the need to develop a credible evidence-base for WDM.

Box 1.1. Quotes from a study carried out in England during the drought of summer 2006

'… we can't demonstrate the benefits of water efficiency until we've done the pilots, so it's a chicken and egg situation'

'…the lack of an evidence-base is one of the main causes of the uncoordinated and fragmented state of water efficiency implementation, because it leads to uncertainty about the economics of water efficiency options'

'Regional specific conditions cause complexity in design of water efficiency policies at the national scale'

The study, which was completed in England during the summer of 2006, provided insights into how the absence of an evidence-base of program costs and benefits constrains demand management implementation. The 10 experts who participated in the study each held a decision-making role within organisations involved in water demand management (WDM) policy development in England and Wales and included practitioners from the Environment Agency, Defra, four of the major water utilities, and Waterwise, all of whom participate in the Water Saving Group, which was set up in England and Wales in 2006 and has been described in detail by Turton & Westcott (2007).

Information was collected through interviews, which were recorded, exploring the current decision processes affecting water demand management implementation in England and Wales. Analysis involved transcription of digital recordings and coding and mapping of causal statements. The results of the study are presented in Appendix A. The study found a common perception among decision-makers that regulatory fragmentation is a result of uncertainty about the need for WDM, as well uncertainty about the potential costs and benefits.

The following section examines water conservation program *design*, which concerns the *in situ* implementation of measures and instruments to achieve water savings in the most sustainable (i.e. economic, social and environmental) and efficient way.

1.3 Designing water demand management programmes

Designing WDM programs requires prior-evaluation of implementation conditions so that decisions can be made about which WDM options are most suitable for a neighbourhood, city or region. The use of indicators to forecast water saving potential at different scales is discussed below.

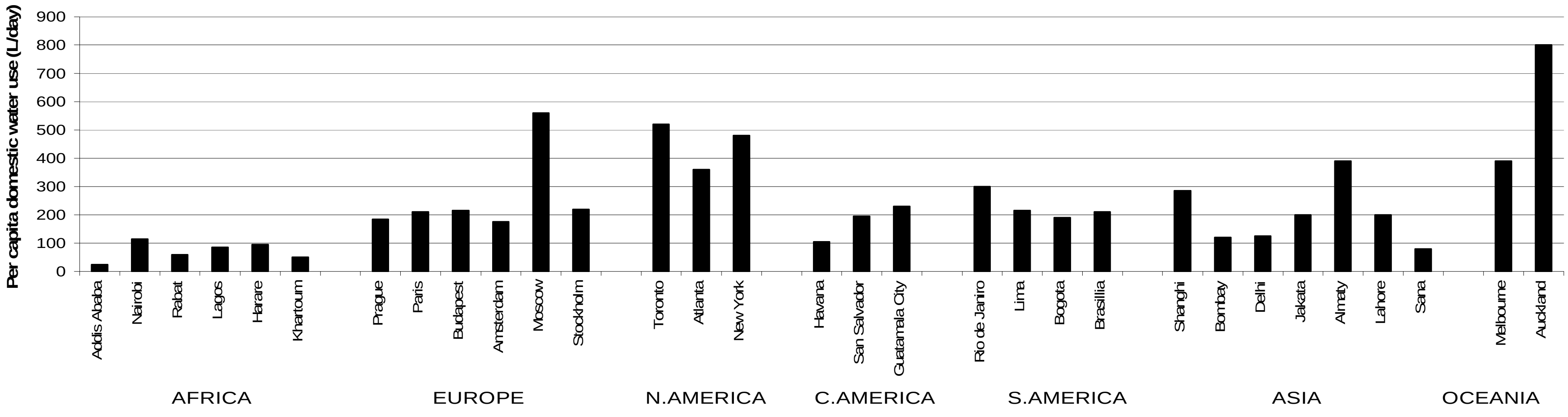
1.3.1 Indicators of water saving potential and demand

Pre-programme *per capita* water demand is a widely used indicator of water saving potential for WDM programmes within a geographic area, the general idea being that the higher the *per capita* demand, the greater the water saving potential for a conservation programme.

Household demand is dependent on a wide range of (indoor / outdoor) variables. The most important factors affecting indoor household water consumption are household occupancy (Mitchell, 2001; Turner *et al*., 2005), household income (Jones and Morris, 1984; Moncur, 1987), and the type of water intensive household appliance installed (Mayer *et al*., 2004a; Decook *et al*., 1988). Alternatively, outdoor water use is affected by: climate factors such as evapo-transpiration rate (Maddaus, 2001; California Urban Water Use Bulletin, 1994), plot size or population density (Renwick and Archibald, 1998; Maddaus *et al*., 1996), irrigation method (Syme *et al*., 2004; Renwick and Archibald, 1998), and also local cultural norms (Maddaus *et al*., 1996).

Per capita demand data (Figure 1.3) and household demand components (Table 1.1) for different countries were collected and are shown below. The comparison between *per capita* demands in Figure 1.3 shows that demand per person varies from 20 to 800 litres per capita per day (l/c/d) indicating large variations in water saving potential. Components of household use (Table 1.1) shows that external use in Australia and the USA are much higher than in Europe, indicating that conservation measures in these countries might best be focussed on the outdoor component.

As well as variations in per capita demand between countries, variations also exist at the local scale between different cities and in different neighbourhoods in different cities. Knowledge about the profile of variables that influence water demand in a population can be used for demand forecasting, as well as to inform WDM programme design.



Data source: World Resources Institute. 1998

Figure 1.3. *Per capita water use in large cities of the world.*

Table 1.1. Micro-component use in different countries (%)

	ENGLAND AND WALES	SCOTLAND	FINLAND	SWITZERLAND	US	AUSTRALIA
Toilet flushing	33	31	14	33	11	20
Bathroom / bathing and shower	20	32	29	32	8	26
Kitchen (washing machine, dishwasher)	17	35	34	19	16	20
Miscellaneous	27	<1	21	14	7	-
External	3	1	2	2	58	34

Data source: Ofwat, 2002a

1.3.2 *Achieving water conservation goals and the importance of evaluating implementation conditions*

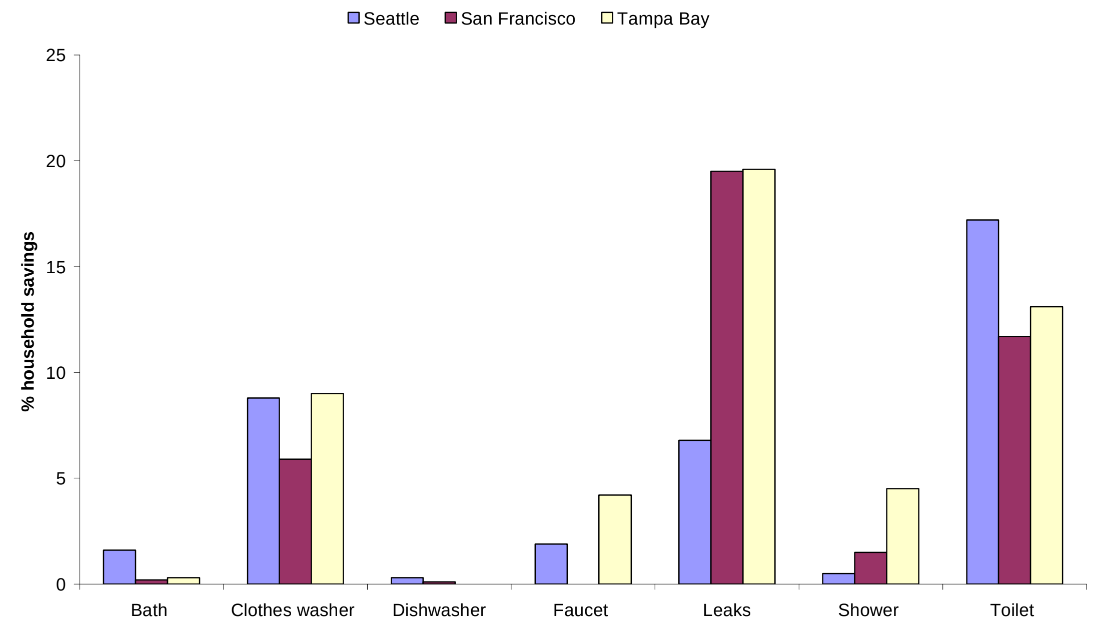
Methods for describing implementation conditions for WDM programmes need to be available to water conservation managers so they are able to target implementation effort at areas with higher potential water savings and participation rates. From efficiency perspective this also improves relative returns from implementation (i.e. cost per m^3 saved) and if the right information is collected, can assist in designing programmes in a way that addresses affordability issues among low incomes.

Mitchell *et al*. (2004) explain how any WDM programme needs to incorporate two basic elements: a *measure* and an *instrument*. A measure is ‘what to do’ (e.g. install a water efficient showerhead) and an instrument is ‘how to do it’. According to Mitchell *et al*., 2004) there are three kinds of instruments for implementing water conservation measures: regulation (e.g. planning controls, minimum water efficiency regulations on appliances sold); communication (e.g. a targeted education campaign); and economic incentives (e.g. a subsidised retrofit programme, rebates on rain-tank installation). The choice of measure, instrument and timing is significant because it dramatically affects uptake and participation rates, and therefore water savings and cost savings.

Two approaches to collecting data of water savings for efficient household appliances are described below. The first is a disaggregate approach, applied in three comparative studies in the USA, where individual households were fitted with water saving appliances to measure savings. This approach can be used in pilot studies to inform prior- evaluations. The second is an aggregate approach used in the Every Drop Counts (EDC) programme in Sydney Australia, where the emphasis is on post- evaluation. The comparison is interesting because it supports the observation that the objectives of monitoring and evaluation (M&E) are different for different stages in implementation, and highlights the need to match these objectives with M&E programme design.

1.3.2.1 Prior- and post- evaluation of WDM measures and their water saving potential

To evaluate the potential for household retrofits to reduce indoor water consumption prior to implementation Mayer *et al*. collected micro-component water use data from a sample of homes in the three cities studies; Seattle - 37 homes (Mayer *et al*., 2000), San Francisco - 33 homes (Mayer *et al*., 2003), Tampa - 30 homes (Mayer *et al*., 2004b). The homes were retrofitted with high efficiency toilets, clothes washers, showerheads, and faucets. Figure 1.4 shows savings for different household appliances as a percentage of total indoor water use for the three cities studies in the USA. Toilet and clothes washer replacement showed the greatest water saving potential for indoor appliances.



Data source: Mayer et al. (2000; 2003; 2004b)

Figure 1.4. *Water savings for different household appliances as a percentage of total indoor water use in Seattle, San Francisco and Tampa Bay*

One of the most important findings from the three studies by Mayer *et al*., (2000; 2003; 2004b) is that leakage, which was mainly caused by faulty toilet valves, accounted for the majority of savings in the Tampa (20.2%) and San Francisco (19.8%) retrofits, but significantly less for the Seattle programme (6.6%). This was due to differences in the initial level of leakage in the different municipalities which were 29.7%, 24.3%, and 10.4% respectively.

The above study is interesting because it gives an example of how water saving potential for different water saving appliances can vary in different cities. The method and results described by Mayer *et al*. are limited, however, because they do not show how these savings would be reflected in a larger sample with different household characteristics and do not permit calculation of confidence limits.

The second example, which focussed on post-programme evaluation, is taken from the Sydney Water Company ‘Every Drop Counts’ (EDC) programme involving the largest ever WDM study in Australia, reported by Turner *et al*., (2005). For research purposes a large sample of over 24,000 randomly selected single residential household participants and an equal number of non participants (representing a control group) were used for the analysis. Between July 2000 and July 2002 the control group increased demand by 80 litres *per* household *per* day (l/hh/d) and participants increased demand by 22.7 l/hh/d. Hence both the controls and participants increased demand in absolute terms, which the authors point out is likely to be associated with the fact that 2002 was a hot dry year compared to 1999. Participants ultimately reduced demand relative to the control group, and the ‘relative savings’ attributable to the programme so far are 57.3 l/hh/d indicating that the programme has achieved savings of approximately 8% of average household demand and 12% of estimated indoor demand.

In the EDC campaign in Sydney analysis of water savings among participants in different Local Government Areas (LGA) showed that in 22 out of 40 LGAs, programme participants achieved significantly higher relative savings when compared to their controls (Turner *et al*., 2005). The range of savings for LGA’s varied from 183.5 l/hh/d to 41.1 l/hh/d. This indicates that targeting specific LGAs with higher per capita savings would be more beneficial in terms of water saving potential than others.

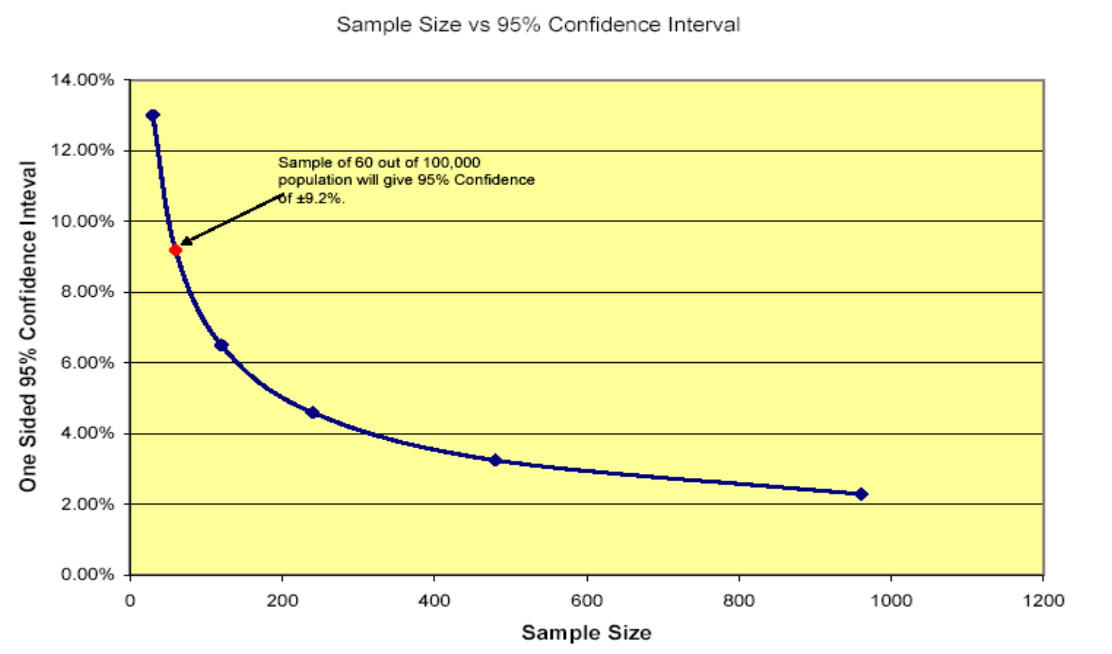
Ongoing evaluation of savings, participation rates and costs as well as customer satisfaction of WDM programmes is essential to ensure that savings are being achieved and maintained and costs minimised. As Turner *et al*. (2007, p927) point out, the importance of evaluation is that “without it, water suppliers are at risk of investing in poor performing WDM programmes that will not achieve the desired outcomes. It is essential that evaluation is embedded as an iterative process into water planning for an area embarking on WDM and that the evaluation methodology is carefully chosen to ensure reliable results.” Sydney’s EDC programme is a benchmark in water demand management best practice because it highlights the importance of pilot studies and evaluation in WDM programmes.

Not all retro-fit programmes result in substantial savings and, as a number of experiences in the UK and USA have shown, the targeting instruments used impact on both realised savings and customer receptivity (Mayer *et al*., 2003; UK

Environment Agency, 1997). Measuring the impact of instruments to facilitate participation is perhaps the most obscure and ambiguous aspect of WDM programme design and designing effective programmes for monitoring and evaluation (M&E) is a similarly challenging task. The following sub-section is a review of a number of reports of implementation effectiveness, and is included to demonstrate the challenges of this aspect of water demand management programme M&E.

1.3.2.2 Uncertainty, statistical significance and sampling

A comparison of the two approaches described above demonstrates the importance of achieving sufficiently large samples in order that the results of large scale evaluations can be tested for their statistical significance. It will be helpful at this point to review how sample size affects confidence limits. If we assume that a given population of homes has a 75% penetration rate of high efficiency shower heads, and there are 100,000 homes in the population, then the confidence interval around the mean is shown in Figure 1.5 for sample sizes ranging from 30 to 960 homes.



Source: USEPA, 2004

Figure 1.5. *Confidence Interval vs. Sample size*

The curve in Figure 1.5 shows that a random sample of 60 homes will be sufficient to identify the 75% penetration rate with 95% significance and a confidence interval of ± 9.2%, whereas if the sample size is doubles to 120, this will double the cost of the data collection and analysis effort, but will reduce the confidence interval by only 29% to ± 6.5%. This is why in a number of studies in the USA conducted by the United States Environmental Protection Agency (USEPA, 2004) a sample size of 60 has generally been used because it balances the accuracy requirements with the need for economy in the study.

The confidence intervals are unaffected by increasing the size of the total population, but decrease as the population gets smaller. So, they represent the maximum intervals we would expect for populations having actual penetration rates of 75%. Conversely, if the real penetration rates are smaller than 75%, then the results from the sample will show this, and lead to the conclusion that additional shower replacement work is warranted. As practitioners in the USA advise (USEPA, 2004), however, the challenge in getting good results lies not in the size of the sample so much as in making the sample representative of the actual service area. The easiest way to do this is to draw the sample from the entire population of customers, and ensure that every customer has an equal chance of being included in the study.

Achieving widespread and effective adoption of water conservation measures depends on a number of factors such as: cost of installation, potential savings, willingness to make lifestyle changes, and access to suitable technology. Examples of instruments for promoting participation in water conservation and measuring their impacts are given below.

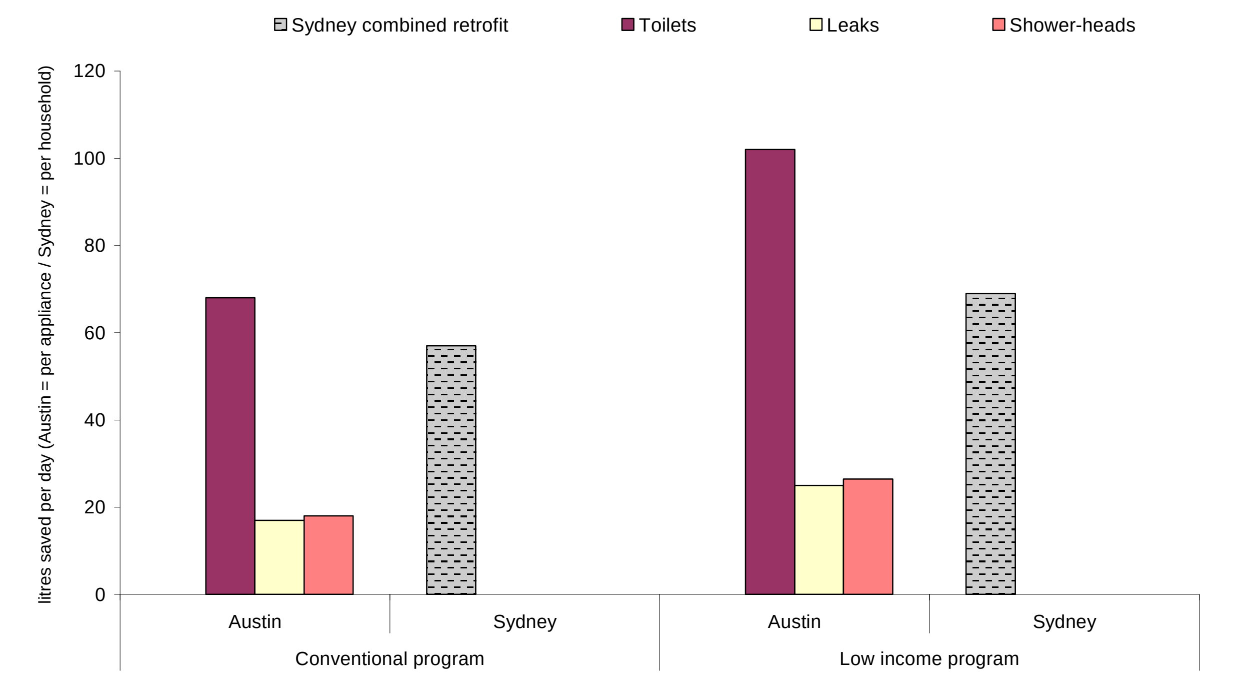
1.3.2.3 Evaluating instruments to facilitate citizen participation

A number of authors have suggested that pricing and metering can incentivise citizens to participate in water conservation programmes (Bruvold & Smith, 1988; Van Vugt, 2001; Campbell *et al*., 2004). Pricing can be used to achieve policy goals, whilst still allowing an element of voluntary behaviour as it allows people to make their own decisions faced with the administered price; as such pricing induces rather than requires change.

Metering has the advantage of improving customers' knowledge about their consumption, particularly 'when combined with specific tariff structures. Research by Bruvold & Smith (1988) and Trumbo & O'Keefe (2005) has shown that customer knowledge about consumption is significantly related to lower demand and is more important than their beliefs about water conservation in reducing water consumption. Furthermore, a number of researchers (Bruvold & Smith, 1988; Van Vugt, 2001) have concluded that the use of an increasing block structure coupled with an information campaign designed to inform customers of their consumption under each block will have a synergistic effects in improving customer knowledge about water consumption, and awareness of the need for reduction.

In preparing this review no studies were available that that were able to measure how pricing and/or metering affects participation in conservation programmes. This is indicative of the difficulty in distinguishing between people's different motivations for displaying conservation behaviour. One study in the USA (Hamilton, 1983) developed a causal model of water conservation behaviour, and results indicated that 'economic motives seemed to be common among poorer, less well-educated households, with more children and high baseline use levels … although the concern did not translate into substantial savings'. This low level of responsiveness among low-income households to pricing and metering would indicate that synergistic relationships between price and non-price mechanisms are limited to those non-price mechanisms that citizens can implement free-of-change (e.g. behavioural changes or freely available water saving technology).

A comparison of reports from Sydney, Australia (Turner *et al*., 2005) and Austin, USA (Poch, 1995), Figure 1.6, shows that the indoor water saving potential of WDM in low-income residencies is 18% and 34% greater respectively than in other households. Turner *et al*. (2005) who investigated the potential influences of income on water saving behaviour concluded that it would be beneficial to seek higher uptake among low-income groups who have higher relative savings. Targeting low income groups would not only provide higher relative savings, thus increasing the overall level of savings of the programme, but also lead to added social benefits for low income households in the community.



Data sources: AWWArf (2001) and Turner et al. (2004)

Figure 1.6. *Water savings in low-income groups compared to average in Austin and Sydney retrofit programmes*

Although uptake figures were not available for either programme, the authors who reported the results of the Austin and Sydney studies conclude that if WDM measures are offered free-of-charge and to low income households, then uptake among this group will be significantly higher, with higher water saving returns per appliance installed (i.e. 100% in Austin, Texas and 16% in Sydney) relative to other socio-economic groups.

In Australia, the National Water Conservation Rating and Labelling Scheme introduced in the 1990s has been replaced by legislation in the form of the Water Efficiency Labelling and Standards Bill 2004. The experience in Australia provides evidence that introducing water efficiency rating schemes along the 'white goods' supply chain, to include, for example, manufacturers and wholesalers of white goods, plumbers, and building contractors, will be most beneficial to improving uptake of water efficient appliances.

The above examples of methods to evaluating WDM programmes to support water demand management programme design, focusing on measures and instruments, demonstrate the need for different carefully designed evaluation research at different stages of design and implementation, and the need for a clear objective if such programmes are to achieve their potential.

Reports of well-designed evaluations and their importance at both the planning and design stages of WDM implementation show that being able to design effective evaluation studies is a required skill for organisations involved in WDM planning and implementation. Making available the necessary time and financial resources for training and research to support programme evaluation requires attention when considering the funding of WDM programmes. Evaluation involves a strong research element and emphasizes the need for communication between science and practice.

The final section of Chapter 1 examines the need for cross-sectoral planning in WDM programme implementation.

1.4 Cross-sectoral planning

Cross-sectoral planning in water demand management involves communication of a number of complex and interconnected issues to all organisations and individuals with a stake in the final decision. As described in the earlier sections of this chapter, forecasting and backcasting studies are required, the evidence-base for options needs to be developed, and outputs from these studies need to be presented in terms of uncertainty, risk and the statistical confidence in the data used. To make the outputs of such models relevant to a wider audience, Oxley *et al* (2002) suggest that where possible results should be presented in terms of recognised social, environmental and economic indicators and communicated to a policy audience through a common interface. This is the task of computer-based decision support tools.

Evidence of the need for tools to facilitate cross-sectoral planning to achieve realisation of IWRM's demand management approaches can be found in the literature (Costanza and Ruth, 1998; Jeffrey, 2006; McIntosh *et al*., 2007). In Europe, the need for research into and analysis of the application of methods to support cross-sectoral planning was recognised notably in the Sixth Framework Programme (FP6) for Research and Technological Development of the European Union where research on the topic has begun with a number of European Commission (EC) -funded projects including: Social Learning for the Integrated Management and Sustainable Use of Water (SLIM) (Ollivier, 2004), HarmoniCOP (Tippet *et al*., 2005), and Aquastress (Inman & Jeffrey, 2007; 2008).

1.4.1 Interactions in water management

For public policy and management decisions related to complex water management and planning problems, Thomas (2004) suggests that there are three main groups of stakeholders that could be represented in the process of problem formulation through to resolution: scientists or researchers, policy makers and managers, and the general public. Figure 1.7 allows visualisation of the potential interactions of some of these parties that could occur at any stage in these processes.

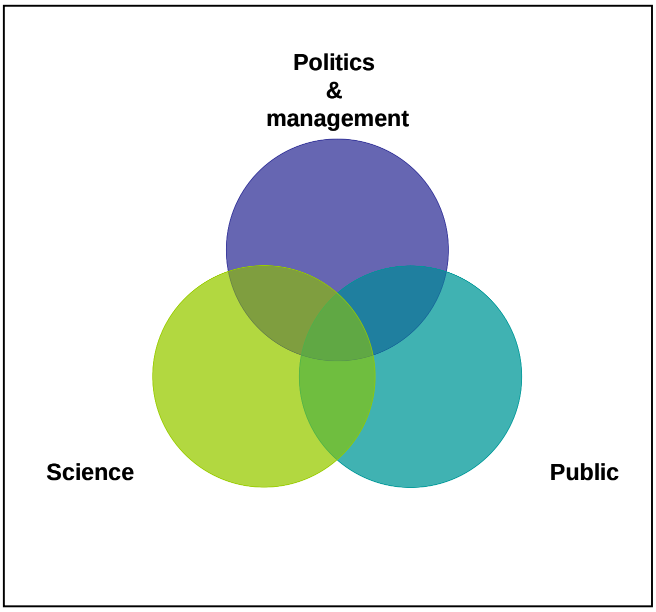


Figure 1.7. *Possible interactions for water management*

Considering the potential interactions of the three parties considered in Figure 1.7, Thomas (2004) presents a critique of water management and planning scenarios for individual and combined actions of the three parties. He exerts that any group acting entirely on its own is likely to be ineffective in significantly improving water management, and each combination working in pairs may have certain advantages and disadvantages. For example, a collaboration between science and politics and management is likely to be more efficient and ensure that decisions are based on sound scientific knowledge but carries the risk that public backlash could occur if the decisions are deemed unacceptable by the wider population. Collaborations between science and the public is likely to improve the knowledge of both sectors which could potentially drive changes to management and policy if lobbying takes place, although if unsuccessful the lack of decision-making power will prove a downfall. For collaborations between only the public and politics and management, policy is likely to be acceptable to the public but lacking in scientific bases which could result in negative impacts such as environmental degradation and poor or technically unfeasible solutions. Combinations of all three parties at some stage throughout the water management process are likely to produce the best, although potentially more time consuming, outcomes especially for complex and uncertain water problems.

The role of research in cross-sectoral planning is perhaps best conceived in recent observations on the need to address science-policy interfaces (Lovebrand, 2007; van den Hove, 2007, Willems & de Lange, 2007) in environmental management. The case study field work presented in this thesis support the view that computer-based DSTs might best be valued as tools for addressing science-policy interfaces by creating a forum for communication between the three main groups described above. Science-policy interfaces involve the two-way flow of information, on one hand from the research community to a wider policy audience, and on the other the absorption of policy issues and processes by the research community. Science-policy interfaces are discussed in more detail in the following section.

1.4.2 Science-policy interfaces

Science-policy interfaces are defined by van den Hove (2007, p.807) as "… social processes which encompass relations between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision-making. They are implemented to manage the intersection between science and policy."

Three theoretical problems and related science-policy interfaces that are considered relevant to WDM implementation, identified from recent review article by van den Hove (2007) examining science-policy interfaces in environmental management, are listed in Table 1.2, below. It should be pointed out that van den Hove (2007) identifies ten science-policy interfaces in all relating to environmental management and the six listed in Table 1.2 are those that are considered particularly relevant to the research reported in the following chapters.

The first theoretical problem in Table 1.2 is associated with the meaning of research as input to policy-making and relates to the complexity, uncertainty and indeterminacy that arise when explaining and predicting human interaction with the environment (O'Connor, 1999). A consequence of complexity, uncertainty and indeterminacy that is relevant to cross-sectoral planning is that "we are unavoidably confronted with an irreducible plurality of valid standpoints and of (objectively and subjectively) valid descriptions of the world" (van den Hove, 2007, p811).

Table 1.2. *Science-policy interfaces relevant to WDM planning*

THEORETICAL PROBLEMS	SCIENCE-POLICY INTERFACES RELEVANT TO WATER DEMAND MANAGEMENT
Complexity, uncertainty, indeterminacy	1. To bring about communication and debate about assumptions, choices and uncertainties, and about the limits of scientific knowledge 2. To allow for articulation of different types of knowledge: scientific, local, indigenous, political, moral and institutional knowledge. 3. To provide room for a transparent negotiation among standpoints (participatory processes).
Issue-driven vs. curiosity-driven science *Prioritising and organising research*	4. To allow for balancing issue- and curiosity-driven science and their articulation in knowledge for decision-making processes 5. To include a reflection on research priorities and research organisation
Roles of scientific networks *Inputs and roles of social sciences*	6. To allow for genuine trans-disciplinary articulation between social and natural sciences

This raises a need for approaches to facilitate communication and debate about assumptions, choices and uncertainties, and about the limits of scientific knowledge (Farrell and Jager, 2005). Accepting the limitations of scientific knowledge is a possible barrier to adopting such approaches but as van den Hove (2007, p809) points out, "…contrary to some a priori fears of relativism that are often found in both scientific and policy communities, such transparency and explicit statement of boundaries does not weaken the power of science—or maybe only some undue power—but can correspond to a reinforcement of scientific quality".

The second theoretical problem relevant to WDM implementation relates to the identification of research priorities and, what van den Hove (2007) refers to as "issue- and curiosity- based science". A number of authors (van den Hove, 2007; Lubchenco, 1998) have recognised that science in general, and particularly environmental sciences are being increasingly driven towards issue-driven approaches and away from curiosity-driven research. This is partly due to "the acute nature of the environmental crisis that gives a sense of urgency to the development of knowledge on which to ground action" (van den Hove, 2007, p818). Lubchenco (1998) further stresses that in a rapidly changing world where complex environmental issues are becoming ever more pressing, the role of science cannot be confined to its ''traditional'' roles as scientists are increasingly called upon to address the most urgent needs of society. Following these observations, any method proposed to address science-policy interfaces in demand-side management planning would ideally support identification of key research priorities. For example, the degree of uncertainty between factors relevant to policy decisions can guide data-collection effort and addressing relevant issues.

The third theoretical problem arises from the need to address issues that cross the disciplinary boundaries of research. For IWRM and demand management impacts of water stress on social, economic and environmental and the interaction between humankind and nature represent problems that are not bound to traditional research disciplines. IWRM and WDM thus require communication across and between research disciplines, and the way knowledge is articulated between disciplines determines how is it is communicated to policy-makers, managers and the public.

Ramadier (2004) refers to the articulation of knowledge across disciplines as 'transdisciplinarity' and describes it as "…the simultaneous integration of two contradictory movements of disciplinary thinking: on the one hand, the compartmentalization of knowledge; on the other hand, the existence of relationships between the disciplines—the aim being to determine how the different forms of knowledge thus produced can be articulated together" (Ramadier, 2004, p424).

Direct parallels can be found between Ramdier's definition and the requirement in WDM planning to combine social, economic and environmental disciplines. Oxley *et al*. (2003) suggest that the extent to which computer-based decision support tools provide an environment that supports inter-disciplinarity is a criteria in determining their suitability to addressing environmental issues.

1.5 Conclusions

Sections 1.1 and 1.2 above made an important distinction between the legislating and design stages of WDM implementation that is referred to throughout this thesis. Modelling and support tool tasks for the two stages are summarised in Table 1.3, below.

As indicated in Table 1.3, developing the evidence-base for WDM is relevant to both stages, although as discussed in Section 1.1.2 above, the objectives of developing the evidence-base for WDM are different for each stage.

Table 1.3. *Water demand management (WDM) involves two clearly defined but interconnected tasks that computer-based support tools need to address*

WDM LEGISLATION	**WDM DESIGN**
▪ Forecasting and backcasting ▪ Uncertainty and risk ▪ Cross-sectoral planning	▪ Prior- evaluation: Identifying effective tools and support of targeting implementation effort ▪ Post- programme evaluation: to monitor programme effectiveness
←Developing the evidence-base→	

For the legislation stage the evidence-base is required to legitimise the introduction of economic regulatory mechanisms to support investment in comprehensive demand-side management, whereas for the design stage the evidence-base is required to achieve the lowest cost per m^3 saved and address issues such as affordability and social acceptability. Recognition of these different objectives is important because it allows support tool tasks to be clearly distinguished between these two stages of WDM implementation.

The evaluation research for assessing the effectiveness of Bayesian networks in facilitating implementation of WDM strategies required a research methodology that incorporated both model development and model evaluation. Section 2.4 in Chapter 2 describes the four-stage research methodology in detail. In summary, for model development, interviews with practitioners working on demand management in the case study area were used to develop causal maps of the WDM planning process from which a number of Bayesian networks (Bns) were developed. The resulting models were populated using data collected from the Sofia water company and from household surveys conducted during 2006. Two approaches to model evaluation were then employed to examine the effectiveness of the developed Bn models in facilitating the implementation of WDM strategies. The first, a technical evaluation, examined the adequacy of Bayesian analytical methods through a number of desk studies. The second, a subjective evaluation, assessed the usefulness of Bns from the perspective of the end-user. Technical and subjective evaluations are two of three possible types of evaluation described by Adelman (1992). The third type of evaluation, an empirical evaluation, would have required a longitudinal study to compare model outputs with actual programme performance, and was not possible within the time constraints of this study.

1.6 Research questions and experimental hypotheses

A set of research questions and experimental hypotheses were initially identified following the literature review of the problem domain and method. These research questions were then refined following the knowledge elicitation with experts to reflect the research requirements in the Upper Iskar case study. The research questions and experimental hypotheses are presented in Table 1.4 and Table 1.5 below.

Table 1.4. *Research questions*

NO	RESEARCH QUESTION	CHAPTER & SECTION
1	How does Bayesian network modelling provide support for analysing uncertainty in water supply and demand forecasts?	Chapter 4, Section 4.6
2	How does Bayesian network modelling provide support for economic analysis of impacts of demand management programmes?	Chapter 4, Section 4.6
3	How does Bayesian network modelling provide support for developing preparedness strategies?	Chapter 5 Section 5.4
4	How does Bayesian network modelling provide support for decisions involving multiple organisations?	Chapter 5 Section 5.4
5	How does Bayesian network modelling address issues of structural uncertainty in the planning process?	Chapter 5 Section 5.4
6	How does Bayesian network modelling provide support for identifying constraints to- and drivers of- water conservation behaviour?	Chapter 6 Section 6.7
7	How does Bayesian network modelling provide support for identifying indicators of ‘favourable’ and ‘unfavourable’ implementation conditions for introduction of different water saving measures?	Chapter 6 Section 6.7
8	Are Bayesian networks perceived to be more or less effective at addressing support requirements for water demand management planning by practitioners from different organisational backgrounds?	Chapter 7 Section 7.2.1
9	Do Bayesian networks promote learning and the development of common understanding of water demand management issues?	Chapter 7 Section 7.2.2
10	Do Bayesian networks facilitate decision-making for water demand management?	Chapter 7 Section 7.2.3

For research questions 8, 9 & 10 in Table 1.4, three experimental hypotheses, which are presented in Table 1.5, were tested through the end-user evaluation

Table 1.5. *Experimental hypotheses*

No	Experimental Hypothesis	Chapter & section
1	H1: End-users perceived effectiveness scores from different professions will vary significantly	Chapter 7, Section 7.2.1
2	H2: End-user perceived effectiveness scores for statements related to learning will be significantly higher than other scores	Chapter 7, Section 7.2.2
3	H3: End-users scores for statements related to decisions stress will be significantly lower when using Bayesian networks	Chapter 7, Section 7.2.3

The components of the case study research are described in the section below.

1.7 Case study research agenda

The case study field work was divided into four phases:

- Problem identification and structuring;
- Model design and construction;
- Model use and
- Model evaluation.

The first three phases concern the construction of models, whilst the aim of the final phase is to evaluate the models constructed in the previous phases. In practice the process of the four main stages was not linear but rather, it involved iterative cycles between stages. The iterative nature of design in IS research has been observed by other researcher (e.g. Hevner *et al*., 2004; Markus *et al*., 2002). Each stage involved a number of model development cycles in consultation with informed practitioners from Sofia, Bulgaria, where the study was based, during which models were developed and re-developed. Each new model developed required an evaluation in itself and called upon the model developer to make analogies between the modelling method and the domain of application.

The four step process described above can be easily likened to Simon's (1977) theory of decision making processes which involves the stages of "intelligence", "design", "choice" and "review" (or "implementation"). It is interesting to note that as well as bearing resemblances to Simon's decision-making process, the four model development phases have parallels with cyclic planning and management processes that were developed for a range of disciplinary fields such as Boyd's OODA loop or "Observation, Orientation, Decision, Action", originally developed for military strategy planning and which is now commonly used for organisational planning and management (Strömgren, 2003). From this observation it might be expected that the process of model development would produce decision artefacts that allow the existing decision process to be perceived in a new light.

During research design, insufficient data was identified as a potential risk to producing usable models. To address this risk and to 'ground truth' the models a triangulation approach (Silverman, 2001) to data collection was used during the field work. Triangulation involves the use of a number of information sources which are then used to support research findings. Information sources used during the case study field work are shown in Figure 1.8.

The case study field work followed an 18 month procedure involving individuals involved in water management decision-making in the Upper Iskar region of Bulgaria, which includes the capital city of Sofia. The field work components and chapters reporting each one are shown in Figure 1.8 below.

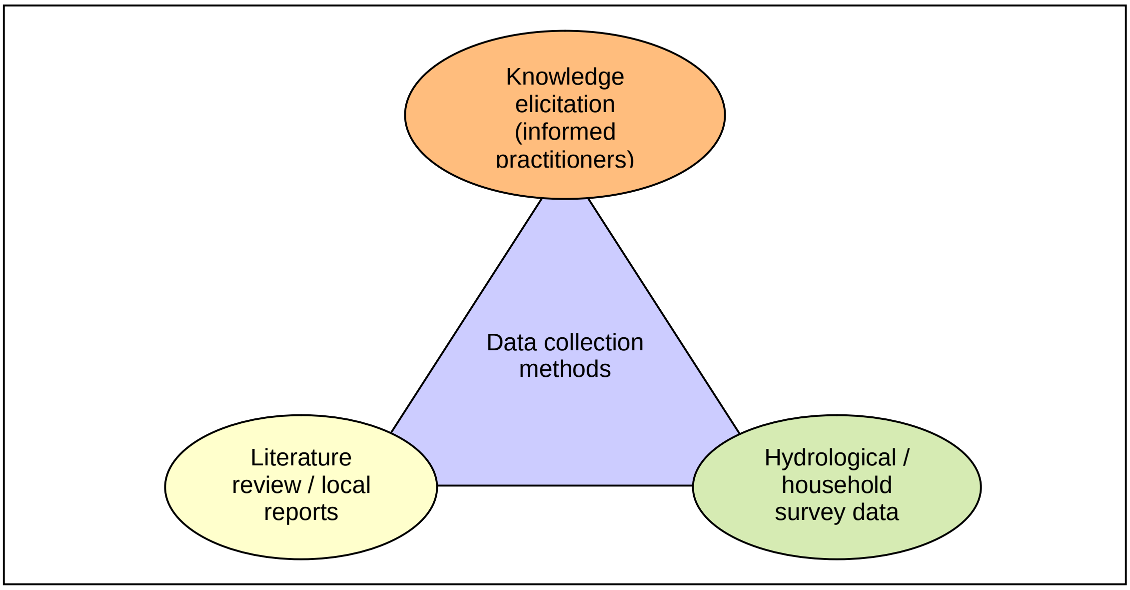


Figure 1.8. *Triangulation was used to address risks regarding data availability and to 'ground truth' models*

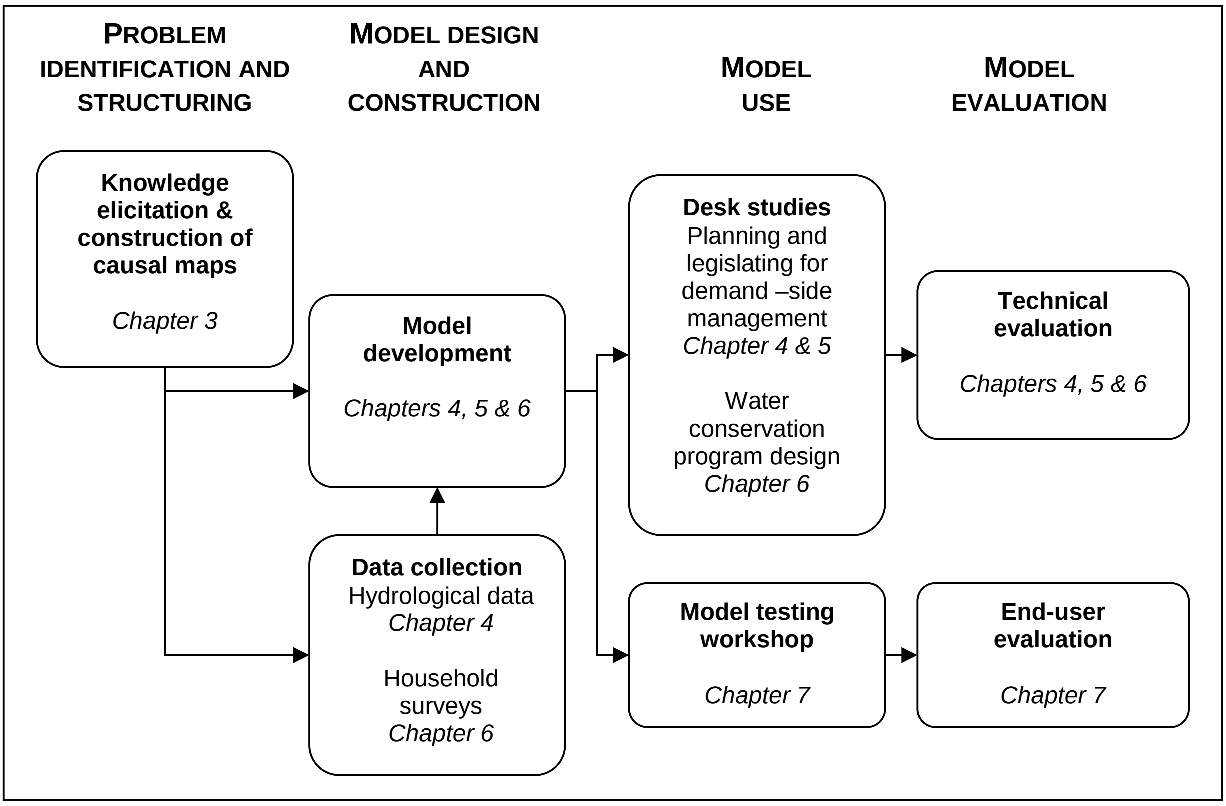


Figure 1.9. *Case study field work components*

The desk studies described in Chapter 4, 5 & 6 provide a technical evaluation of Bns and a level of detail about technical aspects that was not possible during the end-user evaluation.

The objective of the end-user evaluation was to understand how effective Bns are in facilitating cross-sectoral planning, and was achieved by eliciting end-user's perceived effectiveness of Bns in support a number of WDM planning and programme design modelling tasks. The different organisational perspectives (i.e. policy makers, water company employees, academics and water engineers etc) represented by the end-user evaluation workshop participants provided the basis for a formal evaluation of the effectiveness of Bns in cross-sectoral planning.

The following chapter describes the case study region and water stress issues arising from environmental, social and economic factors present. The impact of these factors on WDM implementation is described using the results of detailed interviews with practitioners, policy-makers and researchers working on demand management issues in the case study region.

The section below is an overview of the contents of Chapters 2 to 9 of this thesis.

1.8 Overview of contents of Chapter 2 to Chapter 9

Chapter 2 focuses on the method : Bayesian network modelling that was applied and evaluated during the case study field work and begins with a contemporary review of the use of computer-based support tools in water management to support the reader in contextualising the relevance of the research reported in the middle chapters. Bayesian calculus and Bayesian networks are then described in detail and a review of reported applications from the academic literature is given. The final section of Chapter 2 describes the individual components of the case study field work.

Chapter 3 begins with a description of water stress issues in the case study region: the Upper Iskar River and city of Sofia in south-western Bulgaria. The results of knowledge elicitation interviews with ten informed practitioners working in the water sector in Sofia, and who are involved in implementing demand management, are then described. Results include a description of the current policy process in Sofia and identification of constraints to implementation in the Upper Iskar case. The process of knowledge elicitation to support model development is identified as an important and effective activity in model development that addresses a specific science-policy interface: balancing issue- and curiosity-driven science and the articulation of knowledge for decision-making processes. The research questions that formed the focus of the model development and technical evaluation are presented in Table 3.5 at the end of Chapter 3.

Chapter 4 describes data collection activities to address structural and parameter uncertainties in a conceptual Bayesian network model for WDM legislation for the Sofia case. Collection and modelling of water supply and demand data, and information on economic indicators are described.

Chapter 5 provides a technical evaluation of the use of Bns to support WDM legislation decisions. Instantiation of the conceptual model applied to the Upper Iskar case is described and modelling issues and remaining knowledge gaps are discussed. Conclusions are that Bn modelling is applicable to policy problems where decisions can be ordered in sequence, even over multiple time steps. The process of model development is also beneficial in clarifying and examining the decision process and determining research priorities.

Until recently limitations have existed with modeling feedback cycles using Bayesian networks due to the necessary calculus not being developed (Jensen, 2001). Recent developments (e.g. Montani et al, 2008; Neil et al, 2008), however, mean that there is now scope to use Bns in domains where feedback cycles exist.

Chapter 6 reports the application of Bns to support water conservation programme design. The development and practical implications of four models, which utilise data collected from social surveys in the city of Sofia, are presented and discussed. The three issues addressed are: (i) water conservation behaviour (i.e. constraints, attitudes etc), (ii) implementation conditions described through uptake and water saving potential, and (iii) estimating the value of collecting data prior to implementation. Conclusions are that WDM programme design involves intensive and potentially costly data collection. Collecting the right type and amount of data to support targeting of implementation effort and to reduce uncertainty of programme impacts, is a challenging task. Bayesian networks supported analysis of household survey data and showed potential for further use in addressing sampling issues such as missing or incomplete data. Value of information analysis also shows potential for directing data collection effort to reduce uncertainty about WDM programme impacts..

Chapter 7 presents the result of an end-user evaluation of the use of Bayesian networks to support cross-sectoral planning. The end-user evaluation involved nine individuals at different stages of the WDM implementation process in Sofia testing Bn models during a one-day workshop. The aim of the evaluation was to elicit end-user's perceptions of the effectiveness of Bns in the context of their individual and collective roles as decision-makers, and thereby evaluate the use of Bns in supporting decisions processes requiring collaboration and understanding between multiple decision-makers or organisations. Three research hypotheses were tested by collecting end-users perceptions of the support tools effectiveness following the workshop. Results indicate that Bns perform particularly well in terms of technical suitability and transparency. Policy makers perceived effectiveness scores were highest across five of the seven factors included in the evaluation instrument and were significantly higher (p=<0.05) than engineers and water company employees. The validity of results may be affected by the evaluation instrument design which leaves scope for discussion.

Chapter 8 is a discussion of the use of Bayesian network models in WDM planning and implementation. Results from the end-user evaluation are considered in light of conclusions from the technical evaluations. The role of Bns in legitimisation and validation of information is discussed and issues of evaluating the accuracy and precision of their outputs in problem domains characterised by non-repeatable decisions is discussed. The roles of Bns in systemising decision analysis and evaluation design for WDM during the implementation process and facilitating exchanges between science and practice are also discussed. The methodological lessons about the applicability of Bns to the WDM problem domain and their applicability in terms of transparency and technical suitability elicited during the end-user evaluation compose the main contribution to knowledge in this thesis.

Chapter 9 identifies areas of future research and include developing methods to combine Bns and other modelling approaches and their application in specific areas of the WDM problem domain, i.e. legislation and design. It is suggesting that if Bns are to be widely accepted for policy modelling, methods for (i) parameter estimation, i.e. populating conditional probabilities tables, and, (ii) calculating or eliciting utilities, require further evaluation and systemisation.

Chapter 2

Method: Bayesian Network Modelling

Judgement is essentially a 'backward-looking' system. This is enough for most of our thinking and behaviour but we also need 'forward-looking' design and innovation – De Bono, 1999, p23.

Introduction

Chapter 2 reviews the use of computer-based support tools in integrated water resources management (IWRM) and gives a preliminary justification for selecting Bayesian networks for use in the case study fieldwork. Section 2.1 is a review of how DSTs and integrated modelling have been applied in IWRM and introduces: (i) distinctions between the use of models for research and policy, (ii) the value of the process of model development in facilitating learning and common-understanding and (iii) the importance of modelling the interface between humankind and natural systems. Section 2.2 describes two modelling techniques, System Dynamics (SD) and Bayesian network (Bn) modelling, that have been applied in IWRM to facilitate cross-sectoral planning. Based on reports of their effectiveness in managing uncertainty and risk, and the range of data types that they support, Bayesian networks were identified as a suitable method for use in the case study field work. Section 2.3 gives a detailed description of the terminology and topology of Bns and how they support decision analysis. Section 2.4 describes the components of the 18 month case study fieldwork agenda with an explanation of how this fits into the existing body of integrated modelling methodologies.

2.1 A review of objectives and challenges of applying computer-based decision support tools in integrated water resources management

A decision support system (DSS) is an artificially created (computer-based) environment that is used to facilitate real-world (human) activities. Following standard terminology, in this thesis, a DSS is any combination of computer-based tools that support decision-making, explanation and forecasting. The individual components of a DSS are referred to as Decision Support Tools (DSTs). The overall discipline of developing and evaluating DSSs and DSTs is referred to as Information Systems (IS) research.

The decision support system (DSS) is a powerful tool for application of a systems approach in real-world water resources planning and management (Karamouz *et al*., 2005). The concept of DSSs was developed during the 1960s and 1970s in the field of management information systems (MIS). It was the result of an intersection of two trends. The first one was the growing belief that existing information systems, despite their success in automation of operating tasks in organisational set-ups, have failed to assist the decision makers with any higher level task. The second trend is continuous improvement in computing hardware and software that has made it possible to place meaningful computing power into the development of databanks and complex heuristics (Karamouz *et al*., 2005). Several attempts have been made to develop a more flexible framework for these systems. The spatial decision support system (SDSS), adaptive decision support system (ADSS), and intelligent decision support system (IDSS) are other recent DSS developments.

As discussed in Chapter 1, decision support requirements in IWRM and WDM places a strong emphasis on cross-sectoral planning. This, it is suggested, distinguishes IS research for supporting WDM planning from the main body of IS research, which has mainly focussed on the development of tools to support automation of management tasks (Hevner *et al*., 2004). The result is that for supporting implementation of WDM strategies, there is a need for the model developer to identify modelling techniques that are perceived to be effective from a range of organisational perspectives.

Torrieri *et al*. (2002) assert the view that from a cross-sectoral planning perspective the most important properties of a decision support tool is that they should remain of an open nature that explicitly allow the participation of multiple stakeholders and the interaction and exchange of different viewpoints and perspectives. The methods should also allow for the forward thinking required for the production of objectives and the planning stages to obtain them.

Modelling can be defined as the process of developing and providing an abstraction of reality, in other words, a model (Costanza and Ruth, 1998). As all models are only different abstractions of reality, certain hypotheses are always present in their construction. Indeed, an aim of modelling in research is to deconstruct reality so that these hypotheses and assumptions can be made explicit and then tested. Computer-based tools are widely used in scientific research as platforms for modelling. Alternatively, in a policy context, modelling is a step in supporting decision-makers in making a choice between a number of options or alternative actions, although, as stated by Costanza and Ruth (1998), the building of models is also an essential prerequisite for human understanding.

Oxley *et al*. (2002; 2004) have made a number of important and helpful distinctions between research and policy models. The following section refers to these in the context of a recognised need to facilitate communication between research and practice in IWRM and WDM.

2.1.1 Research and Policy models

Oxley *et al*. (2004, p25) describe research models as being "strongly process-oriented, their temporal and spatial scales and level of complexity being solely determined by the characteristics of the process being examined by the researcher." Such models are often applied to a single scientific discipline. The research model developer uses the model to test hypotheses and further understanding of the world and tends to make use of scientifically innovative techniques to develop a model that is as complex as required. As Oxley *et al*. (2004, p25) point out, "often this will pose difficulties in validating the resulting model, but in the quest for new knowledge the development of the model can be a goal in its own right." Data for populating research models will be gathered, as required, from field sites or other sources. The processing speed and the interactivity of the model are not typically considered, nor is model transparency or user-friendliness, as the model developer is usually the only user of the model (Oxley *et al*., 2002; 2004).

Policy models are different from research models in a number of ways. Firstly, they are oriented towards addressing practical, often issue-driven, policy problems.. Oxley *et al*. (2004) make a number of distinctions between policy and research models. The problem or decision being addressed "determines the temporal and the spatial resolution at which processes are represented. The level of detail and degree of complexity are often determined by the availability of data. Policy models are only interesting because they deliver practically useful output. To achieve this, robust, extensively tested methodologies will preferentially be used. The policy model might be complex, but generally is kept as simple as possible." Oxley *et al*. (2004, p24) propose that, "… policy models are not designed to further understanding of processes but to help explore the possible effects of policies."

Transparency of research model outputs, and how they are achieved, including issues such as uncertainty, risk, and significance in terms of evidence that supports findings, need to be addressed if research models are to be used to inform policy. Analogies can be made between the objective of balancing curiosity- vs. issue-driven research and efforts to use research models in a policy context. For example, Oxley *et al*. (2002) observe that policy models often use the outputs of research model presented in the context of a specific decision.

The fact that all models exhibit underlying assumptions or hypotheses means that they can be challenged or rendered illegitimate or invalid by someone who does not agree with or accept them (Landry *et al*., 1996; Korfmacher, 2001). For all models, and in particular policy models, this property is of extreme importance when they are to be used by a third party or number of parties for decision making, as if the model is deemed illegitimate by these parties then the decision informed by the model also comes under threat of being deemed equally illegitimate and thus open to be challenged.

The following section discusses the role of computer-based support tools in social learning and participatory integrated assessment.

2.1.2 Computer based tools support social learning and participatory integrated assessment

Haas (1992) defines an ‘epistemic community’ as “ a network of professionals from a variety of disciplines and backgrounds, they have a shared set of normative and principled beliefs, which provide a value-based rationale for the social action of community members; shared causal beliefs, which are derived from their analysis of practices leading or contributing to a central set of problems in their domain and which then serve as the basis for elucidating the multiple linkages between possible policy actions and desired outcomes; shared notions of validity—that is, inter-subjective, internally defined criteria for weighing and validating knowledge in the domain of their expertise; and a common policy enterprise—that is a set of common practices associated with a set of problems to which their professional competence is directed, presumably out of the conviction that human welfare will be enhanced as a consequence” (Cinquegrani, 2002, p101). The ideas of the epistemic community are captured in recent research into the use of computer-based tools to facilitate social learning in IWRM.

Social learning has attracted interest as a way of conducting public business, alongside regulation, compensation, stimulation and the operations of the (free) market (Ollivier, 2004). It has also been promoted as essential for the management of complex natural resource dilemmas and as a key process in adaptive management (Henriksen and Barlebo, 2007). Adaptive management (AM) involves learning from management actions and using that learning to improve the next stage of management (Holling, 1978). AM treats policies and management interventions as experimental probes designed to learn more about the system; they are not confident prescriptions (Lee, 1993). Monitoring before and during the intervention, enables the system response to be determined and thereby allows managers to learn from past experience and to translate the best of current IWRM research into practice.

The goal of a number of recent European projects (MERIT, HarmoniCop, NeWater, SLIM) has been to develop methods to support participatory integrated assessment, and a review of research outputs shows an emphasis on the use of computer-based tools. An aim of participatory integrated assessment is “to widen policy-makers and stakeholders scope and to reshape their cognitive map in order to displace participants from their real and immediate tasks, roles, identities and decision contexts, e.g. to move participants outside their normal habits and positions” (Henriksen and Barlebo, 2007, p2), and “to encourage creative thinking, new ideas, and insights” (Parson, 1996; Hisschemoller *et al*., 2001).

Up to now this review has focussed on the use of computer-based tools to facilitate communication between the three groups identified in Figure 1.7, Chapter 1. Water availability is determined by environmental factors whilst, at the same time the amount of water abstracted from rivers and aquifers can have long-term impacts on natural systems. The parallel need for communication and the impact of human activities on natural sytems is identified as a further factor that needs to be integrated into any computer-based tool to support WDM planning, and is discussed below.

2.1.3 Modelling the interface between natural and man-made systems

Water resources systems consist of different elements of two distinct environments: one is the physical, chemical and biological environment, and the second is a cultural environment with social, political, economic and technological dimensions (Karamouz *et al*., 2005). The physical and cultural environments are inseparable. In other words, natural resources and especially water resources systems cannot be modelled effectively without considering social and political circumstances and vice-versa.

It is now widely accepted that models developed for decision-making and planning in water resources management need to adequately represent the relationship between humankind and natural systems (Ilyutovich *et al*., 1996), shown in Figure 2.1 (below).

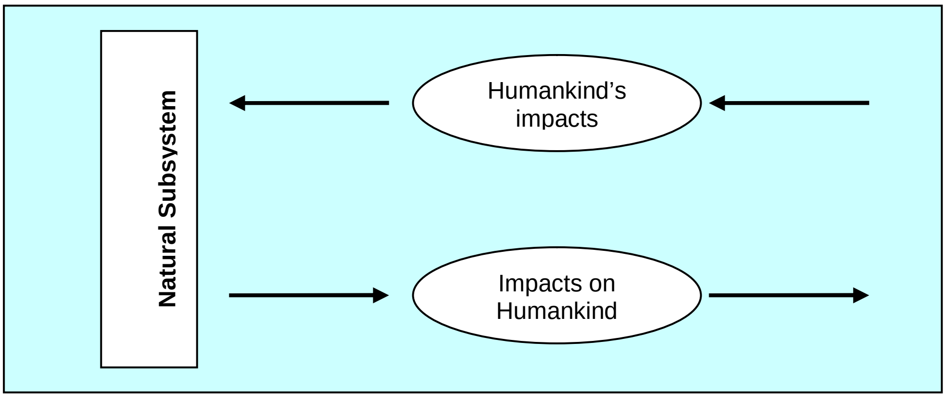


Figure 2.1. *Humankind's interaction with Natural Systems*

Sources of external changes in such models include: unpredicted environmental change, economic development, and population growth. The representation of collective human behaviour to changes in governance in computer models is challenging because of the large number of actors involved; this is a cause of uncertainty that relates to the modelling methods used. Governance responses, experienced as policy interventions, are an additional source of external change and their modelling requires methods for disaggregating and aggregating indicators to address problems of scale as well as changes through time. For example, costs and benefits of WDM are experienced at different scales and in different ways by individuals and organisations depending of their perspective. Whilst politicians may find meaning in national or regional socio-economic indicators, the water supplier may find economic efficiency indicators more relevant, whilst for householders (citizens), their personal water bill and water quality will be paramount. The challenge is emphasized when considered in the context of planning demand-side management as a drought mitigation measure: financial investment is required in the short-term, to avoid crisis in the long-term. Supporting examination of the possible costs and benefits from different perspectives, therefore, requires methods that deal with these temporal and spatial scales.

2.2 A decision support tool is selected for use in the case study fieldwork

In the following section two candidate modelling approaches, Bayesian networks (Bns) and System Dynamic (SD) modelling, are described and considered for use in the case study field work.

2.2.1 Decisions support tools used in water demand management

The analytical approaches used in computer-based decision support tools, and the way outputs are presented on the screen affect how judgements are made (Oxley *et al*., 2003; Hevner *et al*., 2004). For example, deterministic methods, whilst having a number of advantages such as their adaptability, are limiting because the means of estimating the confidence in model outputs and associated risks, i.e. uncertainty of conditional relationships, are not given. Alternatively, probabilistic methods, as well as supporting judgement decisions based on the risk-attitude of the decision-maker, support a number of different types of decision analysis for examining uncertainty, such as estimation of the value of data collection in reducing uncertainty.

Characterisation of the WDM in Chapter 1 identified numerous causes of uncertainty during the planning and implementation stages leading to indeterminacy and complexity in decision-making. As a result it was stated that any computer-based decision support tools used in WDM programme planning and implementation needs to facilitate examination of elements of risk and uncertainty and support users in accounting for these in their decisions.

A table of reviewed modelling techniques that have been applied in water demand management is presented in Appendix B. Most of the reports of model applications reviewed were results of desk studies (i.e. they did not involve application or evaluation to support cross-sectoral planning). As the aim of the revied presented in Appendix B was to identify a suitable modelling approach that could be used in the case study fieldwork, the modelling techniques reported in desk studies, whilst of interest, were not considered as potential candidates because in most cases they only described their use for development of research models and the user interface had not been sufficiently developed for use in a cross-sectoral planning environment.

A number of reviewed papers, however, reported the application of System Dynamics modelling (Costanza and Ruth, 1998; Stave, 2003; Tidwell *et al*., 2004) and Bayesian network modelling (Soncini-Sessa, 2003; Bromley *et al*., 2005; Ollala *et al*., 2005) to support cross-sectoral planning for integrated water resources management in Europe and the USA and were of particular interest to this study. Even though none of these referenced articles report formal evaluations of the modelling techniques used, they were nevertheless useful as a foundation for decision support tool selection.

2.2.2 System dynamics modelling

Models for water resources management and planning based on Forrester's (1961) systems dynamics work have been used almost since the theory's conception in the USA (Yeh, 1985), although using them in a participatory setting by many stakeholders of a planning (or "problem") region is much more recent. System Dynamics modelling attempts to characterise the behaviour of whole systems through their feedback structures. The common format of tools or modelling methods used is a communally built causal-loop diagram (a particular form of cognitive mapping designed to explicitly represent "if-then" dynamic statements between variables). The causal-loop diagram is then translated into a quantitative "stock and flow" type dynamic model using platforms such as STELLA (High Performance Systems, 1992) and VENSIM (Ventana Systems, 1998) that allow simulations to be carried out with the results visualised on the computer. Figure 2.2 (below) shows the causal loop, stocks and flows, visualised results, presented to the user.

Three research articles examining the use of System Dynamic modelling for water resources management in the USA (Costanza and Ruth; 1998; Stave, 2003) and South America (Tidwell *et al*., 2004) describe a number of benefits of applying the method in a participatory context.

Stave (2003) reported that the ability to run model simulations in an interactive forum allowed stakeholders to participate in the evaluation and comparison of different policies. Model simulation provides immediate feedback to participants about their ideas. Model output graphs (Figure 2.2) provide a powerful visual way to compare the results of different policy tests. Multiple feedback relationships lead to the

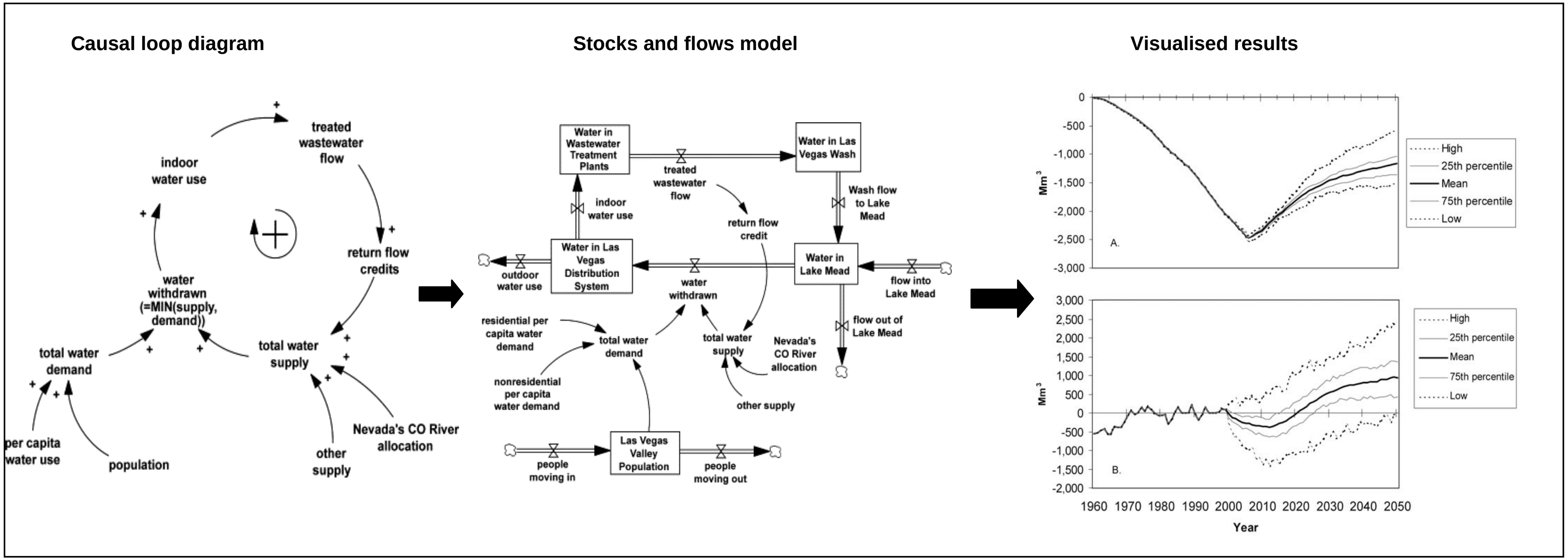


Figure 2.2. *Systems Dynamics Modelling*

somewhat counterintuitive result and seeing unexpected results generated in response to participant suggestions engages their interest and provides opportunities for educating participants about the system in response to their questions.

Tidwell *et al*. (2004) reported that the use of the model not only helps participants better understand the basis for management decisions, but also stimulates discussion among group members and can help build the consensus and support resource managers need to implement their decisions. Limitations cited are that uncertainty is not represented within the model. Human behavioural effects that can only be described qualitatively tend not to be considered in this kind of modelling except when they can be statistically modelled in terms of water use or other easily quantifiable variables. Models are not capable of representing known dependencies, and this limitation is addressed by using combination strategy options, which are limited and case sensitive.

2.2.3 Bayesian networks

Bayesian Networks (Bns) - also known as belief networks, Bayesian belief networks, Bayes nets, and sometimes also causal probabilistic networks - were first developed by the artificial intelligence and machine learning community (Pearl, 1988), and have been successfully applied in the fields of medical diagnosis (Kahn *et al*., 1997) evaluation of scientific evidence (Heckerman *et al*., 1995; Yu *et al*., 1999) market research (Assmus, 1977; Lacava & Tull, 1982; Rossi & Allenby, 1993) and, more recently, to modelling uncertain and complex domains such as ecosystems and environmental management (e.g. Varis, 1997; Cain, 2001; Soncini-Sessa *et al*., 2003; Bromley *et al*., 2005; Uusitalo *et al*., 2005.) Bns are a powerful modelling technique that replicates the essential features of plausible reasoning (reasoning in conditions of uncertainty) in a consistent, efficient and mathematically sound way (Charniak, 1991). Their application in water resources management has been relatively recent. Although knowledge gaps still exist regarding their full potential, where Bns have been applied to water resources management problems involving uncertainty (Soncini-Sessa *et al*., 2003; Ollala *et al*., 2005; Babovic *et al*., 2002) and participation (Henrikson *et al*., 2004; Bromley, *et al*., 2005; Ollala, *et al*., 2005), results indicate that they are a promising tool for facilitating collaboration strategic planning and decision-making under uncertainty.

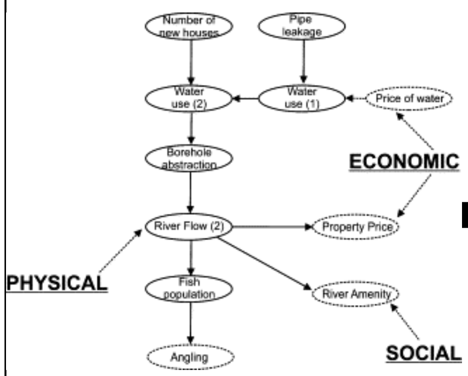
From a review of the literature several features that make Bns useful in examining many real-life data analysis and management questions were identified. Varis and Kuikka (1999) point to the usefulness of conditional probabilities in enabling the modelling of ‘level of determinism’, i.e. a poor knowledge or poor control is modelled by weak conditional probabilities and vice versa”. Bns can show good prediction accuracy even with rather small sample sizes (Kontkanen *et al*., 1997), and they can also be combined with decision analytic tools to aid management (Kuikka *et al*., 1999; Jensen, 2001). Uusitalo (2007) has found that Bayesian networks are also a useful tool for expert elicitation and combining uncertain knowledge when used with care. Building Bn models forces the user to think clearly about the subject, and articulate that thinking in the form of the model which is often beneficial in and of itself (Marcot *et al*., 2001; Walters and Martell, 2004).

Figure 2.3 shows different stages of Bn modelling (Bromley *et al*., 2005). Models structure is achieved using probabilistic (chance) nodes and directed links (structure), and the parameters (influences between variables) are quantified and stored in conditional probability tables.

The above summary of the application of System Dynamic modelling and Bayesian networks in water resources systems modelling identified a number of strengths and limitations of both approaches. Whilst both approaches were considered suitable for further application in the absence of the other, the presentation of model outputs as probabilities, the compatibility with a wide range of data types, and positive reports of their use in collaborative planning for IWRM, indicated that Bns are well-suited for application in the case study work. From a research perspective, the absence of existing formal evaluations of Bns despite positive reports of there use, provided a focus for the case study field work. The absence of any formal evaluations of Bns in case studies involving water demand management in the scientific literature, in spite of positive reports, indicated a requirement for further research.

The following section focuses on Bayesian network modelling in greater detail. A description of probability theory and Bayesian inference is followed by a detailed

Bn model structure



Conditional probability table

Pipe leakage	Price of water	Water use (1)		
		Increase	No change	Decrease
0%	Down (−10%)	0.2	0.75	0.05
5%	Down (−10%)	0.1	0.3	0.6
10%	Down (−10%)	0.05	0.25	0.7
0%	No change	0.1	0.9	0.1
5%	No change	0.05	0.1	0.85
10%	No change	0	.05	0.95
0%	**Up (+10%)**	**0.05**	**0.65**	**0.3**
5%	Up (+10%)	0.05	0.5	0.45
10%	Up (+10%)	.05	0.15	0.8

Instantiated model

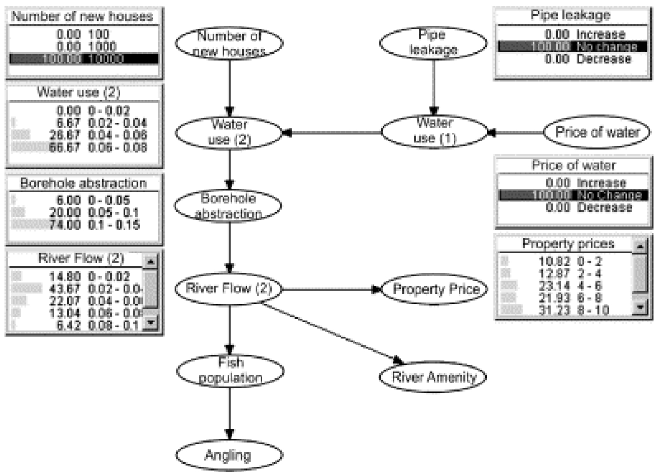


Figure 2.3. *Bayesian network modelling*

description of Bayesian network terminology and topology. Bayesian approaches to decision analysis and managing uncertainty are then discussed.

2.3 Bayesian Network Modelling

2.3.1 Probability theory and Bayesian inference

Using a probabilistic approach, no claim to absolute truth is made; it is a truth relative to assumptions (Jensen, 2001). Any statement on (conditional) probabilities is also a statement conditioned on what else is known. For example a conditional probability statement would be, *"given the event b, the probability of the event a is x".* The notation for the preceding statement is:

$p(a \mid b) = x$ (Eq 2.1)

It should be stressed that $p(a \mid b) = x$ does not mean that whenever b is true, then the probability for a is x. It means that if b is true, and everything else known is irrelevant for a, then the probability of a is x.

There has been a long debate as to whether the procedure of Bayesian inference is justified and is covered by the notion of probability (Harney, 2003). The key question was: Can one consider probability not only as a relative frequency of events but also as a value of truth assigned to a statement. This 'value of truth' approach corresponds to the personal approach proposed by Savage (1954). For the founders of statistical inference, (Bayes and Laplace) the notion of probability carried both concepts: the probability attached to a statement ξ can mean the relative frequency of its occurrence or the state of knowledge about ξ. Harney (2003) explains this by describing different types of probability which, by their nature, require different approaches. The statement 'The probability that the coin will fall heads up is ½' lends itself well to the frequency approach. However, the statement 'It is very probable that it will rain tomorrow' is not amenable to the frequency interpretation - not because the qualitative value 'very probable' is vague, but because 'tomorrow' always exists only once. So the latter statement can only be interpreted as evaluating the available knowledge (Harney, 2003).

In classical statistical approaches, probability is based on the frequency of data alone. In Bayesian models, the frequency distribution from the observed data a given parameters *b,* denoted $p\ (a \mid b)$, is used to modify the prior distribution $p\ (b)$, to produce updated knowledge or a posterior distribution, $p\ (b \mid a)$. The relationship between these frequencies follows from the standard probability equations (Congdon, 2003). Thus:

$p(a, b) = p(a \mid b) \cdot p(b) = p(b \mid a) \cdot p(a)$ *(Eq 2.2)*

and this yields the posterior frequency, known as Bayes' rule:

$$p(b \mid a) = \frac{p(a \mid b) \cdot p(b)}{p(a)} \qquad \textit{(Eq 2.3)}$$

The denominator *p (a)* is known as the marginal frequency (or marginal likelihood) of the data and is found by integrating (or 'marginalising') the observed data frequency distribution over the prior distribution. This parameter plays a central role in some approaches to Bayesian model selection criteria to justify extra parameters in a model. It is comparable to a goodness of fit between the prior frequency and observed data, and can be seen as a proportionality factor so that:

$p(b \mid a) \propto p(a \mid b) \cdot p(b)$ *(Eq 2.4)*

Thus updated beliefs are a function of prior knowledge and the sample data evidence.

The following subsection introduces different types of decisions that are addressed using Bayesian analysis in this thesis. Applying Bns for decision support can involve the use of deterministic (decision and utility) nodes and such models are usually referred to as Influence Diagrams (IDs) (Oliver & Smith, 1990; Jensen 2001). The terminology used in the construction of Bns and IDs and the types of analysis that they support are described below using examples.

2.3.2 Bayesian network terminology and topology

According to Jensen (2001, p28), "… in principle there are two kinds of decisions, namely test decisions and action decisions. A test decision is a decision to look for more evidence to be entered into the model, and an action decision is a decision to change the state of the world." As Jensen points out, "… in real life, this distinction is not very sharp; tests may have side-effects, and by performing a treatment against a disease, evidence on the diagnosis may be acquired. In order to be precise, we should say that decisions have two aspects, namely a test aspect and an action aspect."

The two aspects are handled differently in connection with Bayesian networks, and accordingly are treated separately. Actions should be divided into two types, namely intervening actions, which force a change of state for some variables in the model, and non-intervening actions, where the impact is not part of the model. Although both observations and intervening actions change the probability distributions in the model, they are fundamentally different. To illustrate this, consider the examples in Figure 2.4 and Figure 2.5. From the point of view of entering evidence and propagating probabilities, the two Bayesian networks shown are equivalent. However, the difference becomes apparent when taking an aspirin. If the same utility and decision nodes are added in Figure 2.4, taking an aspirin will cure flu but will have no effect on sleepiness. This would not be a correct (causal) representation because aspirin does not actually cure the Flu (although some may think so) (Jensen, 2001).

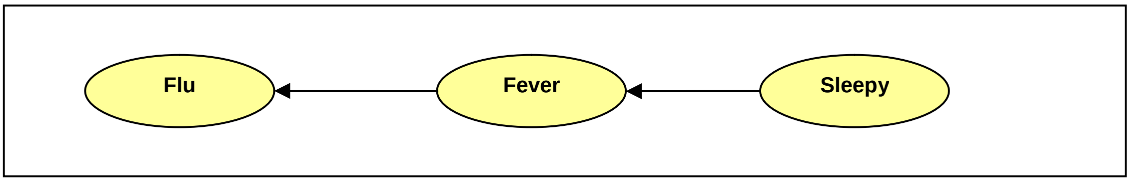


Figure 2.4. *A Bayesian network of diagnostic reasoning equivalent to the one in Figure 2.5*

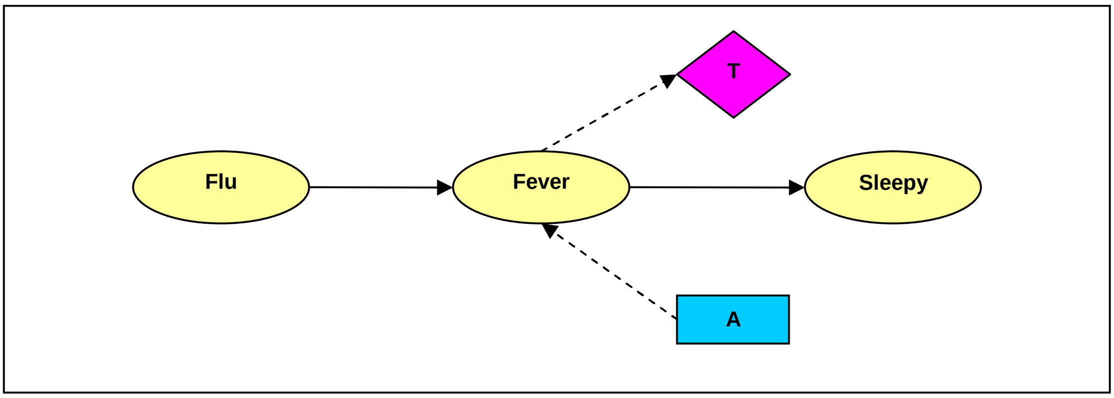


Figure 2.5. *A simple flu decision model with an action (aspirin=A) and a test temperature=T) attached. The action has no impact on P (Flu)*

In practice, diagnostic (reverse) links (Figure 2.5) are only used for test decisions (i.e. when carrying out tests to estimate the value of collecting evidence on different indicator variables). For modelling the impact of intervening, or action decisions - in this case taking an asprin - the links should follow the cause-effect relationship, so as to represent the impact of the action.

A Bayesian network (Bn) consists of a set of *variables* and a set of *directed links* between variables. When describing the relations in a Bn the wording of family relations is generally used (e.g. Jensen, 2001; Castelletti and Soncini-Sessa, 2007):

if there is a link from *A* to *B*, then *B* is referred to as a *child* of *A* and *A* is a *parent* of *B*. A node which does not have any parents is called a *root node* and represents an input variable. A node without children is a *leaf node* and constitutes an output variable. Each node in the network is assigned with a set of discrete values or *states*, which represent all the possible conditions that that variable, represented by the node, can take. In Bns node states can be either quantitative or qualitative. For each node (except the root nodes) a *conditional probability table* (CPTs) is specified. The probabilities entered in the cpt describe the strength and weights of causal relationships (parameters) between nodes when other nodes are in a particular state.

Once the *prior probabilities* of a number of variables (usually the input variables) have been specified in chance nodes, it is possible to calculate the *posterior probabilities* for all the nodes in the network (belief propagation). This is done by employing basic probability calculus and Bayes' theorem, described in Section 2.3.1. As new knowledge about the system is obtained in the form of observations (evidence) about one or more variables, the prior probabilities for *node states* are updated. The procedure of adding evidence, also referred to as *instantiation*, results in the beliefs about states of other connected variables in the network to be updated through *belief propagation*, described below. *Belief propagation* in Bns is essentially a computational tool for communicating probabilistic inference between nodes within a Bn model. In practice, the combination of belief propagation and Bayes' theorem in Bns produces a powerful modelling tool that allows both bottom-up (or backward-looking) probabilistic inference to address diagnostic tasks or top-down (forward-looking) probabilistic inference for predictive/explanatory purposes (Castelletti and Soncini-Sessa, 2007). In the first case, the evidence of an effect is given and the most likely cause is inferred. In the second, the probability of an effect is computed once the evidence for one or more of its causes is provided.

For Bayesian networks the graphical convention shown in Figure 2.6, below, is used, where a rectangle denotes a *decision* node, a diamond denotes a *utility* node and an oval denotes a *chance* node. Each state in the chance node connected to the utility node is assigned a corresponding value in the utility node.

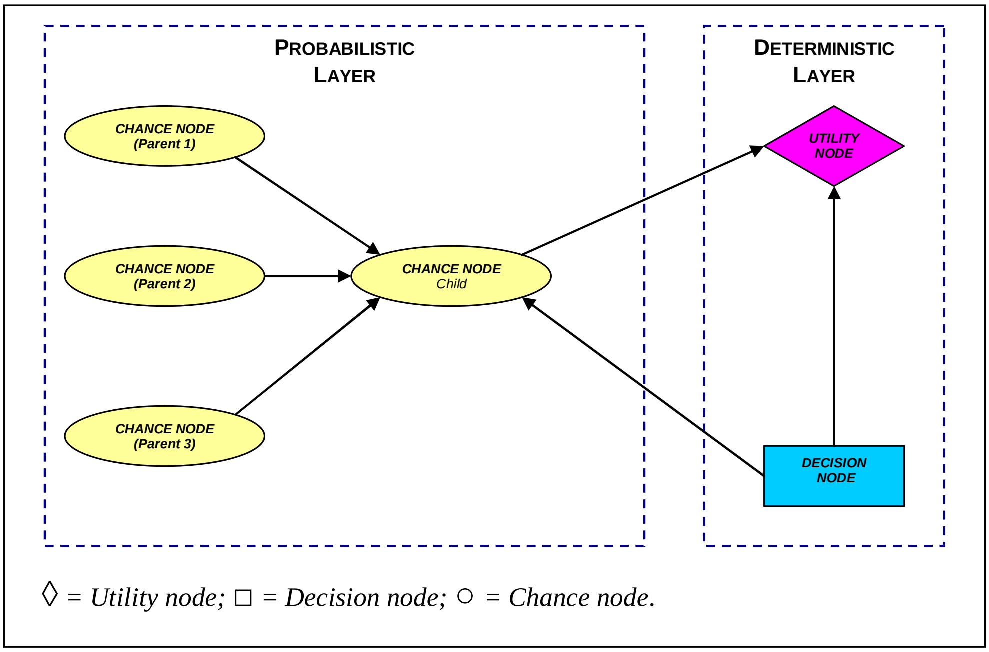


Figure 2.6. *Influence Diagram structure showing three node types*

Chance nodes in a Bayesian network represent the probabilistic layer of the problem domain. As such they are an objective representation of the world. Decision and utility nodes represent human intervention in the model

They represent the utility (or the value) that results from a given decision will have, given the updated probabilities in the chance nodes. Utility nodes use subjective values (*utility functions*) to quantify the value of different states in the connected chance nodes. The maximum expected utility (MEU) is calculated by factorising the different utility functions using the probabilities in the connected chance node.

The model in Figure 2.7, below, is a simplified Bayesian network of a water demand management decision for a city.

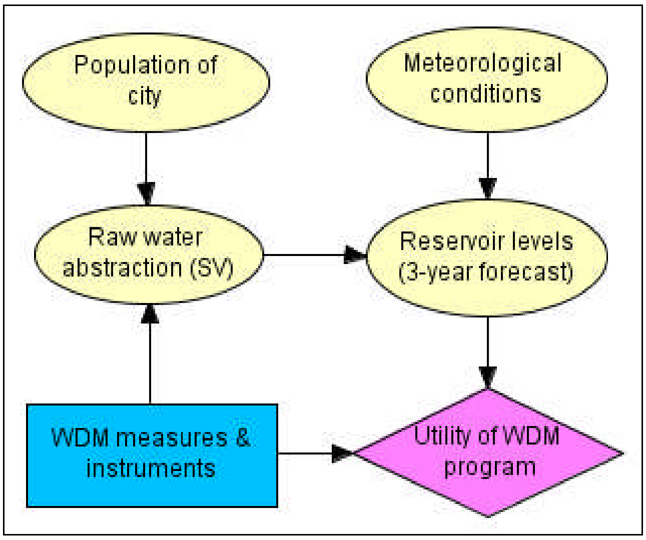


Figure 2.7. *A simplified Influence Diagram of a WDM decision*

The model considers whether, given the reservoir level forecast based on the evidence added in the two parent chance nodes, it is necessary to reduce raw water abstraction by implementing a WDM programme. The directed links show that raw water abstraction and meteorological conditions impact on future reservoir levels.

Figure 2.8 (overleaf) shows the model in Figure 2.7 in use. Four intervention options are assigned in the decision node (no programme, or minimum, moderate, maximum programmes). Node states are shown in the monitor windows overlapping each node. The different model instantiations show (A) the model in its resting state, (B) propagated conditional probabilities give evidence on population of city and meteorological conditions and (C) propagated conditional probabilities and utilities for the decision 'maximum programme'. The utility functions and conditional probabilities are shown in the box in the bottom-left.

2.3.2.1 Decision trees and utility theory

Decisions trees are an alternative way to structure Bns and the decision tree below, Figure 2.9, which is a decision tree for a section of the ID in Figure 2.8, demonstrates how the posterior probability distribution given a set of evidence permits calculation of the maximum expected utility (MEU) for a decision.

A Bayesian network software package called Hugin was selected for use in the case study field work based on a number of technical criteria. The full review of different platforms and technical criteria used is presented in Appendix C.

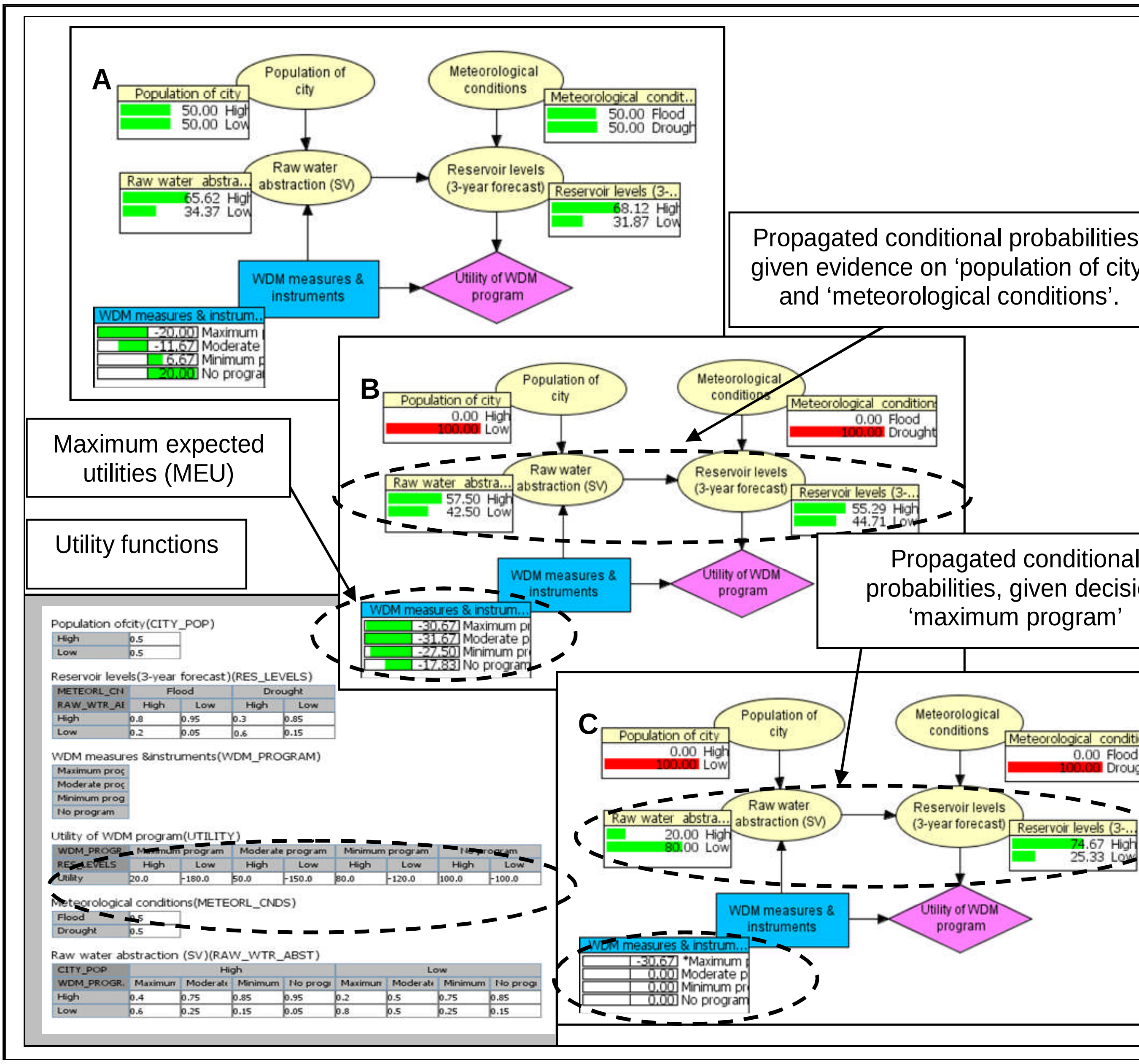


Figure 2.8. *Model instantiations and populated conditional probability tables for the simplified ID of the WDM decision for the Iskar Dam near Sofia*

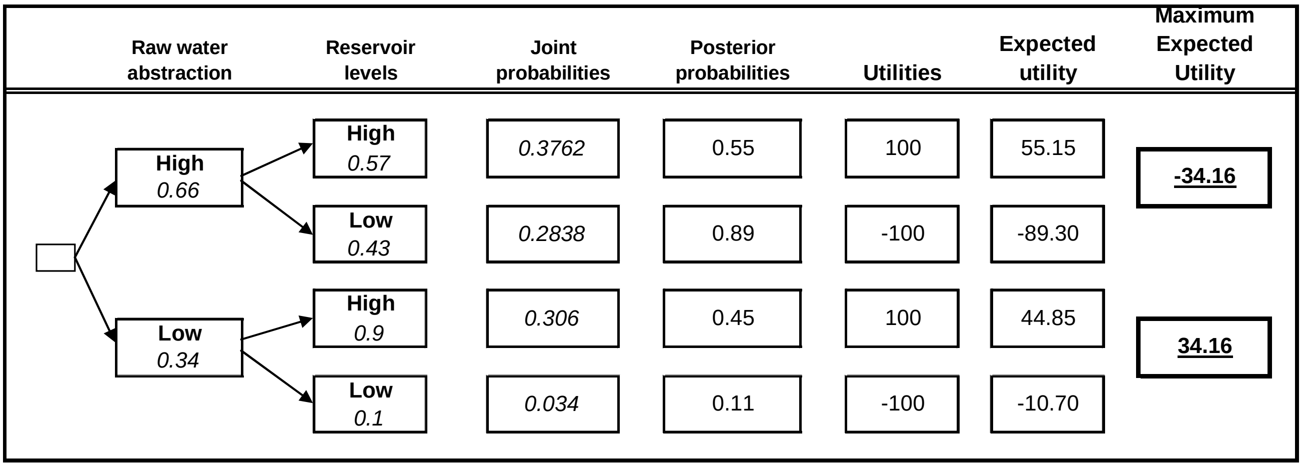


Figure 2.9. *Decision tree showing maximum expected utilities derived from the posterior probabilities*

The following section discusses Bayesian modelling approaches for decision analysis and managing uncertainty.

2.3.3 Decision analysis using Bayesian networks

Bayesian analysis simultaneously addresses two aspects of uncertainty. These are:

a. Structural uncertainty, i.e. Is this the right model structure?

b. Parameter uncertainty, i.e. Is this the right probability distribution?

Bayesian techniques applied throughout this thesis include: structural learning, sensitivity analysis, model instantiation (posterior analysis, and value of information. Box 8.1 in Chapter 8 summarises how each technique addressed structural and parameter uncertainty in the models developed.

A characteristic of Bns identified by Varis (1995), who applied Bns to natural resources management, is that they allow combined use of several methodological and paradigmatic facets that are often seen as being far from one another. Figure 2.10 presents the methodological and paradigmatic (in italics) facets identified by Varis (1995).

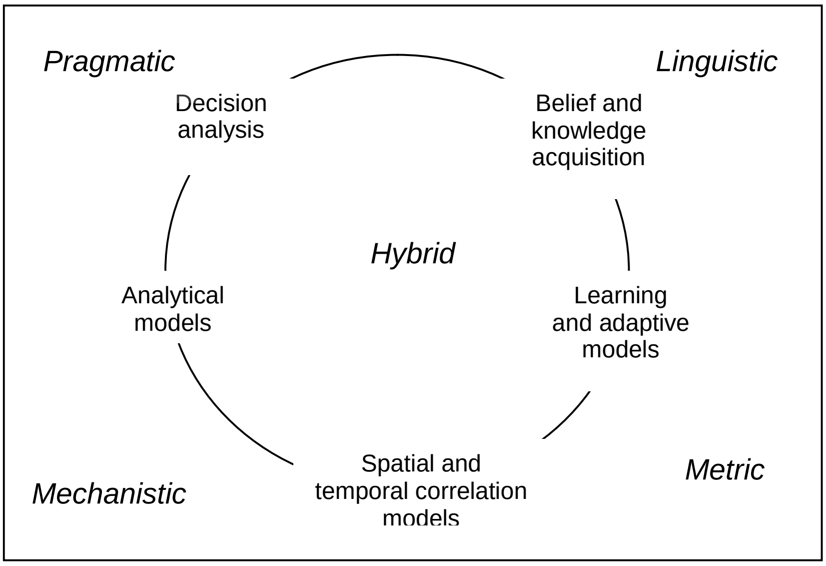


Figure 2.10. *The belief network approach allows combined use of several methodological and paradigmatic (in italics) facets that are often seen as being far from one another*

Oliver and Smith (1990) propose a decision analysis cycle for applying Bayesian decision analysis shown in Box 2.1, below.

Box 2.1. Decision analysis cycle (Oliver & Smith, 1990)

First: The decision basis, the formal description of the problem is constructed

Second: A deterministic sensitivity analysis is performed to see which variables are worthy of probabilistic treatment

Third: Probabilities are assigned to these variables and we determine the alternative with the most desirable probability distribution on outcomes according to the values and risk preferences of the decision-maker.

Fourth: Stochastic sensitivity analysis reveals the importance of each of the uncertain variables and indicates whether further care in their modelling or assessment is desirable.

Fifth: A value of clairvoyance (information) analysis determines the economic value of resolving any uncertainties in the problem.

Sixth: As a result of these appraisal activities, a new basis may be created and the process repeated, or we may decide there is sufficient clarity of action in view of the total problem setting. The decision diagram is of major assistance in all these activities.

Evaluating the effectiveness of Bns in modelling and decision analysis to address WDM issues identified above (research and policy modelling, social learning and participatory integrated assessment, and modelling the interface between natural and man-made systems) and the areas of the WDM problem domain identified in Chapter 1 was the subject of the case study fieldwork that is described in Chapter 3 to Chapter 7. The research provides a technical and end-user evaluation of Bns in the context of cross-sectoral planning for domestic sector water demand management in a region of water stress.

Chapter 3

Case Study: The Upper Iskar River and the City of Sofia, Bulgaria

Introduction

The causes and effects of water scarcity in the Upper Iskar River and the city of Sofia in south-western Bulgaria are described in Chapter 3, below. Water supply and demand data were collected from research institutes and the municipal water supplier in Sofia to identify drivers of water stress in the region, and these are presented in Section 3.1 with commentary on the current and future implications for water management. Interviews with a panel of informed practitioners provided information to support model development and model integration and the results of the interviews are reported in Section 3.2. Section 3.3 includes a discussion of findings from the knowledge elicitation interviews. Conclusions to Chapter 3 are presented in Section 3.4 and include implications for Bayesian network model development and identification of the research questions that provided the focus for the model development in Chapters 4, 5 & 6.

Case Study Selection Process

Identification of a suitable case study for the field work involved analysis of water supply and demand data from eight water-stressed river catchments in Europe and North Africa. The eight river catchments involved in the feasibility study were:

- Guadiana, Portugal
- Flumendosa-Mulargia, Italy
- Vecht / Zwarte Water basin, The Netherlands
- Przemsza, Poland
- Upper Iskar, Bulgaria
- Limassol, Cyprus
- Merguellil valley, Tunisia
- Tadla, Morocco

Regional reports on water stress issues in each catchment were collected with the support of organisations involved in water management in each region. The Upper Iskar sub-catchment in Bulgaria, which includes the capital city of Sofia, was identified as the site most suited for carrying out the fieldwork for a number of reasons.

Sofia is located on a section of the Upper Iskar River that includes the Iskar Reservoir which supplies 80% of all water consumed in the region. The Upper Iskar is characterised by high water abstraction (525 litres *per* capita *per* day), 70% of which is for domestic use. The breakdown of sectoral water demand for the Upper Iskar is shown in Table 3.1, below.

Table 3.1. *Sectoral water demand in the Upper Iskar*

SECTOR	ANNUAL ABSTRACTION IN 2001-2005 (RANGE)
Domestic water demand.	245-320 million m^3
Agricultural water demand	1.2-23 million m^3
Industrial water demand	56-78 million m^3

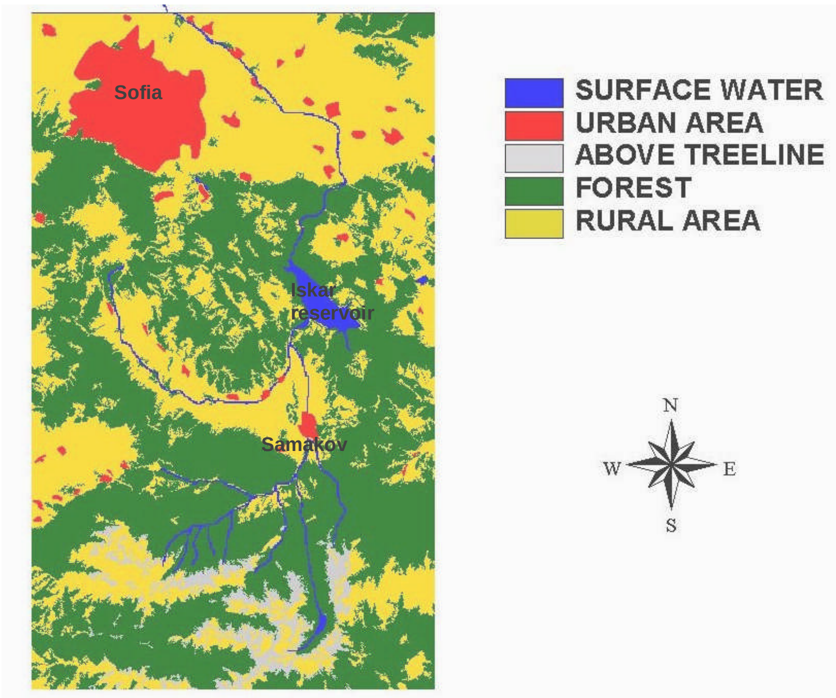
Data source: University of Architecture, Civil Engineering and Geodesy, 2006

Intermittent drought in the region affects water availability which, between 1993 and 1995, resulted in water crises with negative social and economic consequences. The following section describes the socio-economic and environmental drivers of water stress in Upper Iskar sub-catchment.

3.1 Climate change and water crises in the Upper Iskar

At 368 km, the Iskar River, situated in the south west part of the country, is Bulgaria's longest river. It has the third largest catchment area (8.650 km^2) of all Bulgarian rivers after the Maritsa River and the Struma River. The case study sub-catchment, shown in the map in Figure 3.1 (below), begins at the river's spring in the Rila Mountains and ends at the point where the Lesnovska River joins the Iskar from the east, approximately 1 km north of Sofia.

The hydrologic cycle in the Upper Iskar is characterised by seasonal extremes, with intermittent drought during the summer on the one hand, and flooding in the autumn



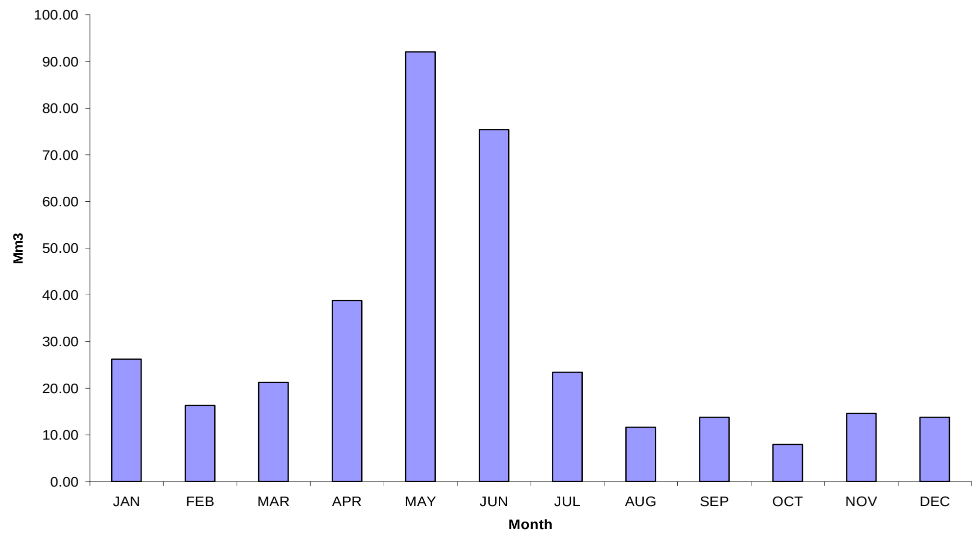
Map supplied by Geonardo, 2005

Figure 3.1. *Land use map of the Upper Iskar test site showing the Iskar reservoir and Sofia city.*

and winter on the other. The Iskar River begins 2000 feet above sea level in the Rila Mountains which, being below the altitude at which glaciers form, means there is no permanent ice. During the winter months snow accumulates in the mountains, and during the spring when the snow melts, it becomes the most important annual source of water in the region, replenishing reservoir levels for the summer months.

The Iskar Dam is the largest reservoir in the Upper Iskar and the main source of water supply for the city of Sofia, supplying 80% of all water consumed in the city. The histogram below, Figure 3.2, shows the mean monthly water inflow to the Iskar Dam for the years 1990 to 1995. It shows that around 50% of the annual recharge of the Iskar reservoir occurs between April and June, and is evidence that the main recharge event in the year is spring snow-melt.

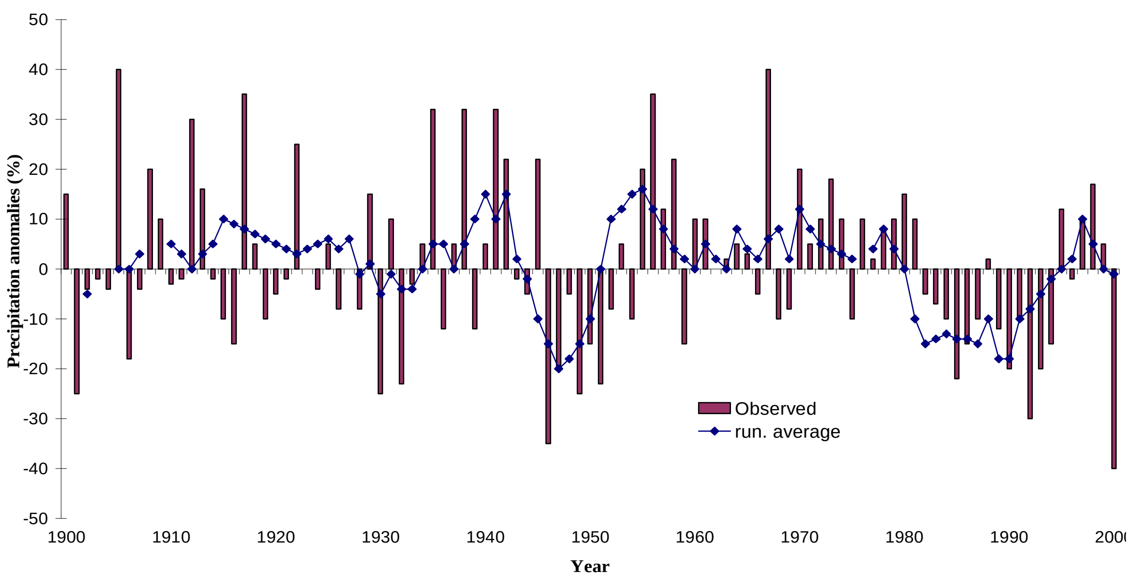
Between 1993 and 1995 citizens of Sofia experienced severe water crises due to water scarcity. Studies into snow-cover in the Rila Mountains from 1921-2000 (Petkov and Koleva, 2005; Petkova *et al*., 2005) conclude that “during recent years, especially in the period 1982-1994, the number of days with snow cover decreased, whilst on the other hand, winter temperatures increased in the same period”.



Data source: Bulgarian Academy of Sciences, 2006

Figure 3.2. *Average monthly inflow, Iskar reservoir: 1990-1995*

As well as the annual cycle of variable water availability hydrologists have identified a longer cycle spanning a period of 20-30 years in the region (Alexander and Genev, 2003). Knight *et al*. (2003) explain that the Upper Iskar sub-catchment is situated on a plain between two mountain ranges – the Rhodope and Balkan ranges – which lies within a latitudinal range that is characterised by drought (Knight *et al*., 2003) and cite these geographical factors as causes of a long-term cycle between water scarcity and inundation experienced in the region. The cycle is evident in the graph below, Figure 3.3, which shows precipitation anomalies from the mean calculated from data collected between 1900 and 2000. From this data hydrologists have identified a "natural hydrologic regime that consists of a 10-15 year period characterised predominantly by flooding, followed by a 10-15 year period characterised by drought." (Knight *et al*., 2003, p117)



Data source: Alexander and Genev, 2003

Figure 3.3. *Precipitation in the Upper Iskar – variation in actual precipitation from the mean for the years 1900 to 2000. The graph illustrates the long-term cycle of flood and drought in the upper Iskar*

Climate change modelling for the region has been reported by Chang *et al*. (2002). They compared two simulation models, one from the United Kingdom Meteorological Office Hadley Centre for climate change prediction and research (HadCM2) and a second from the Canadian Centre for Climate Modelling and Analysis (CCC). Chang *et al*. simulated water resources scenarios into a water balance model for a study area, the Sturma River, the results of which are highly relevant to the Upper Iskar because the grid squares used in the study are 20.625^{o} E ~ 24.375^{o} E / 41.25^{o} N ~ 43.75^{o} N and 20.625^{o} E ~ 24.375^{o} E / 40.8026^{o} N ~ 44.5526^{o} N for the HadCM2 and CCC models respectively, which incorporates the Upper Iskar river catchment. The table below, Table 3.2, summarises the results of the HadCM2 and CCC climate simulations for the Sturma River for 2025 and 2050.

The most notable forecasted variations from the 'base' stream flow, which used data from 1961-1990, are the decrease in run-off during the summer, and the increase in run-off during the winter, a characteristic of the forecast that is repeated in both HadCM2 and CCC models. It should be noted that the data used in the simulations did not include the years of the most recent and severe water crisis, 1993-1995.

Table 3.2. *Changes in seasonal and annual stream-flow in Rila mountains (unit m3/sec)*

SCENARIO	SPRING	SUMMER	FALL	WINTER	ANNUAL
Base	145	78	33	74	83
HadCM2 (2025)	151	70	31	96	87
CCC (2025)	167	74	34	108	96
HadCM2 (2085)	129	43	22	117	78
CCC (2085)	151	40	27	149	92

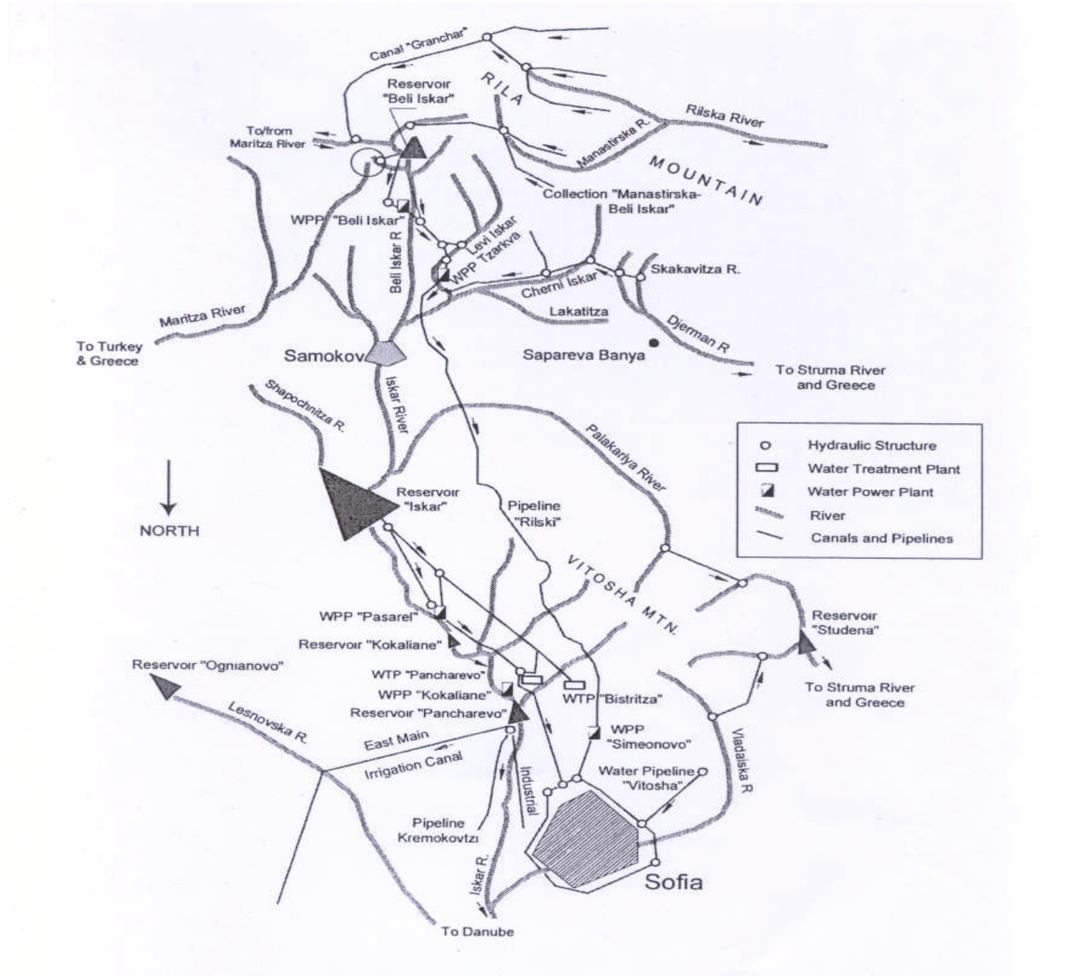
Data source: Chang et al (2002)

These climate predictions indicate that the magnitude of the fluctuation between water shortages and inundations is likely to increase during the next 80 years. The forecasts should be considered in light of the water crisis experienced following the major drought event of 1993-1995, and more recent flood events, both described below. They signal an urgent need for mitigation measures to avoid water stress in the long-term.

The following section describes the social, economic and political context within which water resources management has taken place in the Upper Iskar during the passed 30 years.

3.1.1 Water management during the transition period (1989-1995)

The transition of the political system in parallel with the drive for economic development has come to bear on water resources management in the Upper Iskar. Some commentators (Knight *et al*., 2003; Clarke and Wang, 2003) have suggested that it was the drive for economic development that led water managers to favour supply-side options in favour of demand-side options to address water scarcity. One result is that most of the Upper Iskar's water resources now flow through a complex network of channels and pipelines the city of Sofia. The map below, Figure 3.4, shows the complex network of pipelines and channels that supply water to the city of Sofia. It shows hydrologic structures such as the Rila, Boyana and Iskar pipelines that supply the city from two main reservoirs, the Beli Iskar and Iskar Dams, with water from the Rila Mountains, as well as potable water treatment plants and hydro-power plants.



Source: Knight et al., 2003

Figure 3.4. *Map of water supply network and hydrological structures for the city of Sofia*

The democratisation of the pre-1989 Communist Government resulted in socio-economic changes, and also conflicts over water due to the construction of water diversion projects. The controversy surrounding the Djerman-Skakavitsa water diversion project (Figure 3.4), in the period 1989-1991, is a case in point. Water management activities driven by economic development came into conflict with the interests of sections of society in the rural regions adjacent to a major river upstream of Sofia. The changes were driven by the change in the political system. While the situation in the Bulgarian capital had been difficult in terms of both economic growth and the state of the urban infrastructure, it was even more difficult in the rural "provinces". Rural development under central planning had traditionally been oriented towards the industrialisation of agriculture (through the state farms) and the extensive exploitation of natural resources (Hristov *et al*., 1972; Staddon, 1999). Both sectors were hard hit after 1989, when democratisation of the formerly Communist

Government began, and rapid disinvestment and plant closures occurred in rural areas. Rural unemployment rates were close to double those prevalent in the urban core, a situation made worse by the disinvestment of industrial capital away from rural areas as conglomerates formed behind larger core production units in urban areas (Begg and Pickles, 1998). The communist era's "social industries" policy, which sought to locate some ongoing industrial employment in even the smallest villages, effectively collapsed. This was the case in Sapareva Banya where, in 1991, protests were held against the diversion project, and where as many as 25% of North Rilans were unemployed, having been let go from the soft coal operations at Bobov Dol or other smaller local industrial plants as successive waves of plant closures overwhelmed the state sector after 1989 (Staddon, 1996). The scale of the water diversion project which involved the diversion of surface waters from the Vitosha, Rila and western Rhodope massifs, to the capital, Sofia, is remarkable in European terms, encompassing an area of more than 5000 km2 immediately south of the Sofia Basin. By 1989 this plan had already been partially constructed, with the Djerman-Skakavitsa Diversion in the North Rila Mountains earmarked as the next phase of its realisation.

In February 1991 the Bulgarian government sent Interior Ministry troops into the picturesque town of Sapareva Banya on the northern slopes of the Rila Mountains to quell popular protest against the Djerman-Skakavitsa Diversion designed to help alleviate a water shortage in the capital. This protest pitted residents of the water-scarce capital against North Rila communities fearful of potential environmental damage and angered by the lack of government consultation and dialogue (Knight *et al*., 2003).

3.1.2 Changes in the management of the municipal water supply

The ownership of Sofia's municipal water supply network passed to a concession in 2000. The company Sofiiska voda Ltd, now has a 25-year concession contract for provision of water, sewerage and wastewater treatment services in the city of Sofia. 75% is owned by United Utilities (UU) and the European Bank for Reconstruction and Development (EBRD), while 25% is owned by the public water supply and sewerage company ViK Sofia. Sofiiska voda Ltd manages the water supply and sewerage system of Sofia, and supplies a population of approximately 1.3 million (20% of the population of Bulgaria). It uses two water supply sources – the Iskar Dam (655 million m^3 / yr) and Beli Iskar dam (15 million m^3 / yr). It also operates more than 90 city reservoirs, 4,100 km water distribution network, 147 000 service connections, 2 000 km sewer network, 1 waste water treatment plant, and two large potable water treatment plants - Bistritza (capacity 6.75 m^3/sec) and Pancharevo (capacity 4.5 m^3/sec).

Variation and uncertainty in the hydrological regime and socio-economic and political change characterize water management challenges in the Upper Iskar region were identified above as drivers of water stress. The recent introduction of the private sector in managing domestic supplies has further implications for change in the way water is managed in the region.

The following section describes the first field work activities carried out in the city of Sofia which involved interviews with experts in water demand management to ‘ground truth’ models.

3.2 Knowledge elicitation to support development and integration of research and policy models

A requirement of model integration identified in the literature (Wagner *et al*., 1989; Courtney, 2003) is the need to manage the variation in conceptual understanding between developers and users of computer-based DSTs. McIntosh *et al*. (2007) identify this as a cause of successful or unsuccessful uptake of DSTs by potential end-users. To begin to address this issue and support integration, knowledge elicitation involving informed practitioners working on WDM planning and implementation in Sofia was used to produce relevant model structures. The following section describes the knowledge elicitation method used in the case study work.

3.2.1 Methods

The knowledge elicitation had two objectives:

1. To elicit knowledge about the current decision processes influencing water demand management (WDM) implementation in Sofia and guide the development of Bayesian network (Bn) models for supporting WDM decisions.
2. To identify data collection needs for model development.

The nature of human knowledge is an area of much debate and controversy. In the practice of knowledge engineering, however, it assumes a more concrete form (Goodwin and Wright, 2004, p429). For example, collecting knowledge to support construction of computer-based decision support tools is the skill of obtaining and manipulating knowledge so that it can be built into a computer model which in some way behaves like an individual with experience in dealing with the problem at hand. This is the aim of the knowledge elicitation, i.e. the practice of obtaining knowledge from people rather than documents, described below.

The ‘hidden’ nature of expert knowledge, has led Hayes-Roth *et al*. (1983) to describe knowledge elicitation as a ‘bottleneck in the construction of expert systems’. They describe how communication problems arise because not only is the knowledge engineer relatively unfamiliar with the expert’s area or ‘domain’ but the expert’s vocabulary is often inadequate for transferring expertise into a programme. The ‘engineer’ thus plays an intermediary role with the expert in extending and refining terms. Similarly, Duda and Shortcliffe (1983) conclude that “The identification and encoding of knowledge is one of the most arduous and complex tasks encountered in the construction of an expert system … Thus the process of building a knowledge base has usually required an AI researcher. While an experienced team can put together a small prototype on one or two man-months, the effort required to produce a system that is ready for serious evaluation (well before contemplation of actual use) is often measured in man-years.” Wilkins *et al*. (1984) reinforce this view and note that attempts to automate the ‘tedious’ and ‘time-consuming’ process of knowledge acquisition between expert and ‘engineer’ have so far proved unsuccessful.

Two different approaches can be used to construct Bayesian networks (Bns) – a data-based approach or a knowledge-based approach (Nadkarni and Shenoy, 2004). Data-based approaches use conditional independence semantics of Bayesian networks to induce models from data (Heckerman, 1996). The knowledge-based approach uses the causal knowledge of domain experts in constructing Bayesian networks (Laskey & Mahoney, 1997). The knowledge-based approach is especially useful in situations where domain knowledge is crucial and availability of data is scarce. The method described below conforms to a knowledge-based approach to structuring the planning process and supported consequent model development.

3.2.1.1 Informed practitioners

A number of practitioners involved in the WDM planning and programme design in the Sofia region were contacted and asked to be involved in the study. Ten practitioners were selected based on their experience and their involvement at three levels of water management in the region i.e. Macro, Meso, Micro (Figure 3.5). The macro level corresponds to decision-makers at the regional, metropolitan, and municipal levels, and whose decisions could impact on the bulk water demand from Iskar reservoir. The Meso level refers to the neighbourhood scale or, in terms of managing water demand, to district metering areas (DMAs). Sofia consists of over 230 separate DMAs that are individually monitored as part of the existing leakage monitoring and reduction programme. The micro level refers to individual water users including public and commercial buildings and households.

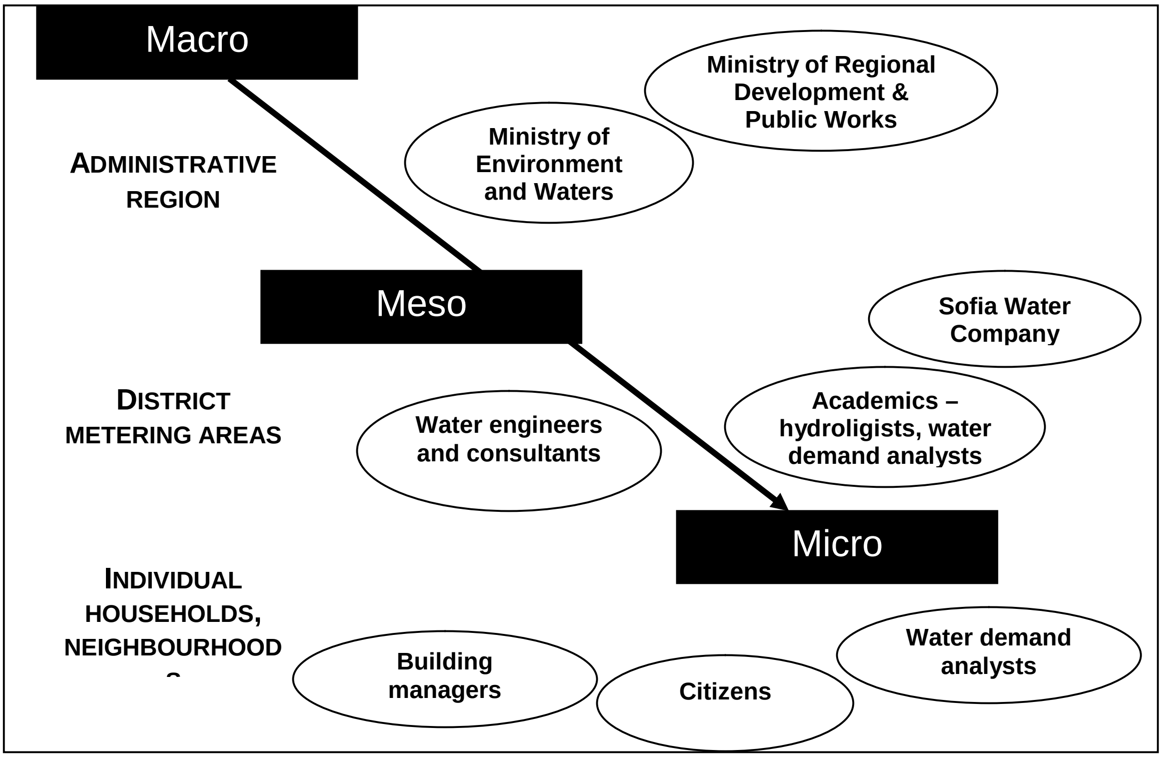


Figure 3.5. *Scales of water management in Sofia*

As well as taking part in the interviews to support model construction, the ten individuals would also be involved in the subsequent stages of the research (data collection, prior model validation and final model evaluation), so their availability for the duration of the whole research project (18 months) was a further criterion in participant selection.

3.2.1.2 Semi-structured questionnaire and cognitive mapping

Knowledge elicitation was achieved through a questionnaire involving both open-ended and closed questions. The questionnaire, described below, was structured in such a way as to elicit information that would be suitable for developing cognitive maps of the WDM policy domain in Sofia. Cognitive mapping (Axelrod, 1976) is a generic term given to methods for representing a person's assertions about some limited domain such as a policy problem. They are designed to capture the structure of the person's causal assertions and to generate the consequences that follow from this structure. The specific mapping method used for structuring knowledge collected from the interviews, known as influence diagrams (Hall, 1978; Roos and Hall, 1980), is described below.

Hall (1978) has stressed the value of explicitly presenting concepts and causal assertions in an influence diagram. The basic elements of an influence diagram are quite simple. The policy variables that can be manipulated, the goals or performance criteria that are to be aimed for and the intervening causes and effects can all be thought of as concept variables. These concepts are represented as points on a sheet of paper, and the causal assertions linking these concepts are represented by arrows between these points. A positive sign denotes that an increase in the concept variable at the tail of the arrow will lead to an increase in the variable at the head, and that a decrease leads to a decrease. A negative sign indicates the opposite movement of the head variable from that of the tail one.

The method was selected for use in the knowledge elicitation based on it being highly suited for performing policy analysis (Roos and Hall, 1980), and because the elements of influence diagrams described by Hall (1976) conform closely to the influence diagram structure of a Bayesian network when deterministic nodes have been introduced.

The questionnaire, which contained twenty-one individual questions and statements, is presented in Appendix D. For deciding on the questionnaire content, the required outputs, i.e. policy variables, intervening variables, goals, and performance criteria for constructing influence diagrams, were first considered. The questionnaire structure followed a problem-solving approach (De Bono, 2000) where experts were asked to identify (a) perceptions of the risk of water deficit, (b) demand-side options for reducing these risks, (c) the potential impacts of these options, (d) constraints to implementation of the options and, (e) how these constraints might be moved forward.

The interview itself used a method described by Rossi *et al*. (1983) called 'open interviews with probes', where a structured interview is used to prompt further discussion between the interviewer and interviewees. In addition to the open-ended questions, the questionnaire included four questions for collection of data to populate conditional probability tables for a Bn model presented in Chapter 4, Section 4.4. These closed-questions used a five-point scale and applied to four questions (5, 6, 12 and 13) in the questionnaire.

Individual interviews with the ten informed practitioners, each lasting approximately 2.5 hours, were recorded and then transcribed so that causes and effects could be elicited and influence diagrams constructed. Analysis of the transcribed text used an open coding method (Cassell and Symon, 2004), whereby a template of concepts is defined a priori and these concepts were then added to and modified as the text was read.

3.2.2 Results

The results of the knowledge elicitation, and a discussion of the implications of those results, constitute the remainder of this chapter. Informed practitioner's perceptions of drought risk, collected during the knowledge elicitation, are reported below. Different perceptions of risk, and how these might impact on the policy-making process, are discussed. Long and short-term demand management measures identified by the ten informed practitioners are then described. For each WDM measure identified, expected water savings, ease of implementation, relative advantages and disadvantages, and constraints to their implementation, as perceived by the ten informed practitioners, are presented. Causal relationships elicited during the interviews were used to develop influence diagrams which are presented and described.

3.2.2.1 Informed practitioner's perceived risk of drought

Each informed practitioner was asked to "draw a line on the graph representing their beliefs about the likelihood that severe drought resulting in supply interruptions and reduced economic productivity will occur in Sofia within the next thirty years". The perceptions of the ten practitioners are presented in Appendix E.

All experts in the study had experienced the water crisis that occurred in the Sofia region during 1994-1995. The practitioners who perceived the lowest risk of future water shortages were representatives from agencies responsible for water policy making. Higher risk was perceived by practitioners from academic institutions, water industry consultants, and the water company – Sofiyska Voda (SV).

A number of the participants considered the 1994-1995 water crises to have been a result of bad decision-making, and asserted the view that the current water management framework was better able to adapt to water scarcity. However, they were cautious to point out that if three years of severe drought occurred again, as happened in 1994-1995, there was still a potential threat to security of supply, and even though the impacts may not result in a crisis, it would still require some kind of demand reduction, with potentially negative economic outcomes, and possible public supply restrictions.

The results indicated a high level of uncertainty among the ten informed practitioners about future risk of water shortages in the Sofia region. It is possible to suggest that such perceptions will affect the demand management decision-making process, most significantly in the decision as to whether drought management in Sofia should take a long-term (risk management) approach, or short-term (crisis management) approach.

3.2.2.2 WDM measures and instruments identified by informed practitioners for use in Sofia

Water demand management (WDM) measures and instruments identified by the 10 informed practitioners during the interviews are shown in Table 3.3 (below). The adjacent columns show how many experts cited each option, the perceived mean water saving potential, and ease of implementation for each measure.

Table 3.3. *Measures and instruments cited by informed practitioners for water demand management in Sofia*

Category	**Measures and instruments**	**No. of times mentioned by experts**	**Mean expected metered water saving (%)**	**Mean Ease of implementation 1 = V. difficult, 2 = Difficult, 3 = Medium, 4 = Easy, 5 = V. easy**
Financial instruments	Metering	3	6.8	2.7
	Increasing marginal price	4	11.3	1.8
	Introduce Increasing Block Tariff structure	5	11.5	2.1
	Loans for installing water saving appliances	1	12.5*	3
Operation & maintenance measures	Repair of hot water circulation pump (HWCP)	3	11.6*	2.1
	Reduce water losses / wastage in public buildings	1	15*	3
	Repair leaks	3	14.2	2
	Install pressure reducing valves / reduce pressure at	5	10.5*	3.2

Category	Measures and instruments	No. of times mentioned by experts	Mean expected metered water saving (%)	Mean Ease of implementation 1 = V. difficult, 2 = Difficult, 3 = Medium, 4 = Easy, 5 = V. easy
	service pipe			
	Oblige water company to invest supply pipe replacement	1	15*	4
Regulatory instruments	Supply interruptions	1	4	2
	Change design norms for new developments	2	-	-
	Reducing losses due to thefts and faulty metering	1	15	1
	Collect unpaid taxes	1	15	1
	Restrict outdoor use	4	9.2	3.4
	Stop hot water during drought	2	7.5	5
	Water efficiency standard	1	12.5*	3
Technological measures	Retrofit of appliances	6	8.9*	2.5
	Rainwater harvesting for rural households	1	7.5*	2
Education measures	Education	5	5.9	3.7

*Only in buildings where implemented

Nineteen WDM measures and instruments were cited by the ten informed practitioners. The mean expected metered water savings should be viewed in context, particularly when combining options because, as indicated, some of the percentages refer only to water savings in the buildings where the measures are applied. To develop the conditional probabilities for the Bn model, described in Section 4.4 Chapter 4, the percentage water savings were applied as a percentage of the component of water demand that they affect, e.g. household, municipal buildings, service industry etc.

Eliciting informed practitioner's perceptions of ease of implementation for different measures and instruments had two objectives: the scores are used in the model development in Section 4.4, Chapter 4, and they were also used to prompt further discussion regarding constraints to implementation, discussed below.

3.2.2.3 Constraints to WDM implementation in Sofia identified by informed practitioners

Questions 8 and 9 in the questionnaire explored the constraints to implementation of the WDM measures cited by the informed practitioners. The aim was to understand how existing social, economic and political factors might affect the WDM implementation process. Sixteen constraints were cited across the ten interviews and were grouped into four categories, shown in Table 3.4.

Table 3.4. *Constraints to implementation of WDM identified during knowledge elicitation interviews*

INSUFFICIENT INFORMATION
• Insufficient information about disaggregated demand to make decisions about specific water conservation options
• Lack of a credible evidence-base of impacts of WDM options
• Uncertainty about future meteorological conditions
• Lack of feasibility studies into the economics of demand management
INSTITUTIONAL CAPACITY
• No single body responsible for WDM implementation and monitoring
• Renegotiation of the concession agreement between Sofiyska Voda and EU-ISPA means there is uncertainty for the future of the Water Company.
• Inefficiency of the legal framework to implement more efficient design norms for new buildings
• Reducing water demand in such a way would also be in conflict with the Ministry of Environment and Waters (MoEW) interests because it would reduce income from abstraction licences.
• The less water used, the lower the revenues for the water company
• Need for change in principle from supply-side to demand-side management
SOCIAL CONSTRAINTS
• Higher prices raise affordability issues
• Receptivity among citizens to implementing water efficiency options
• Problems of equity when collecting unpaid bills
TECHNICAL CONSTRAINTS
• Demand management could affect the function of sewage, e.g. sewage flow
• Over-capacity of the existing water supply infrastructure
• Customer-side wastage (i.e. losses that occur between the mains meter and individual dwellings in multifamily units) is billed as ‘common use’ by the water company, so there is no incentive to reduce these losses

The information collected on societal constraints was used to inform the content of a social survey of 540 households, described in Chapter 6. One of the aims of the survey was to design instruments to improve participation in WDM programmes in Sofia. The most commonly mentioned constraint overall was that there is no single agency responsible for implementing and monitoring WDM in Sofia. Quoting one expert “…in order to meet its financial targets, it requires less effort for the Water Company to raise the water price than to fix leakages, and as such there is need for regulation on this issue”.

A number of experts cited the relationship between water price and average income as key factor that determines the value that people place on saving water and their participation in water conservation. Increasing prices is a sensitive social issue and affordability issues that may arise can lead to negative PR for the Water Company. This may be experienced in the form higher expectations of Water Company performance leading to criticism, and in worse cases non-cooperation in programmes that require voluntary participation.

The influence diagrams developed from the transcribed interviews are described in the following section.

3.2.2.4 Influence diagrams

Experts from the Water Company identified a number of interrelationships between different types of tools. For example, they perceived that financial incentives for citizens were also a form of awareness raising, hence the interrelationship of education with financial instruments, and that regulatory instruments such as water efficiency standards are interrelated with technological measures. Following analysis of the transcribed interviews, therefore, three IDs were developed where education and regulatory instruments were integrated with financial instruments, Operation and Maintenance, and Technological measures. The resulting influence diagrams, presented below, incorporate policy variables in Table 3.3 and the constraints from Table 3.4.

Financial instruments

The influence diagram in Figure 3.6 shows the policy variables, intermediate variables, goals, and performance criteria elicited from the expert consultation that are relevant to the implementation of financial instruments.

Four financial instruments were identified and included three restrictive measures - metering, price increase, and introduction of increasing block tariff (IBT) structure – and one incentive for adopting technology – loans for citizens to install water saving appliances. Expected water savings from increasing water price are dependent upon: (i) a meter being installed, (ii) price elasticity, and (iii) the size of the price increase. The water company, Sofiyska Voda (SV), has already introduced comprehensive metering and, according to company reports, around 98% of households in the city now have a meter installed. The potential impact of pricing mechanisms is examined and modelled in Chapter 4, Section 4.3.

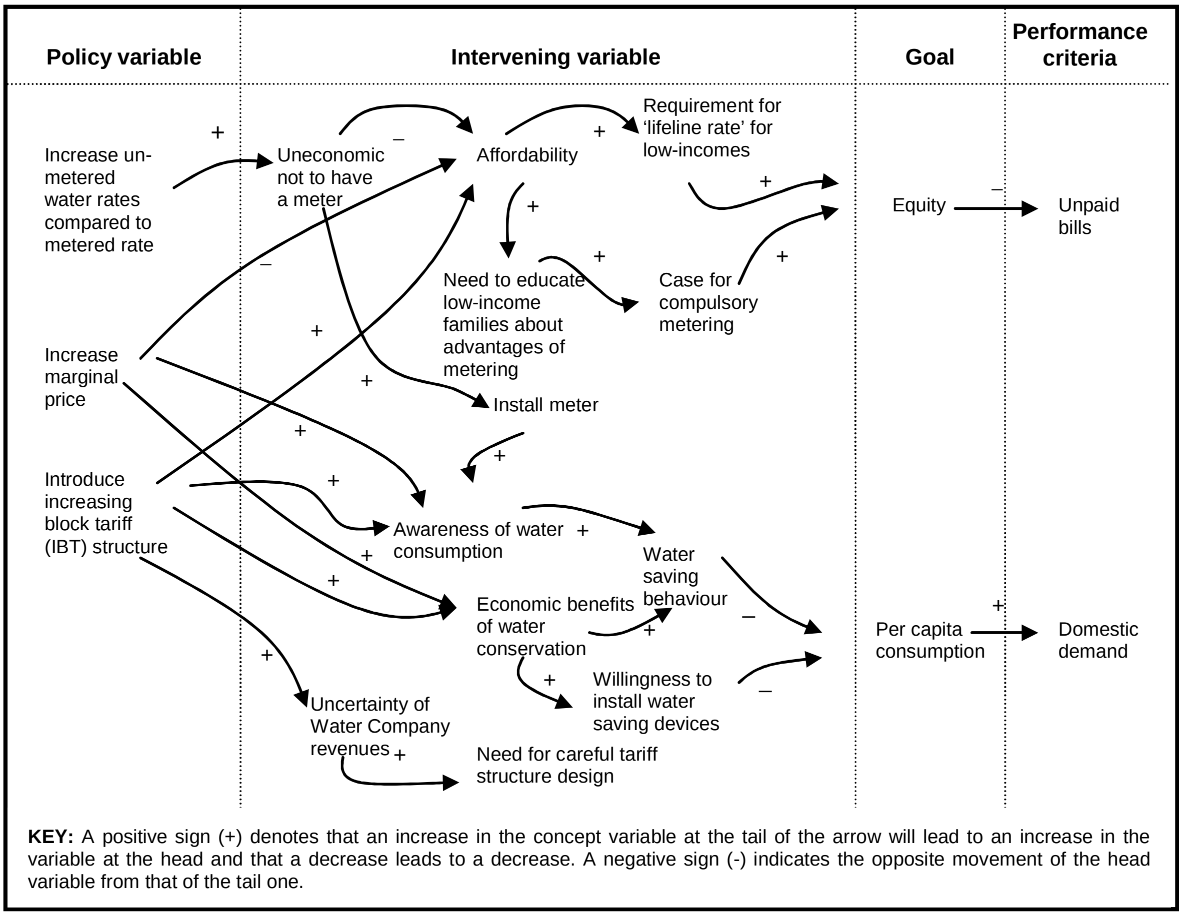


Figure 3.6. *Influence diagram showing causal relationships relevant to the implementation of financial instruments*

Expert perceptions of the ease of implementation indicate that an increasing block tariff (IBT) structure would be easier to implement than a general price increase, i.e. increasing the marginal price, and when explored further, informed practitioners stated that they considered an IBT structure to be more socially acceptable. As a result of this, citizen's receptivity to introducing an IBT structure was explored in the social survey reported in Chapter 6.

Operational and maintenance (O&M) measures

A study into water saving measures in Sofia (EU-ISPA WDM Procedure 6 Report) in 2003-2004 identified non-functioning hot water circulation pumps (HWCPs) and high pressure in multi-family blocks as a major cause of customer-side wastage. The large number of multi-family blocks (around 60% of dwelling in Sofia) means that the water saving potential from addressing these two measures is relatively high. Following recent studies, it has been estimated that installation of a circulation pump may reduce consumption by 10-15%, and installing pressure reducing valves can reduce consumption by 9-10%. Installation is not, however, the responsibility of the authorities or the water company - quoting one expert, “the state authority is not able to go to every building and install a circulation pump or pressure reduction valve - but depends on educating citizens about the potential reduction in their bills; the fraction of the water bill known an ‘common use’. ‘Common use’ is measured (by the water company) by subtracting the total water volume measured by all individual household meters in a building from the volume measured by the revenue meter, i.e. the meter on the supply pipe that enters the building, and then dividing this volume equally among all residents. As a result of these findings a question was included in the social survey, described in Chapter 6, exploring citizen’s perceptions of ‘common use’.

Most customer-side wastage resulting from old in-building infrastructure is currently accounted for by the Water Company through metering and is billed to the customer. As a result, a major constraint to improving efficiency through O & M measures identified by experts is the risk of reduced revenues to the water company. Economic rebalancing through regulating the water price was suggested by experts as an option for reducing negative impacts on the Water Company, and overcoming this constraint to WDM implementation.

The influence diagram in Figure 3.7 shows the policy variables, intermediate variables, goals, and performance criteria elicited from the expert consultation that are relevant to the implementation of O & M measures.

Regulatory instruments

Seven regulatory instruments, requiring governance intervention and policy-making, were identified by experts. Two of these: “change in design norms for buildings” and “water efficiency rating scheme” are discussed below as they also affect the uptake of water efficient appliances.

Collection of unpaid taxes was mentioned as a major issue in Sofia by experts although reported revenue collection efficiency has increased from 82% in 2001 to 89% in 2003. Reducing uncollected revenues would reduce consumption by none paying customers but experts stated that new policies need to be introduced to allow the Water Company to implement measures such as flow-restricted metering. Other regulatory tools include outdoor use restrictions and managing unaccounted for water, as described below.

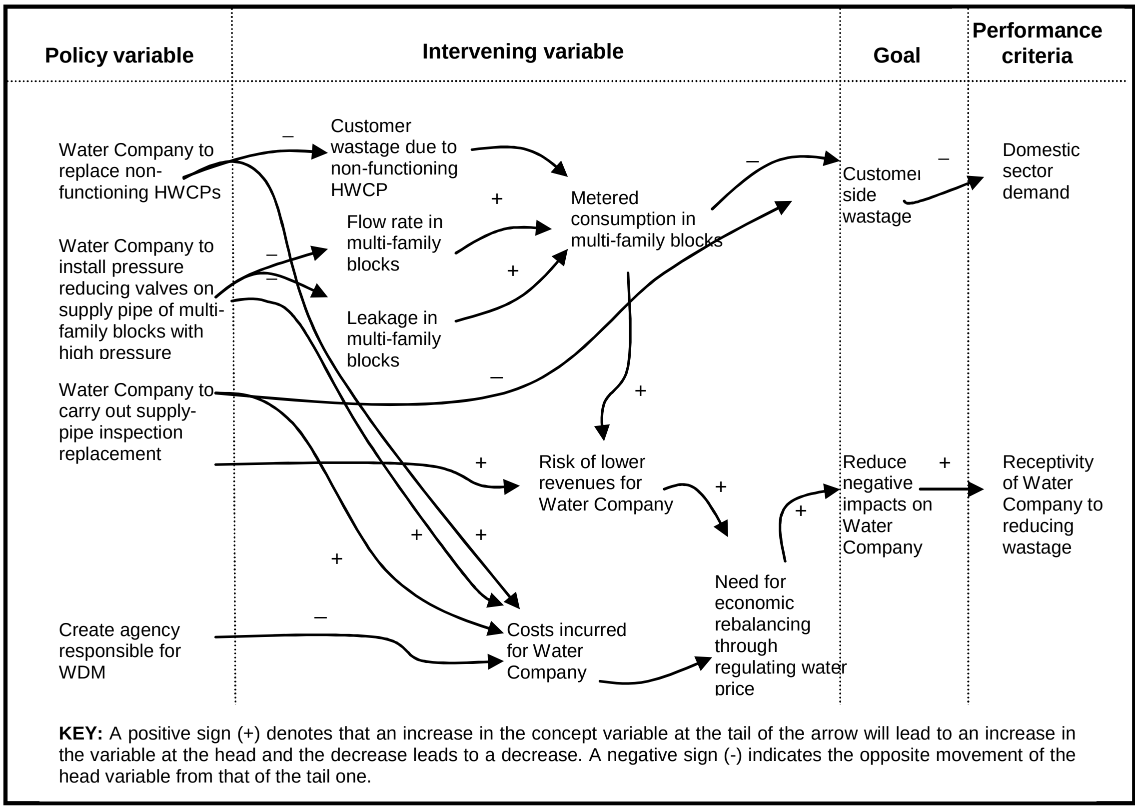


Figure 3.7. *Influence diagram of elicited of causal relationships relevant to the implementation of O & M measures*

Informed practitioners explained that there is a high consumption of potable water in the suburbs and rural areas of Sofia for outdoor use and this is increasing. One expert quoted a recent study which showed that "… in the small towns and suburbs people use approximately twice as much water as urban households because of outdoor use. In the first place the restriction should be imposed on outdoor use and washing cars". Furthermore "… some people have boreholes but the electricity for pumping is expensive so they prefer to use potable water because it is cheaper. Also there is a very strict prohibition for developing a personal borehole. The regime is very slow – 6-7 months, and even for these boreholes, there is a meter installed and bills are paid to the Ministry of Environment and Water (MoEW)".

According to a Water Company expert who works specifically on quantifying unaccounted for water, the high level of UfW (>60%) in Sofia is made up of approximately 65% physical losses (leakage) and 35% trade losses (inaccurate metering and thefts). Thefts, either illegal connections or where customers have by-passed the water meter, are a major problem in Sofia. Since the introduction of the concession in 2001, the Water Company, Sofiyska Voda (SV) has implemented a hydrological model of Sofia's water supply network including 234 district metering areas (DMAs), with no more than 10,000 households per DMA. The water entering and leaving each DMA is metered and by carrying out a water balance, areas with high levels of UfW are being identified.

Technological measures

Informed practitioners referred to existing studies that indicated that water saving showers and toilets have the highest potential to reduce household water use. The cost of installing such appliances, however, means that uptake will be limited unless complimentary policies are introduced. As mentioned in Chapter 1, Section 1.2, the uptake of water saving household appliances can be increased through the introduction of instruments to promote citizen involvements. A number of WDM instruments for improving the uptake of water saving appliances in households have been mentioned in previous sections. The challenge of achieving uptake of water saving appliances in (i) existing housing stock, and (ii) new housing developments, requires specific polices to take advantage of the particular circumstances in the region of Sofia.

According to those interviewed, achieving uptake of water saving appliances in existing housing stock is more challenging than in new developments because it only occurs when water appliances are replaced. In households, opportunities arise in existing households at specific times such as: (i) when a change of occupancy occurs, and (ii) when the existing appliances reach the end of their lifetime. The currently high change of occupancy rate in Sofia, and the growing need for water appliance replacement among the large number of households built during the 1970s, means that there is, potentially, a window of opportunity to implement policies that will lead to benefits in the future. As a result of these findings a question was included in the social survey, described in Chapter 6, exploring replacement rate of water appliances in households in Sofia.

Informed practitioners also identified specific types of building, such as government buildings, universities etc., where replacement can achieve higher savings due to high frequency of use (e.g. toilets), and because these building are usually over 30 years old, with older appliances, and high leakage.

Achieving water efficiency in new housing developments poses different challenges from those in existing housing stock. Recent experience in other European countries has led to a general consensus that mandatory building regulations (design norms) are necessary to minimise the impact of new developments on the water balance. Current design norms in Sofia are 400 litres per capita per day (l/c/d), and 220 l/c/d for smaller towns with populations of less than 100,000. The corresponding German standard is 130-140 l/c/d. It is expected that population growth in the region of Sofia in the next fifteen years will increase the requirement for new housing, and increasing affluence may also lead to the wider use of water intensive products such as washing machines, dishwashers etc. A number of individuals in the study stated that, under the above scenario, there are clear benefits for introducing tighter mandatory design norms, closer to other European countries. As with existing housing stock, there is now a window of opportunity for such policies to be implemented to have maximum effect.

A further advantage of introducing design norms cited by two practitioners was that it would reduce capital costs of network expansion and operational costs that new developments entail, e.g. wastewater capacity, pumping capacity etc. There was a suggestion that this would allow SV to re-direct investment towards network rehabilitation. This issue is discussed further below.

The following influence diagram, Figure 3.8, shows the policy variables, intermediate variables, goals, and performance criteria elicited from the expert consultation that are relevant to the implementation of WDM instruments to promote uptake of household water efficient devices.

Economic regulation and WDM in Sofia

Driven by the political and economic developments and the introduction of the private sector, regulation of the water sector in Bulgaria has undergone rapid change in the last five years. It is perhaps not surprising, therefore, that only a small number of informed practitioners were able to discuss this aspect of WDM planning in detail.

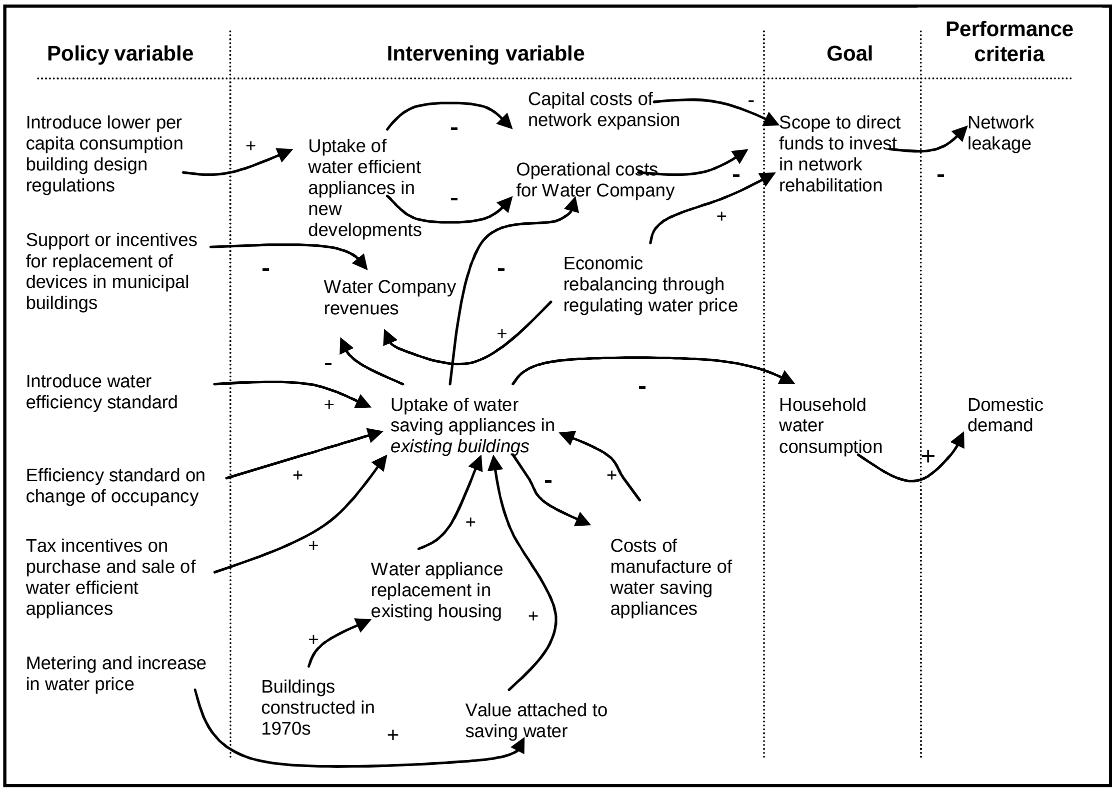


Figure 3.8. *Influence diagram of elicited of causal relationships relevant to the implementation of WDM instruments to promote uptake of household water efficient devices*

Two of the informed practitioners expressed the view that there is still scope for the water regulators - the Ministry of Environment and Waters (MoEW) and Ministry of Energy (MoE) – to collaborate further and put in place regulatory mechanisms and efficiency targets to assure that, where possible, funds are directed towards efficient use and reduced wastage, with the over-riding aim of securing the water supply in the future. From an economic investment perspective the EU-ISPA (European Union Instrument for Structural Policies for Pre-Accession) also has an important role in the WDM decision process.

There are two strong economic drivers that influence investment in WDM in Sofia. The first involves the cycle of EU-ISPA funding that is part of the 25-year concession agreement under which the water company, Sofiyska Voda (SV), operates and makes investment decision. The second is the not yet fully-developed regulatory framework. These influences and how they are managed impact on the ability of SV to achieve the parallel goals of investing in rehabilitation of the existing water supply network whilst at the same time, paying for expansion of the existing water supply network to supply new development.

All experts involved in the consultation recognised the current high level of infrastructure losses as a major constraint to achieving sustainable management of the Upper Iskar's water resources. High levels of leakage (estimated at around 58%) within the water supply network, resulting from the aging water supply infrastructure in the city was acknowledged as the most important water efficiency objective by a number of practitioners, not least because of the social effects. As one expert explained "People are paying a higher water price due of infrastructure leakage because the losses mean that costs to the water company are higher due to increased abstraction, distribution and treatment costs, even though this water leaks out of the system". The problem of high leakage was a driver for the EU-ISPA agreeing to fund an investment programme to support rehabilitation of Sofia's water supply infrastructure over the current 25 year concession.

The flow diagram below, Figure 3.9, presents the funding conditions set by EU-ISPA for the 160 million euros loan, which include the business plan, the basis for the future water price, and the role of the new regulator, the Ministry of Energy (MoE) in this decision.

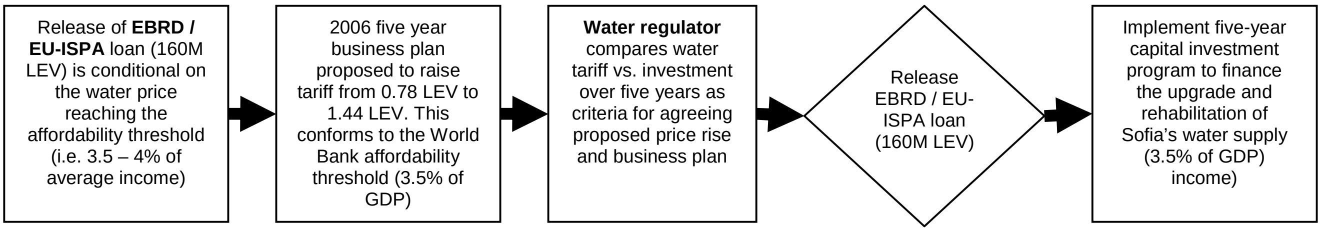


Figure 3.9. *Investment and water price setting decision process involving SV, MoE and EU-ISPA*

The conditions of the next EU-ISPA loan instalment, described in Figure XX, include the water company increasing the water price to the affordability threshold stipulated by the World Bank, i.e. water bills should not exceed 3.5% of average GDP. In countries where a large proportion of the population are still living in relative poverty any water price increases can raise affordability problems and the risk of market failure (de Miras, 2005). The current situation in Sofia introduces a need for monitoring impacts of high prices on low income families.

The parallel need for the water company to invest in network expansion due to new developments draws funds away from investing in rehabilitation of the existing network. As one expert explained "… there is expansion of the water supply network whilst the existing water supply is in disrepair. So at present, the investment is going into expansion, and not into repairing the existing network. Future water scarcity will determine the magnitude of the effects of non-investment in network rehabilitation." Non-enforcement of the existing planning regulations - which are the responsibility of the Ministry for Regional Development (MoRD) – was cited as an area in existing policy that has a detrimental effect of water company operation and investment. Because the water company, SV, is obliged by law to supply all new developments, they have no choice but to expand the network or, where new developments cause the existing network to fall below capacity, replace it. Non-enforcement of planning regulations means that new developments are not always registered with the responsible planning agencies and this, combined with the current design norms in Sofia, which are currently above 400 litres per capita per day (l/c/d). puts pressure on the water company to direct investment that could otherwise go towards rehabilitation of the existing water supply network, towards network expansion to supply these new (unplanned) developments. In effect, the non-enforcement of planning regulation means that they are not consulted during the planning stage.

3.3 Discussion

The aims of the knowledge elicitation were:

1. To elicit knowledge about the current decision processes that influence water demand management (WDM) implementation in Sofia and guide the development of Bayesian network (Bn) models for supporting WDM planning.
2. To identify data collection needs for model development.

The results of the knowledge elicitation provide two main topics for discussion: (i) research and decision support priorities, and (ii) the value of knowledge elicitation in addressing science-policy interfaces.

3.3.1 Research and decision support priorities

For the legislation stage of WDM implementation, institutional constraints (Table 3.4) emphasize the need to set economic conditions for investment in demand management to take place. Firstly the Ministry of Energy (MoE) and the Ministry of Environment and Water (MoEW), who regulate the domestic water price raw water price (i.e. costs paid by SV for taking water from the Iskar reservoir) respectively, can facilitate investment in WDM by incentivising Sofiyska Voda (SV), the water supplier, whilst also addressing the risk of negative impacts of reduced metered demand on

SV's revenues. Secondly, the economic funding cycles imposed by the EU-ISPA (European Union Instrument for Structural Policies for Pre-Accession) on the Water Company under the concession agreement influence SV's ability/willingness to invest in WDM.

A conceptual model developed during the case study work is described in Chapter 5 and addresses decisions relating to the local water regulators, the MoE and MoEW, regarding regulatory decisions and their impact on SV and WDM investment.

The knowledge elicitation results showed variation between the ten informed practitioner's perceptions of future risk of water shortages in the Sofia region. The alternating nature of the water cycle in the Iskar basin (inundation / water scarcity) was cited by a number of individuals as a cause of uncertainty in forecasting the likelihood of water scarcity in the future. Research into drought contingency planning (Wilhite, 2005) suggests that crisis would be much more effectively handled if investments in data, analysis, communication, and relationships were made in advance. Recent experiences of drought in Australia (Turner *et al.,* 2007) emphasize the importance of developing preparedness strategies. The conceptual model developed in Chapter 5 demonstrates how environmental indicators can be used to determine the timing of implementation of drought contingency plans in Bns, using a set of drought risk indicators.

The other areas of uncertainty identified by informed practitioners were the ability of long- and short- term WDM measures to reduce domestic demand and avert water scarcity and the cost of reducing demand. Water saving potential and cost-effectiveness can be improved through efficient water conservation programme design. In Chapter 4, Section 4.5.1, a method called lifetime avoided costs (LAC) is developed for integrating efficiency of implementation into the conceptual model of the WDM legislation stage. An aim of introducing the LAC method was to raise awareness among those involved in economic regulation to consider the need for careful planning so that sufficient investment is provided to support efficient implementation during the design stage.

For water conservation programme design, the lack of a credible evidence-base about the water saving potential of WDM measures, cited in Table 3.4 as a constraint to introducing demand-side management in Sofia, is both an institutional and information constraint that spans the WDM implementation process. Evidence from the knowledge elicitation implied that formal methods for evaluating the effectiveness WDM measures, which would include a set of relevant performance indicators, are not currently in place in Sofia. Without the evidence-base and evaluation methods to support WDM legislation, it will be very difficult to build consensus and move the remaining institutional, social and technological constraints forward. If a legitimised basis or rationale for prior- and post- programme evaluation can be developed, that incorporates uncertainty it would be of great value in moving these constraints forward. Bayesian networks models to facilitate analysis of implementation conditions are described in Chapter 6.

By providing content for inclusion in the household survey the knowledge elicitation supported modelling of constraints to uptake of specific types of water saving measures, and the household survey and models develop are described in Chapter 6. Bn models developed in Chapter 6 also address the need to develop an evidence-base of the potential for uptake instruments to improve WDM programme participation.

3.3.2 Knowledge elicitation to address science-policy interfaces

Reflecting on the knowledge elicitation results and research priorities outlined above, the first stage in the model development process can be seen as providing an opportunity for communication between science, policy and practice. It corresponds to the science-policy interface that van den Hove (2007, p818) describes as *allowing for balancing issue- and curiosity-driven science and their articulation in knowledge for decision-making processes*.

Viewing support tool development as an activity to address science-policy interfaces emphasizes the *process* of problem analysis, rather than the final completed *decision*-making tool as the only viable *product* of model development. The identification of research priorities becomes a tangible output of the modelling process and evaluation of the analytical techniques made available support tool and their compatibility to the problem becomes a valid output of that process. This perception of support tool development puts greater emphasis on the process of decision analysis and in Chapter 8 the role of Bns in decision analysis, and in addressing other science-policy interfaces, is discussed.

3.4 Conclusions

The objective of Chapter 3 was to report on how knowledge elicitation and construction of cognitive influence diagrams (IDs) can inform the development of decision support tools for use in WDM legislation and design. The knowledge elicitation generated highly-detailed and case specific influence diagrams that successfully represented the various viewpoints of informed practitioners involved in the collaborative process.

The knowledge elicitation supported identification of variables to be included in models aimed at examining the impacts of policy instruments on citizen participation and this informed the household survey design. The resulting models are described in Chapter 6, and include relationships between householders' attitudes, values, perceived ability, and intention towards water conservation technology.

For legislating in the Sofia case the need for economic regulation in creating the conditions for investment in demand-side management is emphasized. The knowledge elicitation results indicate that there is no existing systemised approach towards regulating for WDM implementation in Sofia, although water efficiency is included as part of the concession agreement between Sofia Municipality and the water company. The change process brings with it uncertainty and a period of learning to put in place effective regulatory mechanisms. Evidence that existing regulation has not yet been effective in introducing water demand management, however, was found in interview responses where existing regulation and legislation was described as "fragmented and uncoordinated".

The following chapter describes the collection of data and development of sub-models to support WDM *legislation*.

Chapter 4

Data collection to support supply / demand forecasting and economic evaluation

Introduction

Following the knowledge elicitation activity reported in the Chapter 4, data were collected with the aim of identifying variables that are subject to uncertainty when planning legislation for WDM implementation in the Sofia case. The mechanisms by which policy interventions act upon these uncertain variables also needed to be identified. Four areas that were subject to uncertainty were identified: (i) water availability, (ii) the impact of changing water price on domestic demand, (iii) the potential impact that demand management measures would have on total demand and (iv) costs and benefits of demand management programmes.

In Section 4.1 historical water supply and demand data are used to develop a water balance model of the Iskar Dam. The same data is then used in Section 4.2 to develop a water availability forecasting model. In Section 4.3 the potential for using seasonal pricing as a short-term measure is modelled. In Section 4.4 information collected during the knowledge elicitation activity is used to develop a model of aggregate impacts of WDM measures. Section 4.5 describes a method for integrating uncertainty about costs and benefits of WDM into an Influence Diagram. Section 4.6 uses the data collection and model development reported in Chapter 4 to examine and discuss the research questions that were presented in Table 1.4.

The Bayesian network model developed in the following section examines the water supply / demand balance in the Iskar Dam during and leading up to the drought period 1990-1995. The model, presented in Figure 4.1, was one of the sub-models used and evaluated by the informed practitioners during the end-user evaluation presented in Chapter 7.

4.1 A water balance model of the Iskar dam using historical supply and demand data

4.1.1 Method

To develop the water balance model, hydrological data (monthly inflows, reservoir volumes, release volumes, and human consumption volumes for hydropower, industrial, domestic and other demands) collected between 1966 and 2000 was supplied by the Bulgarian Academy of Sciences (BAS) in Sofia.

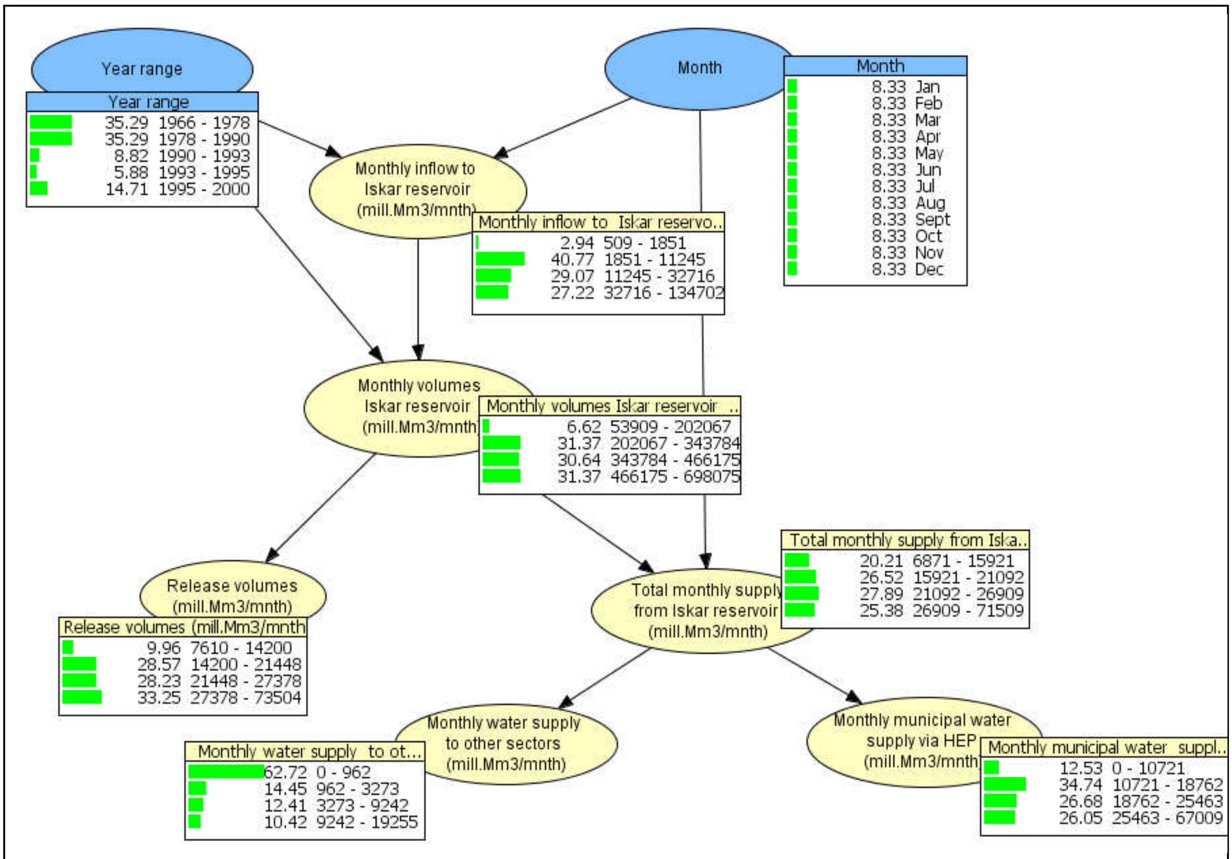
Pre-processing of the data was required to fill gaps in the data-set prior to constructing the model. Because the hydrologic data was supplied as continuous monthly volumes and the missing data spanned no more than two months at a time gaps in the data could be extrapolated manually.

The data were entered in adjacent columns in an Excel spreadsheet and the model structure was developed using the structural learning algorithm. The Hugin software uses a structural learning algorithm known as *Necessary Path Condition* (NPC) (Steck, 2001) which derives a model structure through statistical tests for conditional independence. NPC is a criterion developed by researchers at Siemens in Munich for solving some of the problems of constraint-based learning algorithms like the PC algorithm. Informally, the necessary path condition says that in order for two variables X and Y to be independent conditional on a set S, with no proper subset of S for which this holds, there must exist a path between X and every Z in S (not crossing Y) and between Y and every Z in S (not crossing X). Otherwise, the inclusion of Z in S is unexplained. Thus, in order for an independence statement to be valid, a number of links are required to be present in the graph (Steck, 2001). The interested reader is referred to the literature for a more detailed description of the theory behind the NPC algorithm. See e.g. Steck, 2001; Steck & Tresp, 1999; Steck *et al*, 1999.

As the main objective of the modelling was to explore causes and effects of the 1990-1995 water crises, additional nodes were added to permit the user to view differences in reservoir management between different years and different months and thereby compare water supply and demand for drought years and non-drought years.

4.1.2 Results

The water balance model is shown below in Figure 4.1, overleaf. The model was used by end-users during the end-user evaluation workshop to explore the causes and effects of the 1993-1995 Sofia water crises. The model allows the user to compare components of the water balance components for five time periods. For example Figure 4.2, also overleaf, presents inflows and reservoir volumes for each period and shows that there were no occurrences of the inflow volume falling into the lowest discrete range prior to 1990, although the frequency of inflows in the second lowest discrete range increased between 1978 and 1990.



Data source: Bulgarian Academy of Sciences, 2007

Figure 4.1. *Bayesian network water balance model for the period 1966 to 2000.*

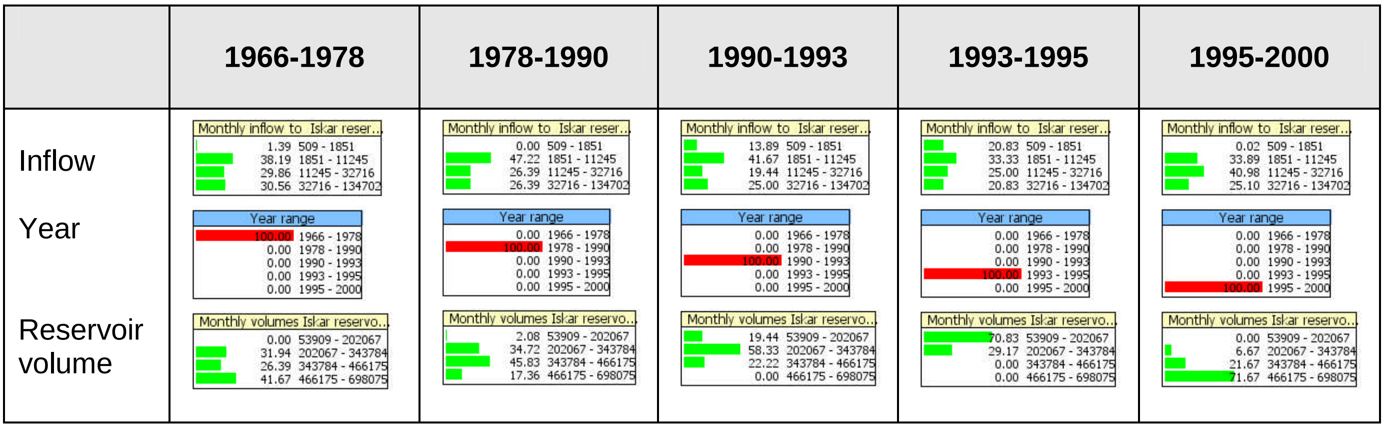
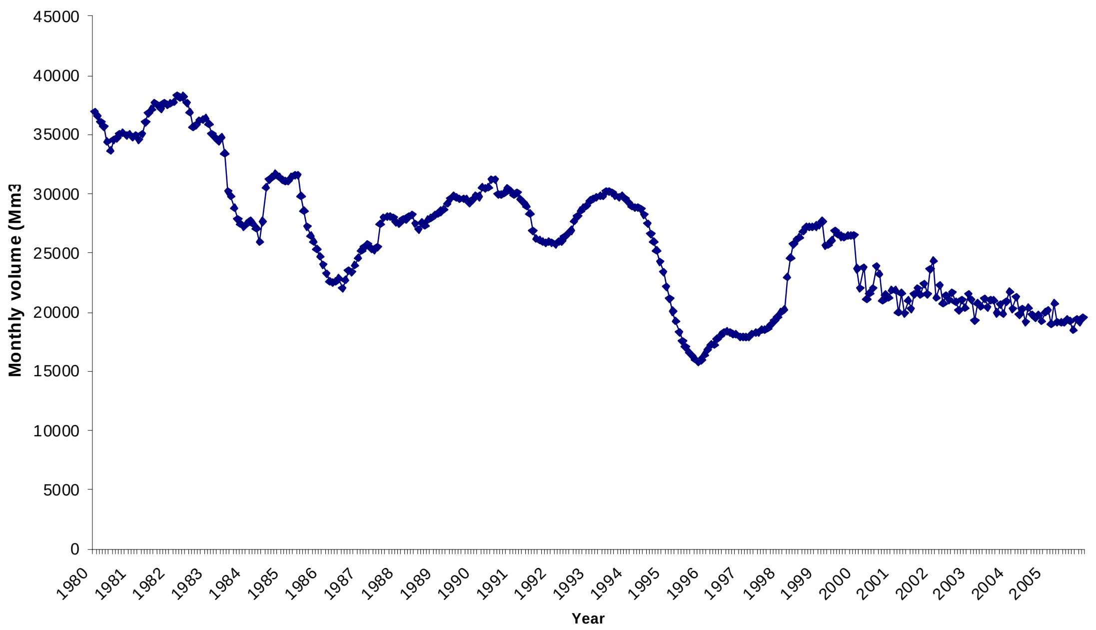


Figure 4.2. *Probability distributions of water demand from the Iskar reservoir for five time periods*

Between 1990 and 1993, however, monthly inflow was in the lowest range 15% of the time, and between 1993-1995, 20% of the time. The model reveals that the onset of the 1994-1995 water crises in Sofia could be traced to the cumulative effects of reduced water availability over a five to ten year period. The gradual decrease in reservoir volumes in the period is evidence of slow-onset drought in the Upper Iskar region and this has implications for forecasting and drought contingency planning.

We wished to see whether the water balance model could be used to estimate the required reduction in demand, given a repeat of the conditions that led to the 1993-1995 water crises. Recent water demand data was provided by Sofiyska Voda, the water company, for the years 2000 to 2005, and are presented below, (Figure 4.3). Monthly domestic demand between 2000 and 2005 ranges from 19,500 to 22,000 million cubic meters (Mm^3).

Total abstraction volumes for all sectors are represented in the node labelled monthly water supply from Iskar Dam. All water for domestic supply first passes through the hydro-electric plant (HEP), Passarel. This is modelled by disaggregating supply into two child nodes (monthly municipal supply via HEP Passarel, and monthly water supply to other sectors).



Data source: Sofiyska Voda, 2007

Figure 4.3. *Monthly abstraction volumes for domestic demand from the Iskar reservoir (1980-2005)*

The maximal propagated probabilities for the disaggregated water supply nodes, instantiated for each time period i.e. 1966-1978, 1978-1990, 1990-1993, 1993-1995 and 1995-2000 are shown in Appendix F, where an explanation of the max-propagation method is also given. They show the most likely configuration of states in the three water demand nodes during the drought years their. The very low occurrences of domestic demand between 1990-1993 and 1993-1995 reflect a one-in-three day (three days off, one day on) water supply regime that was imposed by Sofia authorities during the summers of 1993, 1994 and 1995 to address the problem of water scarcity.

Using the maximal probabilities in equation 4.1 and given a repeat of the conditions that led to the 1994-1995 water crises, the evidence infers that there is an 82% probability that the current demand would not be maintained given the same drought conditions.

$$\frac{p(S_3 \mid evidenceA)}{p(S_1, S_2, S_3 \mid evidenceA)} = p(S_3 \mid evidenceA) \qquad \textit{(Eq 4.1)}$$

Where:

evidenceA = Max-propagated probabilities for supply nodes in period 1993-1995

S_1 = maximal probability for state 1 in node monthly municipal water abstraction

S_2 = maximal probability for state 2 in node monthly municipal water abstraction

S_3 = maximal probability for state 3 in node monthly municipal water abstraction

Using equation 4.2, if demand can be reduced below 18000 Mm3, however, the probability that current demand would not be maintained is 23%.

$$\frac{p(S_2, S_3 \mid evidenceA)}{p(S, S, S \mid evidenceA)} = p(S_2, S_3 \mid evidenceA) \qquad \textit{(Eq 4.2)}$$

These results hold true only if *everything else known is not relevant*, for example reducing demand in other sectors, or other factors that might impact on the water balance.

The steps involved in processing the hydrological data for use in forecasting reservoir level volumes are described in the following section.

4.2 Hydrological data are used to develop a water availability forecasting model

4.2.1 Method

The graph below (Figure 4.4) shows monthly volumes and inflows for Iskar reservoir between 1967 and 2000. The graph reveals how the reservoir acts as an equaliser by compensating for the large fluctuations in monthly inflow. The delayed response of reservoir levels to low water availability (inflow) over a number of years is clearly visible. The average delayed response of volumes to inflows is approximately 18 months although this is influenced by release volumes which are stipulated by the Ministry of Environment and Waters, but may be adapted depending in the conditions (flood or drought).

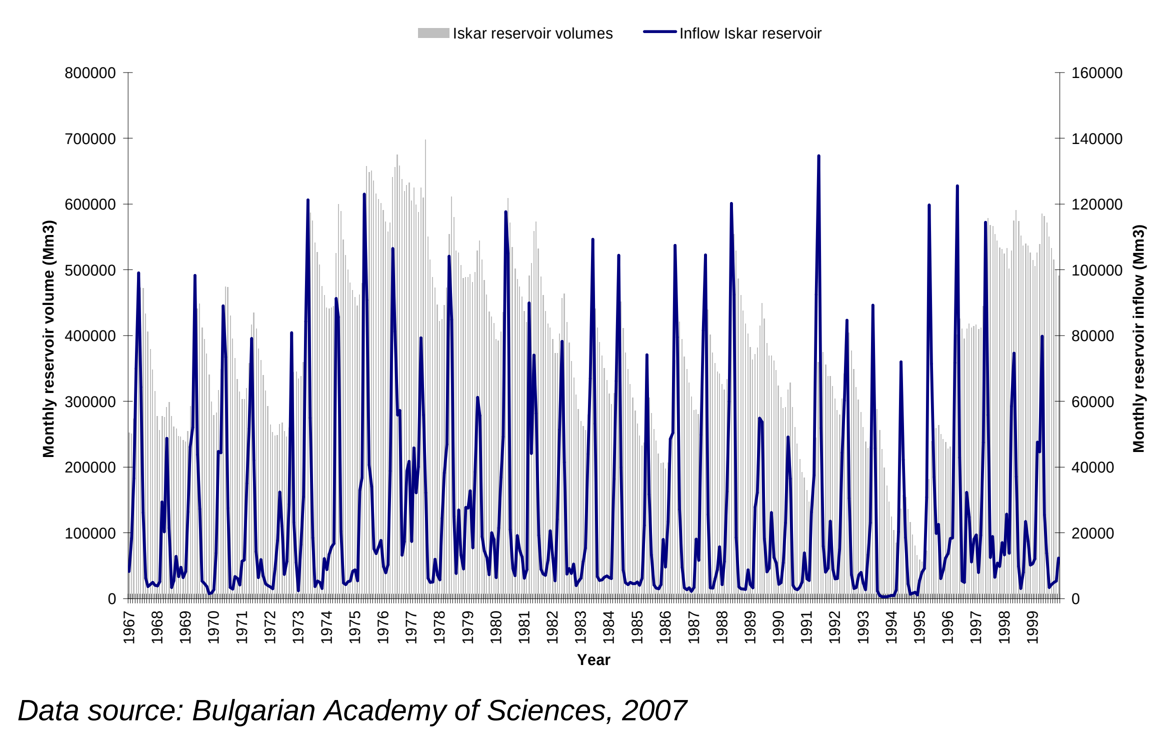


Figure 4.4. *Iskar dam inflow and volume for the periods 1966 to 2000.*

Understanding of the response time of the reservoir and the conditions leading up to the 1994-1995 water crisis informed the time step for the forecasting model. For demonstration purposes three components of the water balance - current reservoir level, average monthly reservoir volumes over the previous 12 months, and average monthly inflow volumes over the previous 12 months - were used as water availability indicators. Additional environmental indicators might be added to the model, such as average winter snow cover, if the modelling approach were to be adopted for decision support in the Upper Iskar.

To calculate the conditional probabilities the data for each node was assigned a single column in a spreadsheet. By off-setting the data column containing the 18 month reservoir volume forecast 18 months ahead of the columns containing the data for the three indicator nodes, the Hugin software was able to compute the conditional probabilities for forecasts based on all the water balance data from 1966 to 1999.

4.2.2 Results

Parameter sensitivity analysis can be used to identify variables in a probabilistic network whose change in state has a large or small impact on the probability distribution of a hypothesis variable. Sensitivity analysis was performed using a diagnostic model developed from the forecasting data, presented in Appendix G, and revealed that out of five indicators analysed (total supply, release volumes, current inflow, current reservoir volumes, average monthly inflow over previous 12 months and average monthly reservoir volumes) three indicators could explain 80% of the variance in reservoir volumes forecast. The structure and resting state conditional probabilities of the forecasting model using the three indicators are shown in Figure 4.5, below.

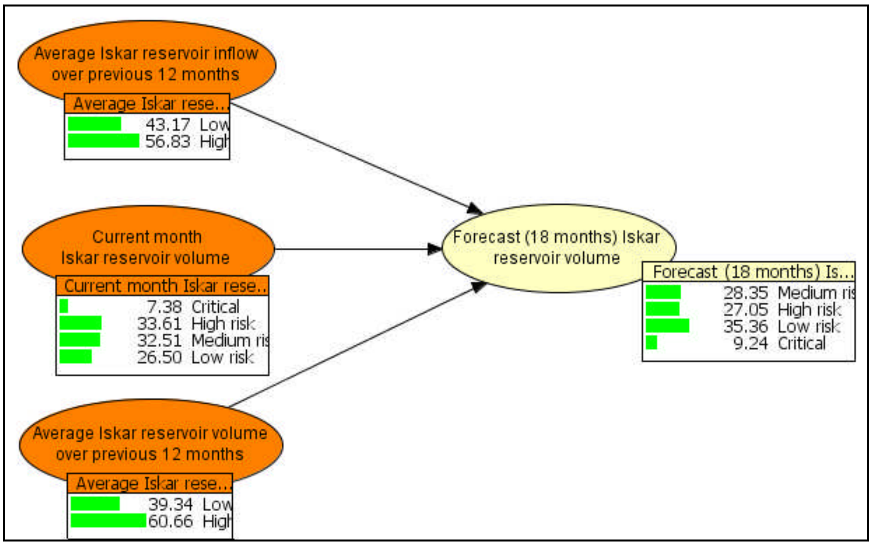


Figure 4.5. *Iskar dam forecasting sub-model*

The number of parent variables and parent states in a model, referred to by Jensen (2001) as the parent space, influences the significance of findings in a Bn model. For example, if there are five parent variables each with three states we already have a parent space of 3^5. A section of the conditional probability and experience table tables for the node 18 month forecasted reservoir volume shown in Figure 4.6 (below) demonstrates how the number of states in a model influences the significance of findings.

Forecast (18 months) Iskar reservoir volume (V18MTH)

V_MNTH	Critical				High risk				Medium risk		
I_1YR	Low		High		Low		High		Low		Hi
V_1YR	Low	High	Low	High	Low	High	Low	High	Low	High	Lo
Medium risk	0.44	0.25	0.25	0.25	0.35	0.68	0.14	0.57	0.01	0.21	
High risk	0.48	0.25	0.25	0.25	0.32	0.16	0.32	0.41	0.29	0.36	
Low risk	0.01	0.25	0.25	0.25	0.12	0.15	0.45	0.01	0.42	0.21	
Critical	0.07	0.25	0.25	0.25	0.21	0.01	0.09	0.01	0.29	0.21	
Experience	27.0	0.0	0.0	0.0	57.0	25.0	22.0	19.0	7.0	33.0	

V_MNTH	Medium risk		Low risk			
I_1YR	High		Low		High	
V_1YR	Low	High	Low	High	Low	High
Medium risk	0.11	0.35	0.25	0.01	0.01	0.31
High risk	0.55	0.34	0.25	0.01	0.01	0.09
Low risk	0.27	0.31	0.25	0.97	0.97	0.57
Critical	0.07	0.01	0.25	0.01	0.01	0.03
Experience	30.0	49.0	0.0	9.0	1.0	87.0

Figure 4.6. *Conditional probability table for the node Forecast (18 months) Iskar reservoir showing experience counts in the bottom rows*

A problem that is immediately apparent in Figure 4.6 is the zero scores in some of the columns in the row labelled 'experience'. The count in the experience table shows how many observations have been made so far. So a zero score might indicate that a particular combination of states is rare or extremely unlikely. Alternatively zero scores may be due to a limited sampling period that does not cover all scenarios. It is conceivable that changing the data range of a state will alter the experience counts in that and other states Also, reducing the number of states in a Bayesian network can potentially results in loss of detail, what Jensen (2001) refers to as second-order uncertainty, as opposed to first-order uncertainty, which refers to the significance of data dependencies expressed as experience counts for each possible instantiation in the model. To demonstrate second-order uncertainty, observe the two conditional probabilities tables in Figure 4.7, below.

Current month	High				Medium				Low				Critical			
Inflow (12 month average)	High		Low		High		Low		High		Low		High		Low	
Volume (12 month average)	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
High	0.41	0.32	0.16	0.32	0.34	0.55	0.37	0.29	0.09	0.01	0.01	0.25	0.25	0.25	0.25	0.48
Medium	0.57	0.14	0.68	0.35	0.34	0.11	0.21	0.01	0.31	0.01	0.01	0.25	0.25	0.25	0.25	0.44
Low	0.01	0.45	0.15	0.12	0.31	0.27	0.21	0.41	0.57	0.97	0.97	0.25	0.25	0.25	0.25	0.01
Critical	0.01	0.09	0.01	0.21	0.01	0.07	0.21	0.29	0.03	0.01	0.01	0.25	0.25	0.25	0.25	0.07

Current month	High				Low			
Inflow (12 month average)	High		Low		High		Low	
Volume (12 month average)	High	Low	High	Low	High	Low	High	Low
High	0.83	0.56	0.71	0.485	0.45	0.26	0.26	0.71
Low	0.17	0.44	0.29	0.515	0.55	0.74	0.74	0.29

Figure 4.7. *Two conditional probability tables developed from the same forecasting data, but with a different number of states for the current and forecast reservoir volumes.*

When computing the conditional probabilities and data dependencies in a Bayesian network from data using the NPC algorithm, the experience counts, and therefore the significance of model outputs, decreases as the number of node states is increased. The result is actually an increase in first-order uncertainty. When using structural learning to construct models from large data sets, therefore, the model developer aims to achieve a balance these two types of uncertainty and work within the limits of the available data by choosing the most efficient discretization intervals.

Alternatively if knowledge elicitation is used, where experts or the model developer inserts conditional probabilities manually, parameter sensitivity analysis is a useful tool for identifying and focussing data collection resources on the variables that are most influential on the posterior probability of a hypothesis given evidence. That is, parameter sensitivity analysis can be used in an attempt to focus knowledge elicitation resources in the model construction process. In this case experience tables can be added to the cpt and be filled in by the expert to represent their confidence in their beliefs, thus allowing some measure of first-order uncertainty to be included in the model. Furthermore, Hugin also provides belief updating during structural learning, where conditional probabilities and experiences counts computed using the NPC algorithm can be updated using expert knowledge during structural learning. This approach offers a possible solution where model constructed from historical data result in low or zero experience counts.

The following section describes data collection and model development for the first decision made by the Ministry of Energy (MoE), the water regulator, regarding the domestic customer water pricing strategy.

4.3 Modelling domestic water pricing and impacts of demand reduction on the water company

The aim of the data collection and model development was to understand the potential impacts of different seasonal pricing strategies on aggregate and metered domestic water demand. An early model representing domestic water pricing variables is shown in Figure 4.8.

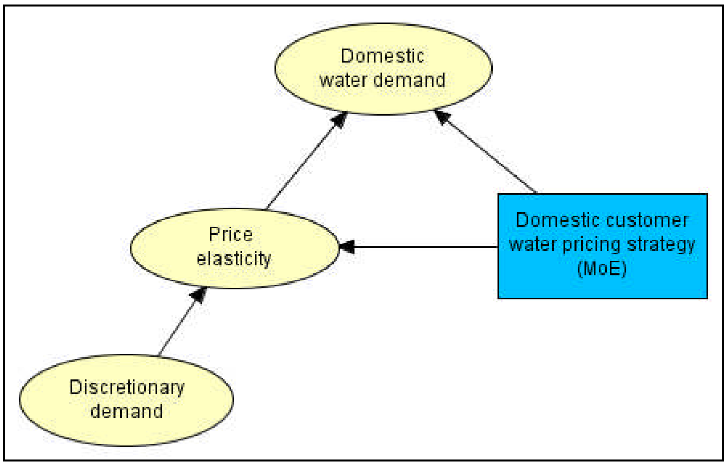


Figure 4.8. *Information requirements for domestic customer pricing decision*

The model in Figure 4.8 shows how price elasticity for domestic water demand is strongly influenced by discretionary use, usually approximated as the difference between the summer and winter demand. This is the fraction of total demand that is generally expected to be responsive to a change in price. Price elasticity measures changes in the quantity demanded as associated with price changes for the good or service. The price elasticity of demand is a negative number. Based on price elasticity of -0.2, for example, a 10 percent increase in price is associated with a two percent decrease in usage.

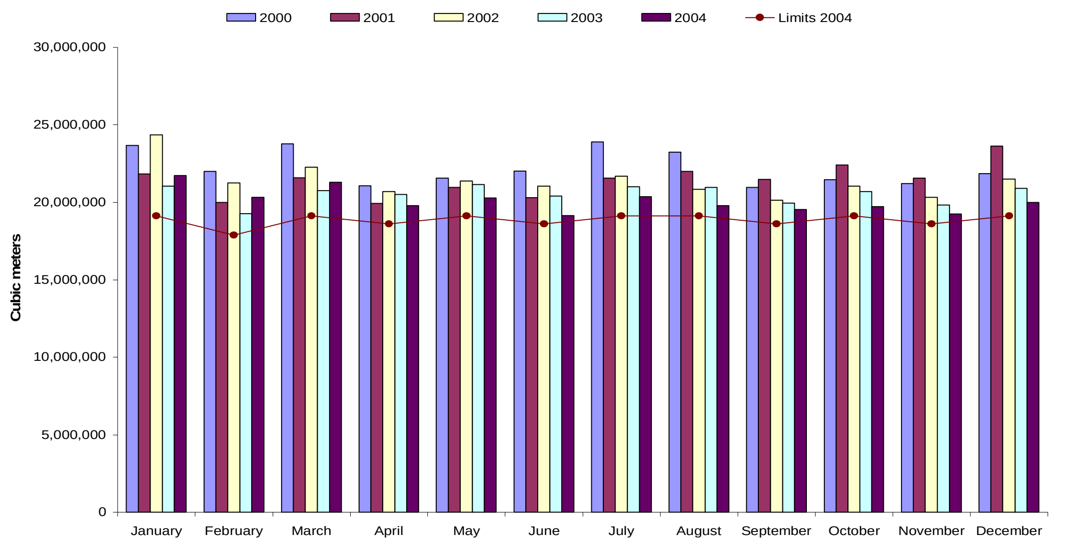
Pricing can only be effective as a conservation tool if a meter is installed in the household. This is because a metered rate produces a water bill that varies with the amount of water used. Higher use results in a higher bill, and lower use results in a lower bill signalling in the mind of the consumer a need to be careful about their water use. This was the main driver for introducing universal household metering in Sofia in 1999 when the 25-year concession contract was agreed and International Water commenced management of Sofia's municipal water supplies. As a result the water company estimates that around 98% of households in Sofia now have a meter installed.

4.3.1 Method

To examine discretionary demand (i.e. the difference between summer and winter use) in Sofia and the potential for using price as a conservation tool, monthly water demand data between 2000 and 2004 were supplied by the water company, Sofiyska Voda.

4.3.2 Results

The histogram in Figure 4.9, below, shows monthly water demand in Sofia for the years 2000 to 2004.



Data source: Sofiyska Voda, 2007

Figure 4.9. *Monthly water supplied by Sofiyska Voda 2000-2004*

A comparison between summer and winter months shows that discretionary demand is very low indicating that price will not be an effective conservation tool in the Sofia case. Consultation with members of the panel of informed practitioners revealed that there may be a number of reasons for this. One reason cited was that many people in the suburbs access water for irrigation and livestock watering from their own boreholes. This water is not metered and would not be affected by any price increase. A second reason cited was that most people in the city (around 60%) live in multi-family housing blocks and do not have gardens.

These findings are interesting from a cultural perspective because in most western developed world cases, i.e. in the USA, Australia, UK and Germany, discretionary demand accounts for between 15-50% of summer demand, making price mechanisms an effective short-term measure for controlling demand, especially during a dry summer.

Although it is possible that, in future, changes might occur that will result in higher discretionary demand in Sofia, e.g. increased affluence, charging for groundwater, larger gardens and an increase in outdoor water use etc, the present very low discretionary demand means seasonal pricing will have a negligible impact on domestic water demand.

4.3.2.1 Impacts of price and WDM measures on Sofiyska Voda revenues

When considering impacts of demand management options on water company revenues, only a reduction in *metered* water demand is relevant. Therefore, in order to model the impacts of price and other WDM measures on *total* water demand as well as on the water company's revenues it was necessary to disaggregate the *metered* component of domestic water demand from the *total* demand. It was also necessary to first consider the impacts of WDM programmes in terms of their impact on different components of water demand, and only then could they be combined to develop the conditional probability table representing their impacts (i.e. water savings) on total demand.

Figure 4.10, below, shows the disaggregated demand components used by Sofiyska Voda for operational purposes which were helpful in understanding how different WDM options impact on domestic demand.

<table>
<tr><td rowspan="4">Unaccounted for Water (UfW)</td><td colspan="2">Leakage</td></tr>
<tr><td rowspan="3">Unbilled water</td><td>Incorrect measure</td></tr>
<tr><td>Thefts</td></tr>
<tr><td>Technical losses</td></tr>
<tr><td rowspan="4">Metered demand</td><td colspan="2">Household demand</td></tr>
<tr><td rowspan="3">Other metered demand</td><td>Municipal uses (government offices, universities, public spaces etc)</td></tr>
<tr><td>Service industry (hotels, restaurants, sports facilities etc)</td></tr>
<tr><td>Other industrial uses (other businesses)</td></tr>
</table>

Figure 4.10. *Components of Sofia's domestic water supply*

Using the above information the Influence diagram structure for impacts of domestic water price and disaggregated demand was developed as shown in Figure 4.11. Low discretionary demand is represented by the conditional probability tables: *p(domestic water demand* | *domestic water price)* and *p(metered water demand* | *domestic water price*. Impacts of different WDM programmes on disaggregated demand are represented by the the conditional probability tables: *p(domestic water demand | WDM programme water savings | WDM programme options)*.

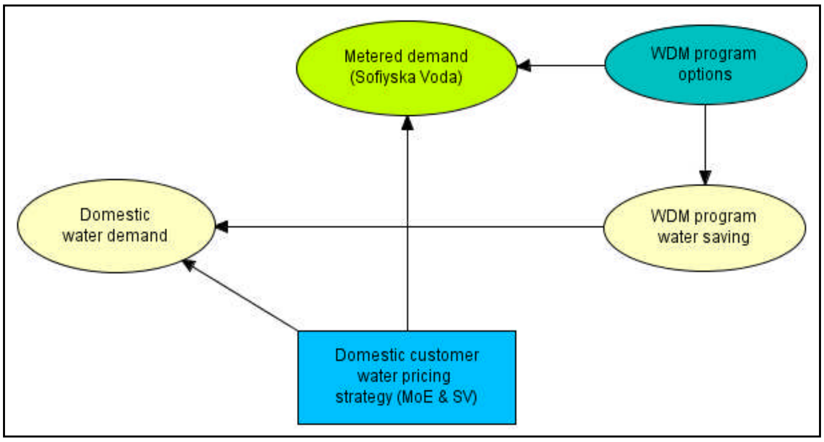


Figure 4.11. *Influence diagram structure for impacts of domestic water price on total domestic demand and WDM programmes and water price on metered demand.*

The following subsection describes how the data collected during the knowledge elicitation were used to develop conditional probabilities to forecast the water saving potential of different WDM programmes.

4.4 Data collected from informed practitioners are used to develop a Bayesian network model to forecast the water saving potential of WDM programmes

4.4.1 Method

Conditional probabilities for water saving potential and ease of implementation were calculated using information collected during the knowledge elicitation described in Chapter 3. For each WDM measure mentioned informed practitioners were shown the show-card for (i) ease of implementation of different WDM options and (ii) water saving potential of different WDM options (Appendix D).

The method used to calculate conditional probabilities follows the most basic Delphi technique reported by Jilson (1975) which uses a single round of consultations. Other Delphi techniques (*e.g.* Ford, 1975; Sahal and Yee, 1975) including multiple iterative rounds of collection of expert knowledge and calculation of probability density functions are described in Appendix H and the need for research into the suitability of alternative approaches is recognised as an areas for future research. Time constraints, however, meant that only a single iteration was possible during the knowledge elicitation in the Sofia case.

To calculate water savings for a single WDM measure and relevant conditional probabilties the number of practitioners who said that the measure would achieve a specific water saving range was divided by the total number of practitioners who cited that specific WDM measure. So, if five practitioners cited an education and awareness campaign, and one forecasted savings of 3-5% and four forecasted savings of 5-10%, the conditional probabilities for different water saving potentials would be: 3-5% = 1/5 = 0.20, 5-10% = 4/5 = 0.80.

Using the above technique, conditional probabilities for water saving potential and ease of implementation for the seven most frequently mentioned WDM measures, over two different implementation horizons, are presented in two tables in Appendix I. In most cases conditional probabilities are distributed between one, two or three states. The number of practitioners who cited each option is shown in the column headed “Experience”.

Water demand management programmes will usually involve the co-implementation of a range of WDM options in order to achieve the required savings. To calculate conditional probabilities for combined programmes, the mid-point of the water saving potential ranges were used. Practitioners indicated that some options would only affect a fraction of the population and, for these options, percentages were only applied to the component of demand they would affect.

4.4.2 Results

Figure 4.12, below, shows the Bayesian network model and probabilities calculated using the above method. The model shown is instantiated for a three month implementation horizon, and shows a combined programme involving: an education/awareness campaign, introduction of an increasing block tariff (IBT) price structure, pressure reduction and outdoor restrictions. Two nodes that were populated using data collected during the household survey, described in Chapter 6, that show householders perceptions towards price increase and installation of efficient appliances / pressure reducing valves, are also included in the model.

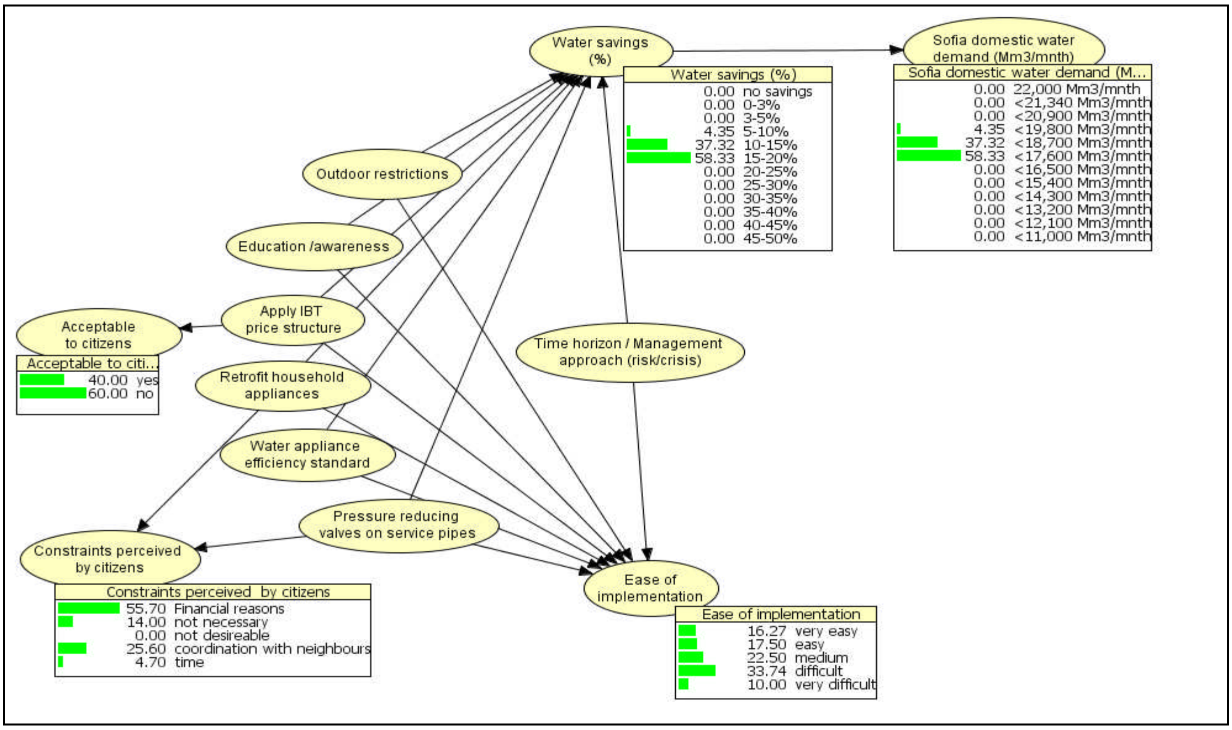


Figure 4.12. *A Bayesian network constructed from data collected during the knowledge elicitation showing water savings for a combined programme, with a three month implementation horizon.*

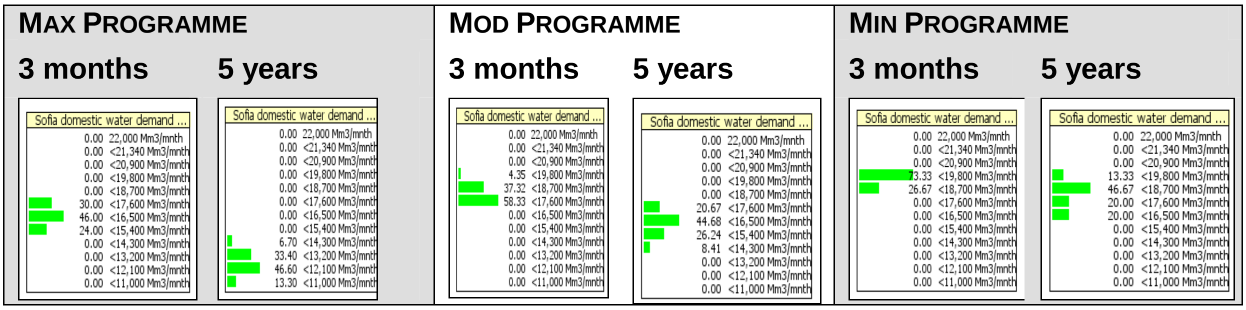


Figure 4.13. *Conditional probabilities for total domestic water demand following implementation of three programmes over different time periods*

Water saving conditional probabilities for different programmes, Figure 4.13, indicate that for the longer (five year) implementation horizon, the probabilities are dispersed over a larger number of states indicating higher uncertainty between practitioners. The potential water savings forecasted by informed practitioners are higher over a five year period than would be achieved over three months. The results indicate that practitioners generally perceived shorter term programmes to be easier to implement. This reflects the perception that, in a crisis, people act with greater urgency. Individual measures included in the three combined programmes are shown in Table 4.1

Table 4.1. *WDM options in three combined programmes*

PROGRAMME	WDM OPTIONS
MAXIMUM	- Education/Awareness campaign - Introduction of Increasing Block Tariff (IBT) price structure - Pressure reduction programme - Outdoor restrictions.
MODERATE	- Water efficient appliance standard - Household water appliance retro-fit - Education/Awareness campaign - Pressure reduction programme
MINIMUM	- Education/Awareness campaign - Outdoor restrictions

The following section reports the development of a sub-model for examining the potential economic savings of demand management options from the perspective of the water company.

4.5 Modelling economics of water demand management

In order to design a WDM programme water companies must make a prior evaluation of different WDM measures and instruments available to them. Prior evaluation usually relies on economic appraisal and there has been much debate about the economic methods used. An early study in the USA by Hirshliefer *et al* (1960) criticised the then prevalent practice of comparing water projects by measuring the ratio of the present worth of benefits (PWB) to the present worth of costs (PWC). The authors demonstrated that it was in fact the NPV (net present value), the absolute difference between the two that should: (i) determine whether a given one-off water scheme should go ahead or not and (ii) form the basis of scheme ranking.

More recently it has been recognised that residential water savings can lead to a number of quantifiable benefits for water utilities which are overlooked in some economic evaluation methods. Advantages include: reduction in operation and maintenance costs, deferral or downsizing of capital facilities, and reduced water purchases from wholesale providers (Maddaus, 1999). Least cost planning (LCP) has emerged as the way forward for water utilities in regions where water conservation has become an objective or where ongoing supply expansion is constrained (Fane *et al*, 2004). LCP originated in the energy sector in the United States during the 1980's for comparing energy conservation programmes with increased generation from sources of supply (Beecher, 1996). Evidence that the LCP process currently used by Australian and UK Water Companies biases supply-side options over demand-side options, however, can be found in recent publications (e.g. Herrington, 2006; Fane *et al*, 2002) which have attempted to develop the method further.

The following is a description of the lifetime avoided costs (LAC) method developed during individual consultations with informed practitioners to incorporate WDM programme costs and benefits from the perspective of the water company, Sofiyska Voda (SV) into the decision model. The method accounts for inherent uncertainties in programme implementation efficiency.

4.5.1 Lifetime Avoided Costs method

The basic premise of the LAC method is that a positive lifetime avoided costs value is dependent on the lifetime of the WDM option being greater than the programme payback period. The LAC is an aggregate utility, as opposed to most methods which result in a unit cost, which meant that it could be used as a utility function in the decision model. The components of the LAC calculation are as follows:

LAC = (LofO – PPP)*VC*PWS *(Eq 4.3)*

where:

LAC = Lifetime Avoided Costs (LEV)

Lof O = Lifetime of the Option (years)

PPP = Programme Payback Period (years)

VC = Variable Costs (LEV/m3/)

PWS = WDM Programme Water Savings (m3/year)

Programme Payback Period uses the programme costs divided by the value of water saved per year, determined by the variable cost (described below) as follows:

PPP = PC / VC*PWS *(Eq 4.4)*

where:

PPP = Programme Payback Period (years)

PC = Programme Costs (LEV)

PWS = Programme Water Savings (m3/year)

VC = Variable Costs (LEV/m3/)

4.5.2 Results

Figure 4.14, below, shows two early versions of Bn models developed using components of the LAC method. Model (b) was evaluated by informed practitioners during the end-user evaluation.

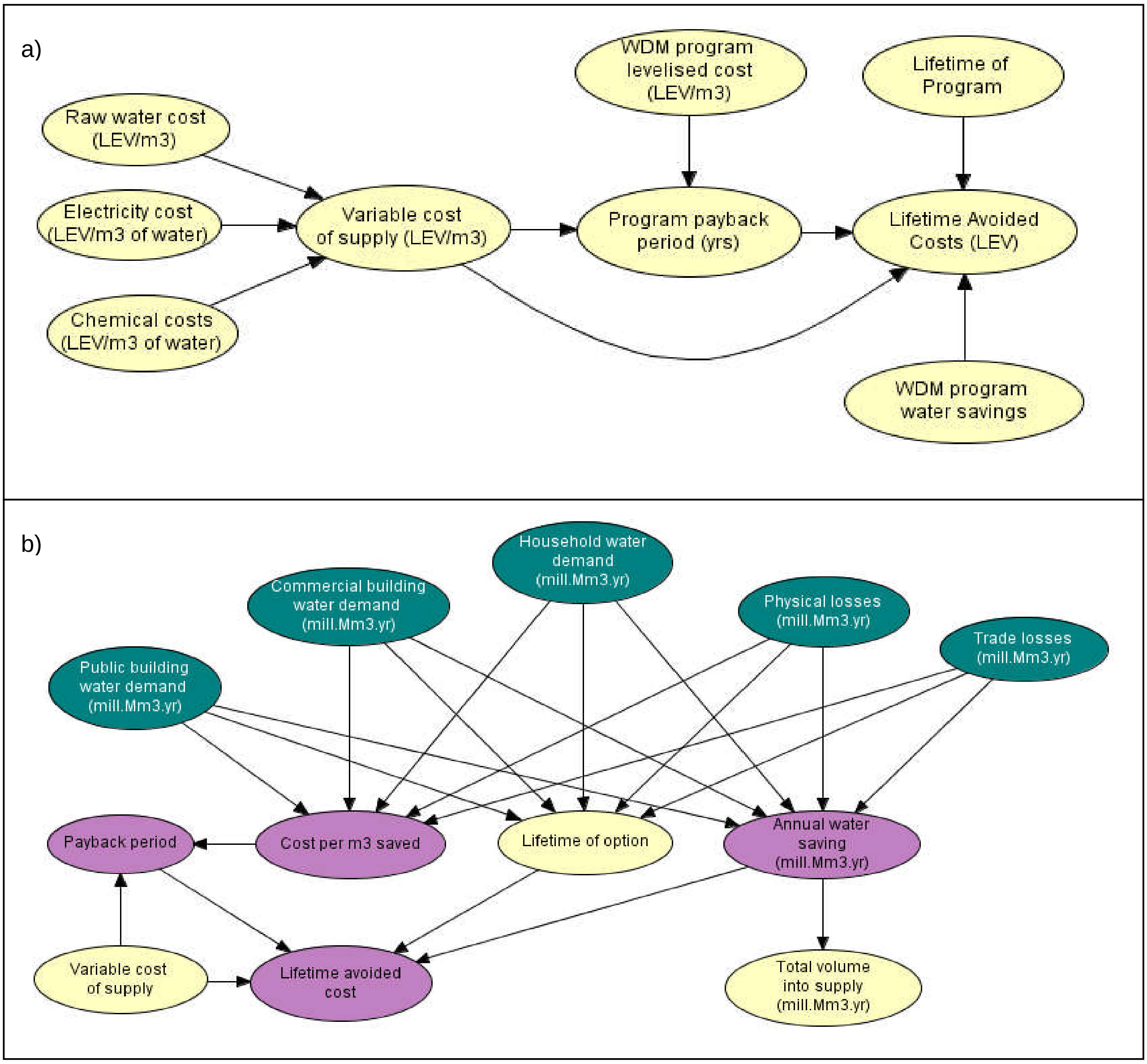


Figure 4.14. *Two earlier versions of the Bayesian network of the lifetime avoided costs method.*

4.5.2.1 Abstraction costs represent the main variable operating cost for the Sofia water company

For operational purposes, water company costs are divided into two components: variable operating costs and fixed operating costs. The variable operating costs are those costs that are determined by the throughput of treatment plants (potable or wastewater) run by the water company (Sofiyska Voda), so, importantly, from SV's perspective, are the only costs that are relevant when considering the benefits of reducing water demand. Variable operating costs can be further disaggregated, and for SV, there are three key components: raw water costs, chemical costs, and power costs.

The water company supplied information on variable operational costs of supplying water (i.e. raw water, power and treatment costs) for the year 2005 and 2006 (these are presented in Appendix J). The data presented in Table A and Table B permitted a comparison of variable operating cost components. The data shows that raw water costs make up approximately 75% of the total variable operating costs. As described in the LAC method, a change in variable operating costs affects the payback period from WDM measures, and as such, the Ministry of Environment and Water's (MoEW's) decision regarding abstraction permit and raw water costs is a policy area that needs to be addressed in the context of water efficiency.

Further consultation revealed that two factors result in power costs being remarkably low for operation of the water network in Sofia. Firstly, the water supply network in Sofia is gravity-fed and secondly there is no reliance on aquifers for public water supplies so there is no requirement for pumping groundwater. These factors mean that the variable operational costs and, therefore, the actual avoided costs from WDM are relatively low in Sofia compared to other cities. This information is valuable in the context of developing generic models to facilitate water conservation decisions in other river basins.

Comparing the Bayesian networks of the LAC method in Figure 4.14 (above) with the Influence Diagram in Figure 4.15 (below), which is the sub-model for the decision to introduce WDM programme used in the conceptual model described in Chapter 5, demonstrates the process of analysis that occurs during the development of Bn models for use in policy analysis.

The only remaining chance nodes in the version shown in Figure 4.15 from the diagnostic Bn models in Figure 4.14 are the nodes, 'WDM programme water savings', 'WDM programme payback period' and 'Lifetime of the WDM programme'. These nodes represent uncertain variables that remain in the mode and require consideration at the planning and legislating stage. These variables are subject to different approaches to WDM programme *design* and are examined in Chapter 6.

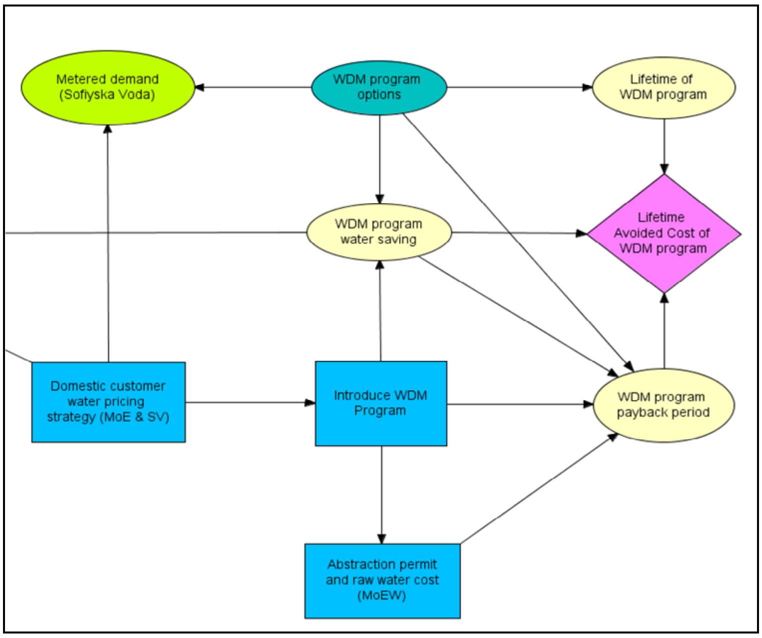


Figure 4.15. *Lifetime avoided costs components as represented in the conceptual model presented in Chapter 5*

As explained above, the only variable operational costs component that is subject to change is the raw water cost (Figure 4.14a) and this is determined by the MoEW's decision. This cause-effect relationship is represented in Figure 4.15 by a directed link between the decision node labelled abstraction permit and raw water costs (MoEW) and the chance node labelled WDM programme payback period.

Because different WDM components will impact on metered demand differently (e.g. reducing pressure in the water network will reduce UfW but will have less impact on metered demand), a directed link is included from the node, 'WDM programme options', to the node, 'metered demand'.

4.6 Conclusions

The model development described above supported identification of strengths and weaknesses of Bns relating to the research questions presented in Table 1.4. The findings are summarised below.

Research question 1: How does Bayesian network modelling provide support for analysing uncertainty in water supply and demand forecasts?

Strengths of Bns for water supply and demand forecasting were identified from the model development reported in Chapter 4. In Section 4.2.2, structural learning and parameter sensitivity analysis were applied to hydrological data collected from the

Iskar dam between 1966 and 2000, and the results were used to develop a water balance model and forecasting model of future water availability. In practice, the resulting models (Figure 4.1 & Figure 4.5) supports exploration of scenarios to identify risks of low water availability. The forecasting model also demonstrates how Bns can be used to model over a single time-step. In Chapter 5 the forecasting sub-model (Figure 4.5) is included as part of a larger conceptual model for supporting water management policy decisions in the Upper Iskar.

A further strength of Bns is the wide range of data types (see below) that can be used to populate conditional probability tables (cpts). This addresses some of the issues of data availability often encounters in forecasting and backcasting. Four types of information that can be used to populate cpts in Bns have been identified. These are:

- Raw data collected by direct measurement (e.g. River flow or reservoir levels, population measured by census, income measured by accounting).
- Information collected from regional reports (e.g. from water companies, environment agencies, research institutions) of water demand and supply.
- Raw data collected through stakeholder elicitation (e.g. stakeholder perceptions of water availability, population and income).
- Output from process-based models calibrated using raw data collected by direct measurement.

With regard to using Bns for hydrological modeling, until recently limitations existed with modeling feedback cycles using Bayesian networks due to the necessary calculus not being developed (Jensen, 2001). Recent developments (e.g. Montani et al, 2008; Neil et al, 2008), however, mean that there is now scope to use Bns in domains where feedback cycles exist.

Because historical hydrological data rarely include all possible scenarios of water demand (i.e. all possible demand management scenarios) it will be desirable to use outputs from other hydrological models (i.e. simulation models). However, this is a universal problem with collecting data for hydrological modelling and the facility to use expert knowledge in Bns in combination with actual data has potential advantages.

Research question 2: How does Bayesian network modelling provide support for economic analysis of impacts of demand management programmes?

The strengths of using Bayesian networks for analysing causes of uncertainty in economic evaluations of demand management options were examined in Chapter 4, Section 4.5.1. The lifetime avoided costs (LAC) method described in Section 4.5.1 is only one of many methods that could potentially be used to support economic evaluations of demand management. In Section 4.5.2.1 the LAC method was used to support structuring of a Bn model and demonstrates how Bayesian networks support quantification of conditional dependencies between variables. When quantified, the model was used to identify the variables that could be affected by interventions to reduce uncertainty about potential programme impacts. This makes it possible to understand how human actions (adaptive policies) will lead to more certainty about implementation effectiveness. Regarding the use of knowledge elicitation to support model development, the use of supply curves, as reported in Turner *et al.,* (2003), will be a helpful approach for structuring future knowledge elicitation activities. An example of a supply curve is given in Appendix K.

In addition to the above strengths and weaknesses addressing research questions 1 & 2, a number of advantages and disadvantages of using discrete ranges (i.e. states) in Bns were identified from the model development in Chapter 4 and these are listed in Table 4.1 below.

Table 4.1. *Advantages and disadvantages of using discrete ranges in Bayesian network forecasting models*

Advantages	**Disadvantages**
▪ Discretisation allows identification of model parameters with dispersed probability distributions, allowing research to be focused on areas of greater uncertainty ▪ Encourages the identification of tipping-points between model variables ▪ Conditional probabilities for discrete ranges can be used to derive utilities using utility theory	▪ The use of states can be counter to the objective of reducing uncertainty ▪ Increasing the number of states reduces statistical significance during structural learning ▪ Increasing the number of states may make knowledge elicitation impractical

The suitability of Delphi methods for developing CPTs and combining expert knowledge with other data is an area for further research. Methods used would ideally be (i) efficient in terms of resources used in the collection of data, whilst (ii) achieving sufficient accuracy to provide valid models. Four Delphi approaches are described in detail in Appendix H.

The following chapter presents the conceptual model for WDM legislation in the Upper Iskar case which incorporates issues addressed in the models developed above (i.e. water availability forecasting indicators, impacts of water pricing, impacts of WDM on water company revenues and uncertainty about economics of WDM).

Chapter 5

Technical evaluation 1: Bayesian networks to support water demand management legislation decisions

Introduction

A conceptual model of the decision process for WDM legislation as identified through the knowledge elicitation, that integrates the various issues and sub-models described in Chapter 4, is described in the sections below.

Section 5.1 describes the regulatory mechanisms, as defined by informed practitioners during the knowledge elicitation, which influence WDM programme implementation and presents the structure of the conceptual model. Section 5.2 demonstrates how the conceptual model is applied to answer and explore policy questions about WDM legislation and planning in the Upper Iskar. Section 5.3 reflects on how the development and use of the conceptual model addressed the modelling requirements identified in Chapter 1 (i.e. cross-sectoral planning, science-policy interfaces modelling decision process, developing the evidence-base) and support tool tasks identified in Chapter 3 (i.e. timing of implementation of drought contingency plans, decisions processes involving multiple decisions and organisational perspectives).

Three research questions, Box 5.1, are examined in Chapter 5.

Box 5.1. Research questions examined in Chapter 5

Research question 5: *How does Bayesian network modelling provide support for developing preparedness strategies?*

Research question 6: *How does Bayesian network modelling provide support for decisions involving multiple organisations?*

Research question 7: *How does Bayesian network modelling address issues of structural uncertainty in the planning process?*

The following section describes the decision process and structure of the conceptual model.

5.1 Structuring the conceptual model

Three policy decisions identified during the knowledge elicitation shown below, Figure 5.1, were integrated into the conceptual model.

Figure 5.1. *Decision influencing investment in water demand management in Sofia*

The first decision involves the Ministry of Energy (MoE), the newly appointed economic regulator, deciding on the potable water price that the water company, Sofiyska Voda (SV), are permitted to charge their customers. Domestic water price in Sofia is negotiated between the MoE and SV and is based on the UK regulatory model. It has two implications for WDM planning: the use of price as a conservation tool, and the availability of financial resources for SV to make investment in WDM.

The second decision in the sequence refers to which WDM options, if any, to implement. The utilities for WDM implementation are distributed between two criteria: (i) benefits in terms of security of the future water supplies which are influenced by domestic demand levels and (ii) an assessment of the costs and benefits of WDM from the perspective of the water company, SV. One of the tasks of developing the conceptual model was to integrate these criteria into the decision process. This is achieved by including two utility nodes in the conceptual model: one linked to the reservoir level forecast, and one linked to the lifetime avoided cost (LAC) components.

The third decision involves the Ministry of Environment and Water (MoEW) decision regarding the abstraction permit strategy and raw water price for the next 12-18 months. The MoEW decides on abstraction costs and permitted volumes for all major water users (i.e. domestic, agricultural, industrial, hydo-power users etc) for a given time period, usually six months. The current price that SV pays the MoEW for water abstraction is 0.02 LEV per m3. If SV exceed the permitted abstraction volume in a given month a fixed penalty is incurred which is payable to the MoEW. As described in Chapter 4, this decision impacts on the costs and benefits of WDM from SV’s perspective by affecting variable operational costs.

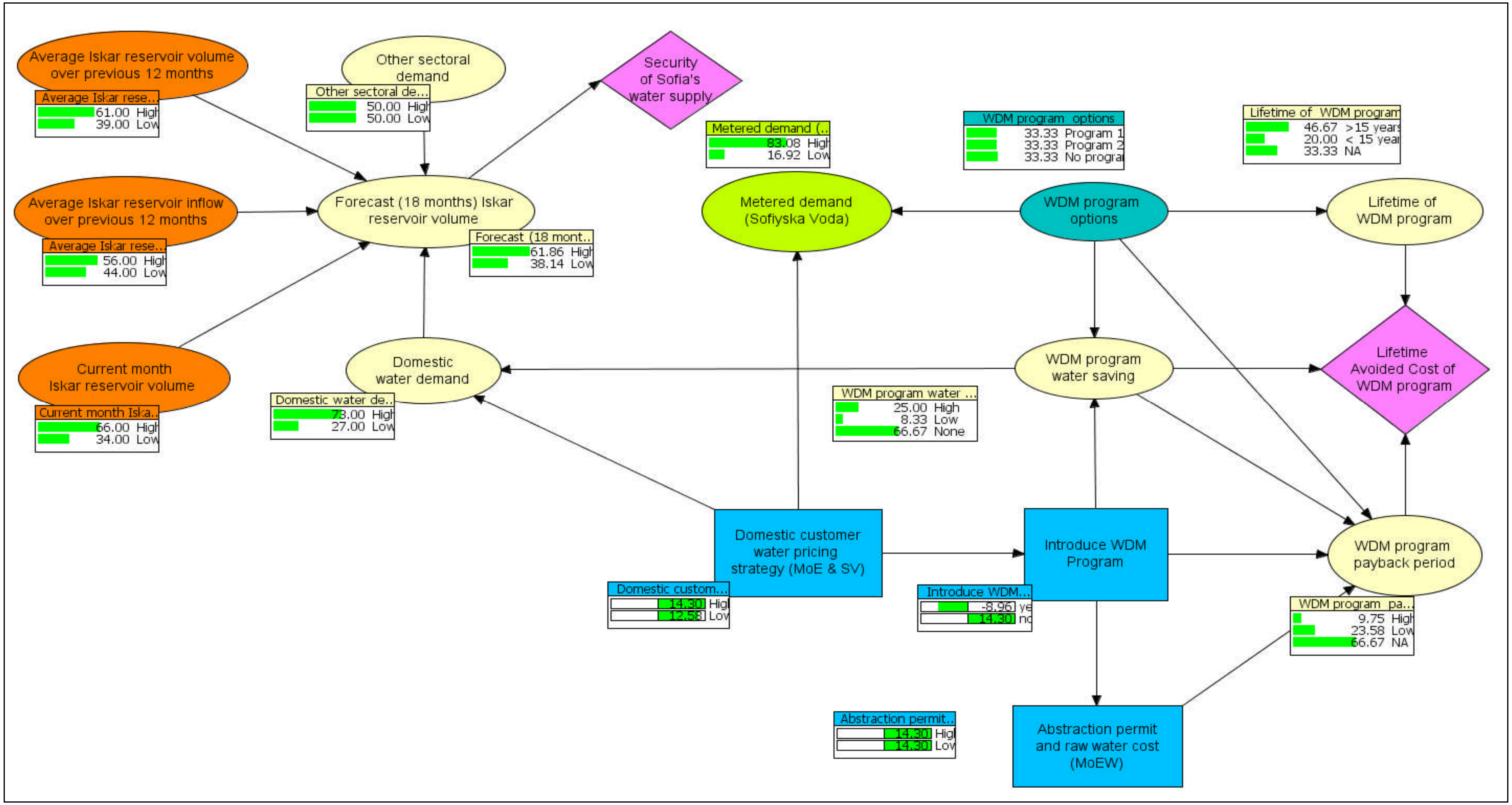


Figure 5.2. *Conceptual model of the three-step decision process for planning and legislating for demand-side management in Sofia, each node allocated two states.*

The conceptual model that represents the above decision steps and influencing factors is shown in Figure 5.2 on the previous page. Decisions in Influence Diagrams must be ordered linearly to support propagation of utilities throughout the model. A directed link, therefore, connects the Ministry of Energy, Sofiyska Voda and Ministry of Environment and Water decision in the conceptual model.

For simplification the model uses binary states although the CPTs conform to the findings in Chapter 4. It was not possible to elicit utilities for the model and the ones used, shown in Appendix L, are for demonstration purposes only. Conditional probabilities in Figure 5.2, shown in the monitor windows, represent the resting state of the model and were developed using the data collected in Chapter 4.

The following section describes the procedure for applying the conceptual model, given the information collected and described in the above sections.

5.2 Using the conceptual model

The decision problem faced by SV, the MoEW and the MoE, is to secure future water supplies to all sectors (i.e. ecological needs and agriculture, industry, and domestic demand) whilst simultaneously setting the economic conditions that will encourage (through incentives) and permit (by allowing sufficient economic resources) implementation of the required water demand management measures. The instantiation procedure for the conceptual model (Box 5.2, below) to examine the impacts of different decisions is described in the following section.

Box 5.2. Model instantiation procedure

➲ 1. Instantiate the chance node 'WDM programme options' to the state *no programme*

➲ 2. Instantiate the three reservoir forecasting indicator nodes using evidence (i.e. hydrological data).

Steps 1 & 2 show the utility of taking no action, given the reservoir level forecast

➲ 3. Change the state in the decision node 'domestic customer water pricing strategy' and observe the impacts of each decision on model utilities and connected chance nodes.

Step 3 shows the impact of changing water price on total domestic demand and metered demand node probabilities

➲ 4. Select a programme in the chance node 'WDM programme options' and observe impact on model utilities and connected chance nodes

➲ 5. Change the state in the decision node 'introduce WDM programme' node and observe the impact on domestic demand and reservoir level chance nodes

Steps 4 & 5 show the impact of introducing WDM on domestic and metered demand, the reservoir forecast, node probabilities and the impact on security of supplies.

➲ 6. Change the state in the decision node the 'abstraction permit and raw water costs' and observe the impact of the different decisions on model utilities and connected chance nodes.

Step 6 demonstrates how variable operational cost, represented by the raw water price, impacts on lifetime avoided costs for the water company

➲ 7. Repeat the above procedure for different WDM programme options

5.2.1 Model instantiation procedure

Steps 1 & 2: Figure 5.3 (overleaf) shows the model instantiation for steps 1 and 2 in Box 5.2. Utilities are shown in the monitoring windows of the decision nodes and the updated utilities and conditional probabilities for the set of evidence: *p* [hypothesis | average 12 monthly inflow (*low*), average 12 monthly reservoir volumes (*low*), current reservoir volumes (*high*)] based in their being *no programme*, are shown in Figure 5.3 below.

Step 3: The Ministry of Energy's (MoE's) decision to permit SV to introduce a *high* or low water price, and propagated probabilities are shown in Figure 5.4, below. The objective of the MoE's decision regarding the water price is to ensure an affordable, efficient and reliable water service for Sofia's citizens, whilst maintaining economic stability for the water company. The MoE's decision regarding the domestic water pricing strategy and its impact on the decision process is achieved by two directed links to achieve the conditional probabilities: *p (metered demand* | *domestic water price) and p (domestic demand* | *domestic water price)*.

The observation from Chapter 4 that SV revenues are only affected by WDM measures and changes in pricing through their impacts on the metered demand components is modelled by the directed link, *p (metered demand* | *domestic water price*. The findings from data collection to investigate the potential for changes in price to affect domestic demand in Sofia were reported in detail in Chapter 4 and indicated that seasonal pricing would not be an effective conservation tool in Sofia due to very low discretionary demand levels and is represented in the conditional probabilities.

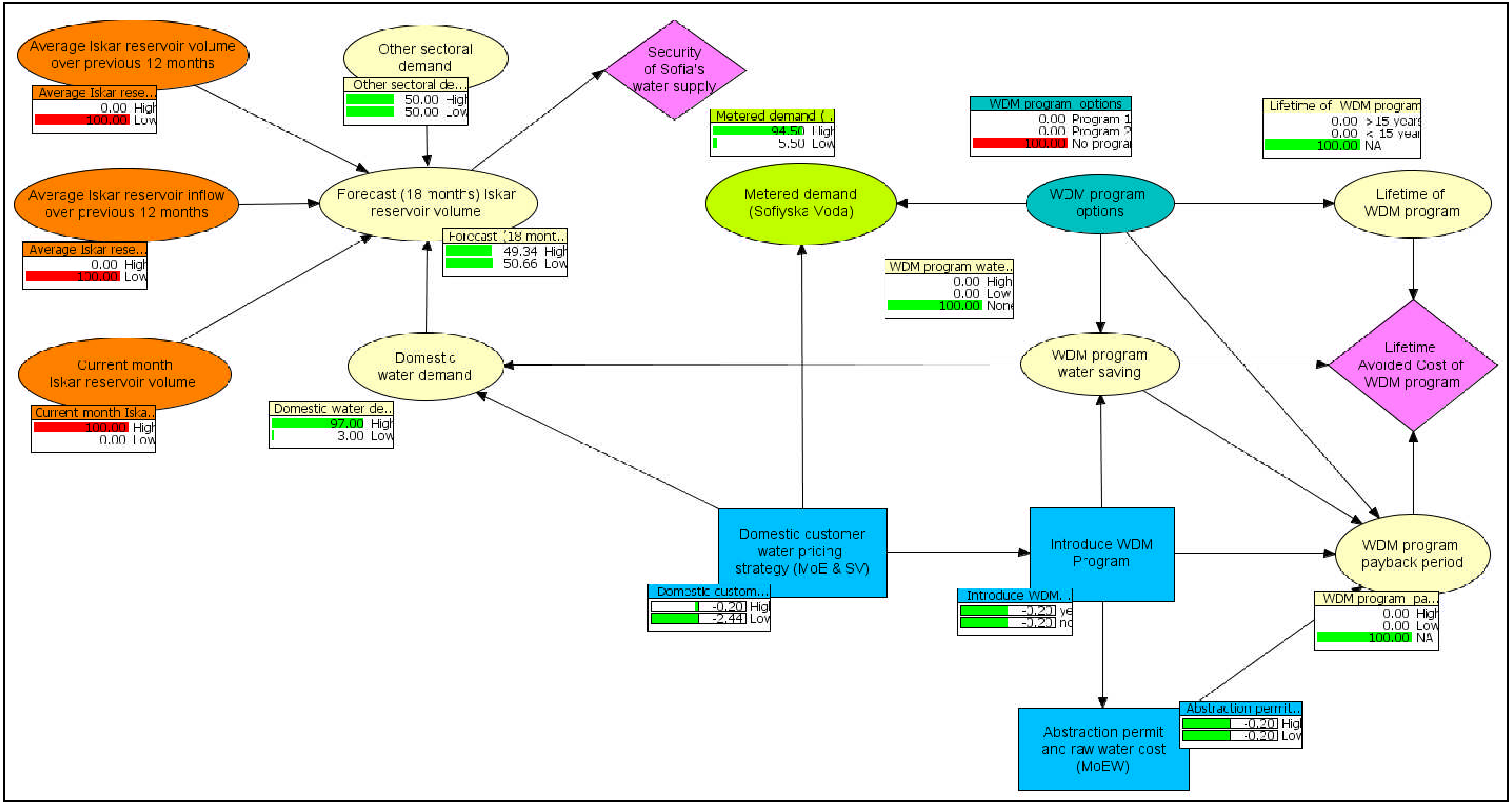


Figure 5.3. *Utilities and conditional probabilities for the evidence set: p [hypothesis | average 12 monthly inflow (low), average 12 monthly reservoir volumes (low), current reservoir volumes (high)] based in their being no programme*

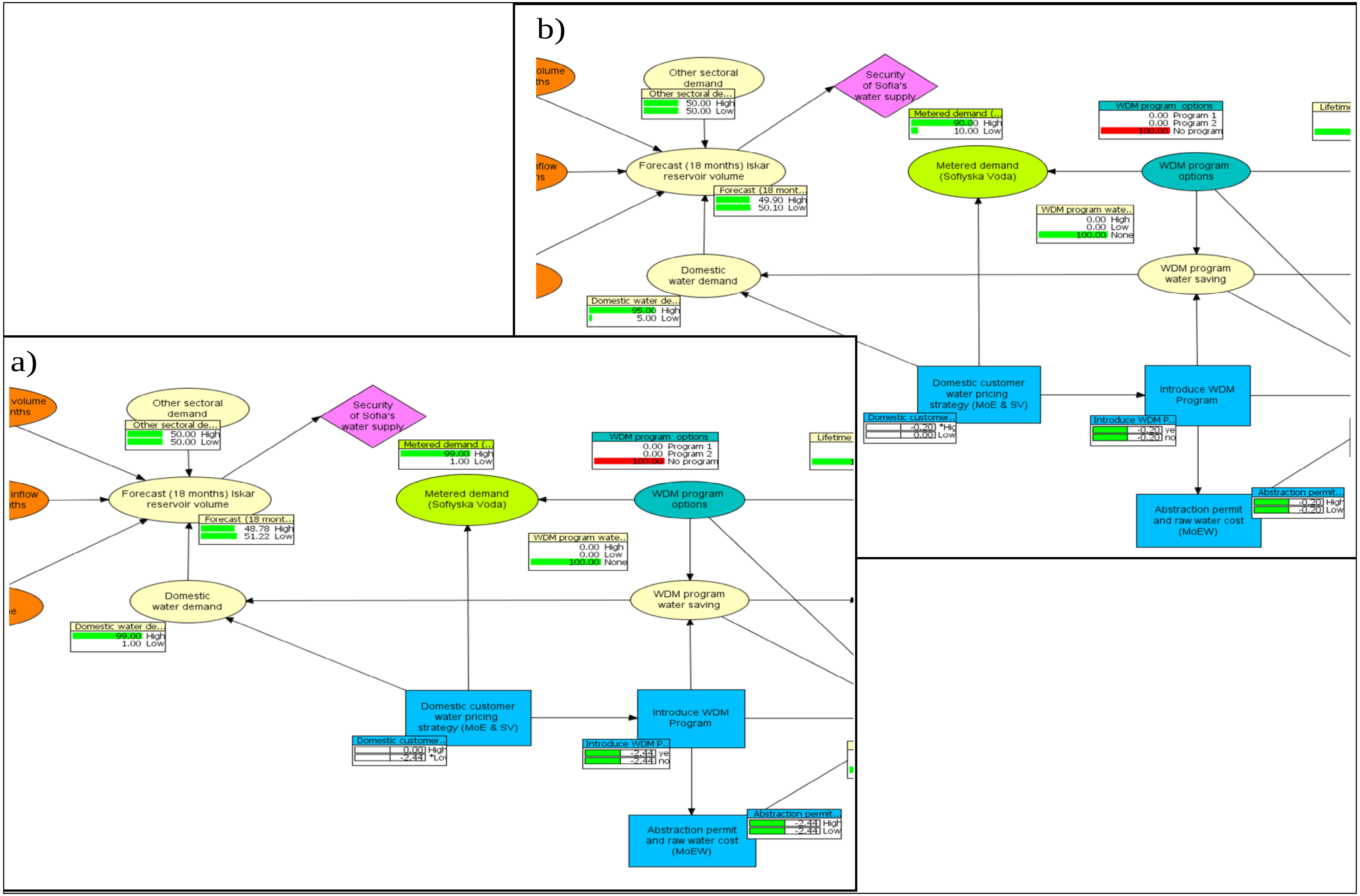


Figure 5.4. *The MoE's decision to permit SV to introduce a low (a) or high (b) domestic water price, and its impacts on metered and total domestic demand*

Steps 4 & 5: Step 4 allows the user to explore impacts of different WDM programmes on domestic demand, reservoir level forecasts, and the security of supplies. From the perceptive of water company costs and benefits the decision regarding which WDM programme to implement involves four chance nodes: WDM programme payback period, lifetime of WDM, that are components of the method for calculating the programme utility or lifetime avoided costs (LAC).

The version of the conceptual model in Figure 5.5 (a), below, shows the utility for introducing and not introducing programme 2, based on the current reservoir forecast, utilities are shown in the states *yes* and *no* in the monitoring box for the decision node, 'introduce WDM programme'. Selecting 'yes' in the decision node, Figure 5.5 (b), updates the conditional probabilities in the four chance nodes, as well as the water demand and availability nodes 'domestic demand' and 'reservoir forecast' allowing the user to assess the negative utility of the WDM programme in the context of the risk to security of supplies. The instantiation in, Figure 5.5 (b), shows that the only remaining decision to be made is the MoeW decision regarding abstraction and raw water costs.

Step 6: The objective of the MoEW, when there is a threat of water scarcity, is to assure security of water supplies to the human population and natural systems downstream of the Iskar Dam. In theory, the mechanism by which this is achieved is the abstraction permit and raw water price which effectively places a value on the cost of taking water from the river. As described above the mechanism by which the MoEW's decision to raise raw water costs affects the economics of WDM from the perspective of Sofiyska Voda (SV) is through the water company's variable operational costs. This cause-effect relationship is achieved in the model by the directed link, *p (WDM programme payback period* | *abstraction permit and raw water cost)*.

The model instantiation in Figure 5.6 shows that a high abstraction permit and raw water cost will produce more favourable utility.

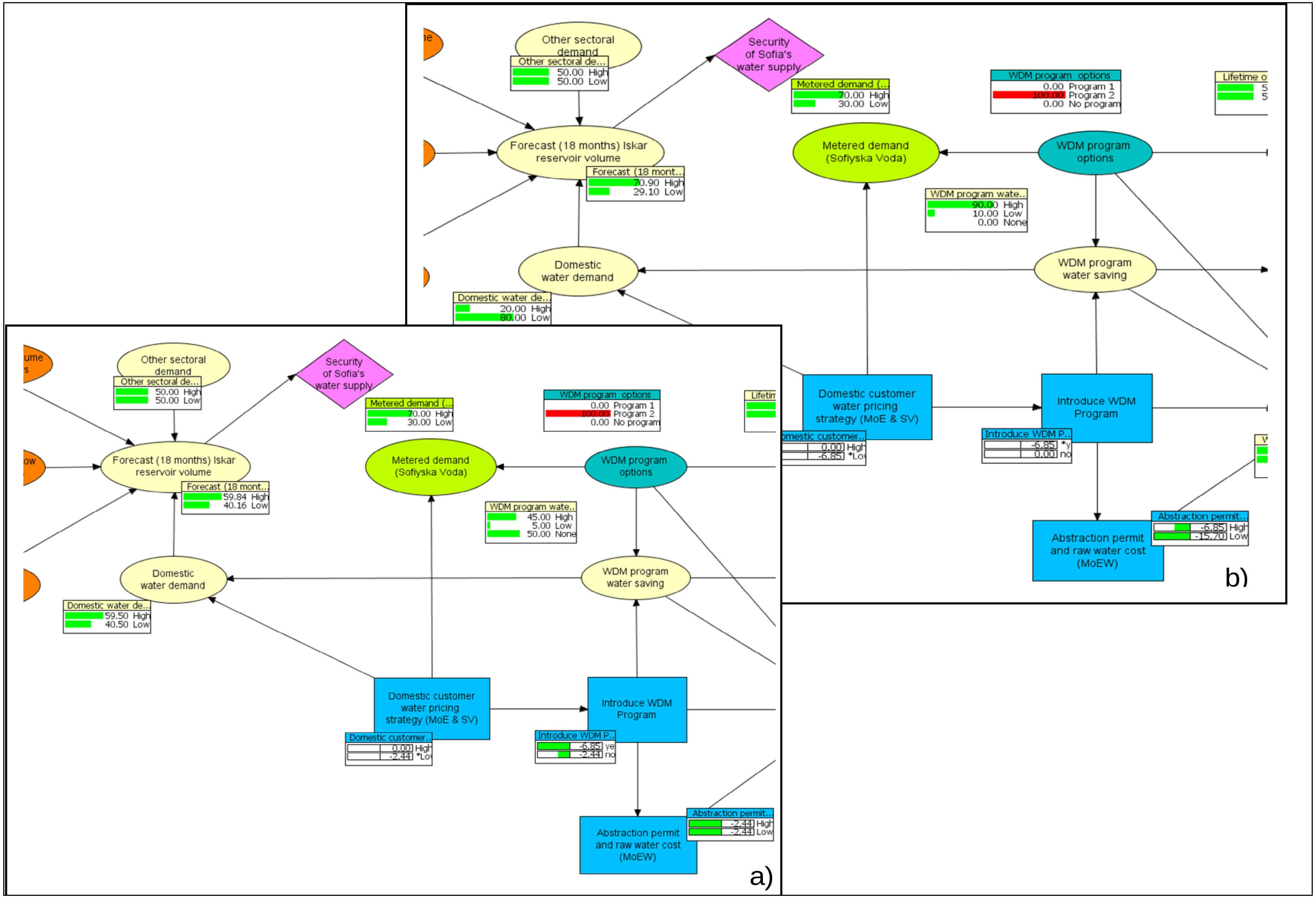


Figure 5.5. *Selecting WDM programme option (a) and observing forecasted impacts on domestic demand and reservoir level forecasts (b)*

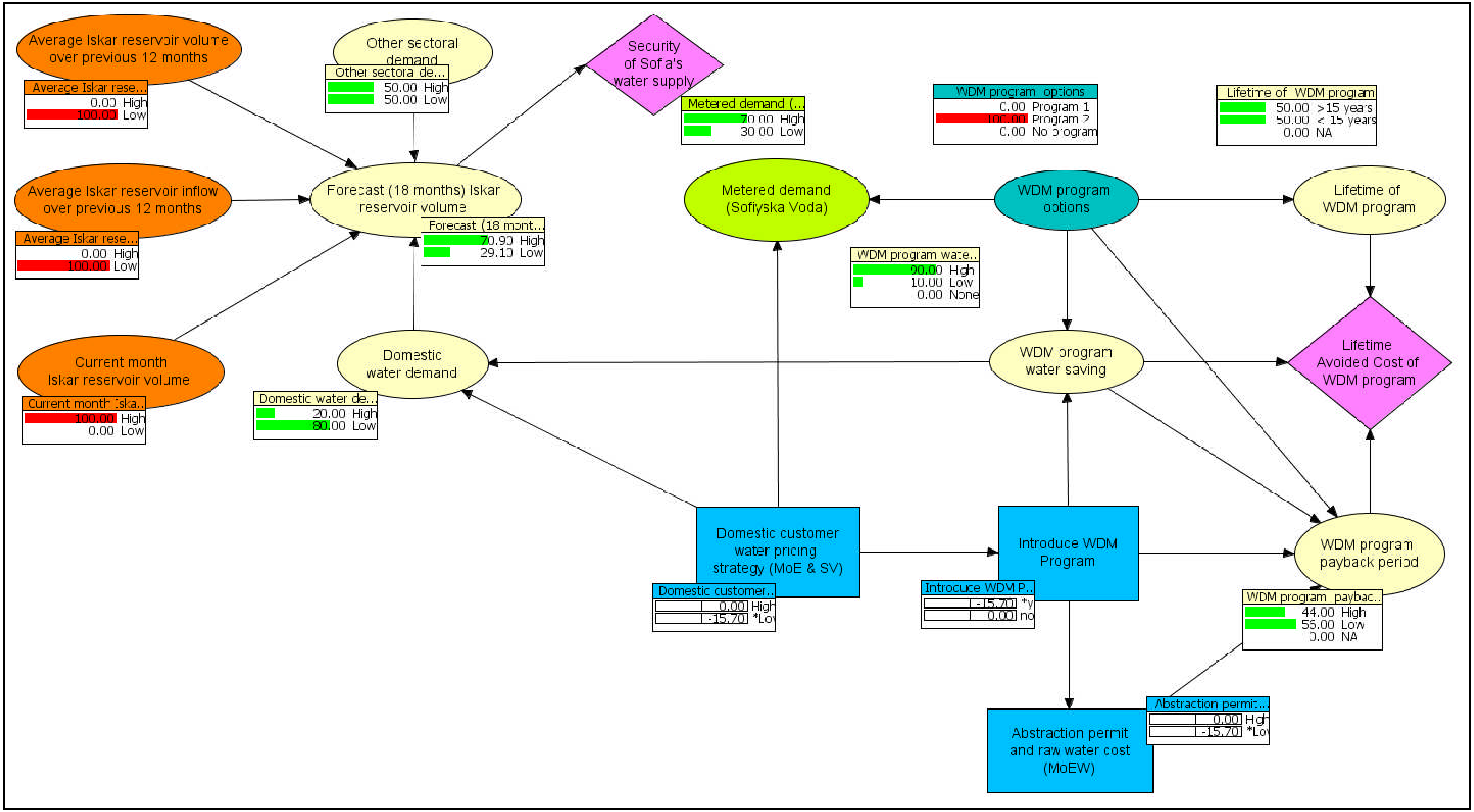


Figure 5.6. *The MoEW decision updates the conditional probabilities in the chance node labelled WDM programme payback period.*

The MoeW decision needs to be considered in terms of the possible negative impact the raising the raw water price might have on SV, and representing this cause-effect relationship allows for more transparency in the debate about the distribution of costs for WDM. The model raises a number of issues about who pays for WDM (i.e. the water company, the local or national authorities, or the public).

The following section uses the development of the conceptual model reported in the above sections as a basis for a discussion about the effectiveness of Bns in addressing the modelling requirements identified during the knowledge elicitation in Chapter 3 including: how Bns support the design of preparedness strategies, cross-sectoral planning and developing the evidence-base for WDM legislation. Further discussion topics include how Bns were used to address structural uncertainties in the decision processes and valuing Bns as a dissemination tool to support WDM legislation. Chapter conclusions return to the research questions presented at the start of this chapter.

5.3 Modelling issues arising from development of the conceptual model for WDM legislation

5.3.1 Development of preparedness strategies

The use of a single time-step in the conceptual model implies that it might be used in real-time decision-making involving the collection of evidence on water availability indicators at regular time to signal a requirement for changes in water conservation policy. However, using the model in this way might be criticised as encouraging a crisis approach to water management which is not recommended in the Sofia case. Development of the conceptual model demonstrates that, theoretically, Bns could be used in contingency planning. To use the conceptual model developed in Chapter 5 above for contingency planning would require further detail in the forecasting sub-model, modelling of water supply to other sectors, and further analysis of risk thresholds for hypothesis variables. The characteristic of Bns to reverse probabilities, which allows both top-down and bottom-up belief propagation, supports their application for both backcasting and forecasting studies.

5.3.2 Cross-sectoral planning

Developing of the conceptual model highlighted the need for an in depth understanding of the decision process and local context. Three interconnected decisions and three organisational perspectives provided the basis for the conceptual model. The model effectively represents the causal relationships influencing a multi-organisational decision process and inter-dependency between the MoEW's, MoE's and SVs decisions Although each decision could, in practice, be modelled individually, modelling the decisions as a decision stream is interesting because it prompts the user to question the role of the three organisations (i.e. MoEW, MoE, and SV) in WDM implementation and raises questions about who pays for WDM.

An aim of the field work described in Chapters 4 & 5 was to determine whether the collaborative decision process described by practitioners during the knowledge elicitation could be modelled using Bns. The results indicate that the combination of chance, decision and utility nodes can be used to model decision processes that involve decisions made by multiple organisations.

5.3.3 Developing the evidence-base for WDM legislation

The data collection for the conceptual model demonstrates a number of ways in which Bn model development facilitates the development of an evidence-base and management of uncertainty for water savings and WDM costs.

Knowledge elicitation can be used but requires careful planning and evaluation. Water demand needs to be disaggregated into separate components (e.g. see Figure 4.10 in Chapter 4) and potential water saving allocated accordingly, rather than using aggregate demands. Local reports provide a further potential source of data and, if not available, once demand has been disaggregated into components, reports from WDM programmes in other regions can be used to construct and populate CPTs.

Further options for forecasting water savings are presented in Chapter 6 using increasingly data intensive methods including: knowledge elicitation, survey data and household metered demand data, to forecast water saving potential at the neighbourhood scale.

Developing methods for eliciting and calculating utility functions in Influence Diagrams (IDs) was not addressed in the case study field work and is an area that will need to be addresses if Bayesian modelling is to be used to inform policy decisions. The issue of the measuring the economics of conserving water is discussed briefly in the following section.

5.3.4 Estimating utility functions in Influence Diagrams

Water conservation results in several potential socio-economic and environmental benefits that are experienced in different ways at different scales and at different moments in time. For example, it contributes to a community's resilience to drought conditions but as Bruneau *et al* (2003) point out, quantifying the benefits associated with building resilience into social, economic, and environmental systems continues to elude economists.

The European Union assert that the 'full costs' of water should be considered when making water allocation decisions. The different components of full costs are shown in Figure 5.7 below. The incremental build up of full costs is described in Appendix Q.

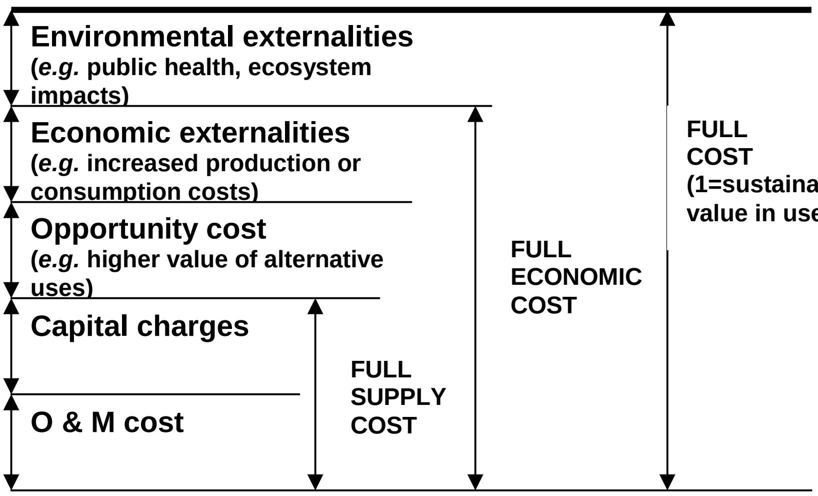


Figure 5.7. *General water costs and value definitions (after Rogers, 1998)*

The difficulty in quantifying benefits from conserving water will have an affect on how Influence Diagrams can be applied to support WDM implementation. Evaluation of the use of IDs and testing of different methods for eliciting utilities are identified as areas for future work in Chapter 9.

The following section discusses how Bns addressed structural uncertainties in modelling WDM legislation in the Upper Iskar.

5.3.5 Addressing structural uncertainties in the planning process

Structural uncertainties encountered during development of the conceptual model for the legislation stage arose from the initial lack of knowledge about uncertainties in cause-effect relationships and the mechanisms by which policy mechanisms impact on these. Each cause-effect relationship required analysis of uncertainty so as to determine its candidacy for inclusions in the conceptual model.

The information flow requirements in Bns, i.e. decisions must be linearly-ordered so that there must be a path that contains all decision, determined how the conceptual model of WDM legislation in Sofia was structured and presented in two ways

Limitations of modelling feedback loops with Bns raises constraints in using them for forecasting the impact of different WDM programmes on future reservoir levels. Knowledge elicitation and analytical approaches more suitable for hydrological modelling (e.g. System Dynamics) may provide a solution to support the development conditional probability tables and more detailed forecasts.

Secondly, the requirement to linearly-order decision nodes means that utilities for each separate decision are aggregated into the next decision node and the result can only be evaluated by the user once all the decision nodes have been instantiated. This characteristic of Bns may constrain the applicability of Bns in some cases, for example, if the decision involves feedback cycles. For the decision process represented in the conceptual model in Chapter 5, however, a sequential modelling approach using chance, decision and utility nodes, appears to work well and successfully captures the interconnected nature of the three decisions being addressed as well as the uncertainty and risk inherent in the indicator variables (e.g. metered demand, reservoir volumes, pay-back period). The utilities are determined by the reservoir level forecast (security of water supplies) and the cost and benefits of the WDM from the perspective of the water company.

Deciding on the position of arrows and their direction in a Bayesian network depends upon information flows, not physical flows. Achieving a model structure that conformed to the rules of information flows to achieve the logical cause-effect relationships required for the Sofia case involved numerous iteration and versions.

The value of the conceptual model as an artefact of the decision process can be considered as a viable output of the research that supports dissemination of knowledge. Examples of how the conceptual model could support structuring and prioritisation of data collection for WDM legislation in other river basin are given below.

5.3.6 *Valuing the Bns as a dissemination tool*

Firstly, development of the conceptual model identified the discretionary (outdoor summer) demand to total demand ratio as a useful and accessible indicator of (i) the feasibility of using seasonal pricing as part of a WDM programme (ii) the capacity for reducing water demand in the short-term using other measures to reduce outdoor use.

Secondly, to forecast water savings and their impacts on the water utility revenues, domestic demand requires disaggregation into different components (e.g. in the Sofia case these were: unaccounted for Water (UfW) and metered demand). These two components may be subject to further disaggregation, as shown in Figure 4.10 in Chapter 4.

A third transferable lesson is that, from the perspective of the water company, the payback period for WDM measures will always be determined by its variable operating costs which are composed of: energy costs, chemical costs, and raw water costs. The ratio of these components will vary for different regions. For example, the city of Sofia receives most (80%) of its water from the surrounding mountains so the Sofia water supply network is mainly gravity-fed, and this is the cause of very low energy costs. However, water companies who have large groundwater resources will have proportionally higher energy costs because pumping groundwater is more energy intensive than a gravity-fed system. Such regional characteristics change the proportion of variable operating cost components and, therefore, affect the payback period and economic feasibility of WDM measures.

The demonstration of the use of Bayesian networks in Chapters 4 & 5 provides evidence that Bns are suitable as a tool for recording examples of approaches to water management. Evaluation of the perceived effectiveness of Bns as a communication tool is reported in Chapter 7. If Bns can be applied effectively to communicate water demand management issues to a wider policy audience then it will provide evidence for their candidacy as a tool for disseminating knowledge to support WDM implementation between river basins. If used in this way they would provide a valuable secondary resource to facilitate the process of change required to achieve the demand-side ambitions of IWRM.

5.4 Conclusions

Development of the conceptual model in Chapter 5 provided evidence to examine three research questions, and the results are reported below in terms of strengths and weaknesses of the Bayesian approach.

Research question 3: How does Bayesian network modelling provide support for developing preparedness strategies?

For development of preparedness strategies, a strength of Bns demonstrated in Chapter 5, Figure 5.2, is the use of forward and backward propagation of conditional probabilities. This allows Bn models to be used to support both forecasting and backcasting studies. However, to avoid misunderstanding or discussions becoming unfocussed, the objective of the model needs to be clearly stated during the early stages of model development.

Once the network has been constructed, model instantiation makes it possible to quickly evaluate the impact of a range of future scenarios. This, along with their visual representation, which makes it easy for the user to gain a quick understanding of how the system works, makes Bns a potentially valuable too for supporting development of preparedness strategies.

Weaknesses of using the Bn approach for supporting preparedness strategies identified from model development are that although modelling over time-steps is possible with Bns, it increases model complexity. If the length of a time-step needs to be changed, all cpts in the model need to re-specified, which can be very time-consuming, and former research (Jensen, 2001) recommends that for modelling over multiple time-steps, the Bn model for each time-step should only include a minimum number of nodes (e.g. 3-5).

Research question 4: How does Bayesian network modelling provide support for decisions involving multiple organisations?

Bayesian modelling, and specifically Influence Diagrams (IDs), were demonstrated to provide potentially useful characteristics for supporting decisions involving multiple organisations. The ID in Figure 5.2 effectively represents the causal relationships and inter-dependency in a multi-organisational decision process involving three interconnected decisions. The sequential structure of IDs together with a suitable model instantiation procedure allows the user to see how each policy mechanism effectively determines who pays for demand reduction. In addition, the visual representation in Bns makes it easy to demonstrate how a system functions.

Weaknesses of using Bns for decisions involving more than one organisation include the complexity of modelling over more than one time-step already mentioned above. Also, finding sufficient data to quantify links between different disciplines, for example, when trying to place an economic value on water availability for human needs and in the environment, can be constraining when constructing a large Bn. However, this is a universal problem for all interdisciplinary approaches, and can be helped by networks being well documented.

Research question 5: How does Bayesian network modelling address issues of structural uncertainty in the planning process?

Using Bayesian networks, it is easy to demonstrate the way in which a system functions through the use of nodes and directed links. This is relevant not only to physical flows, as demonstrated in the water balance model in Figure 4.1, but also to information flow as demonstrated in the conceptual model in Figure 5.2. The Bn model in Figure 5.2 is valuable as an artefact of the WDM implementation process. It is a viable output of the research that supports dissemination of knowledge about indicators and cause-effect relationships between them, to guide implementation of demand management strategies in other river basins. Once populated, parameter sensitivity analysis allows each cause-effect relationship in a prior model to be analysed for uncertainty so as to determine its candidacy for inclusions in the final model.

A weakness identified relating to research question 5 is that in large networks there is a danger of having too much information to take in and an instantiation procedure is therefore required in order to avoid subsequent analysis becoming unfocussed.

5.4.1 Recommendations for water demand management in the Upper Iskar

Construction of the conceptual model answered questions about the required timing of WDM implementation in Sofia. Data collected to support construction of the conceptual model indicated that a long-term planning approach to WDM is advisable in the Upper Iskar and Sofia case because measures such as seasonal (conservation) pricing and outdoor restrictions, which are usually used to achieve short-term savings, will have little impact on total demand in the Sofia case.

Although it was not possible to elicit conditional probabilities and utilities for the LAC nodes with informed practitioners within the time constraints of the case study field work, initial analysis revealed that the pay-back period for different options will be relatively long (i.e. greater than 25 years) and that the most cost-effective options (i.e. those with a shorter payback period) that should be considered in the first instance are pressure reduction and repair of the existing network, to reduce unaccounted for water (UfW).

Conclusions from constructing the conceptual model indicate that a risk management approach, involving long-term WDM measures with low-pay-back periods such as pressure reduction, repair of faulty pipes, and regulatory measures including a reduction in new-build design norms, should be introduced immediately in Sofia. Introducing an efficiency standard on household water appliances to improve coverage of water saving technology is a further option that should be considered for immediate introduction and evidence was collected during a household survey to model the potential impact of such a policy and is presented in Chapter 6.

During the knowledge elicitation reported in Chapter 3 the need to develop an evidence-base for WDM programme design was identified as a constraint to achieving commitment to full-scale demand-side management. The constraint arises from the uncertainty of impacts of WDM measures that raises risks as to the feasibility of making investments in WDM. Furthermore, pilot studies are required and these can be costly in themselves. The use of Bns in addressing this and other issues relating to uncertainty about programme impacts at the design stage is examined in Chapter 6.

Chapter 6

Technical evaluation 2: Bayesian networks are used to support water conservation programme design

Introduction

The importance of evaluating water conservation programmes has been emphasized in research by Turner *et al*. (2005; 2007), and experience from Australia shows that poorly-planned water conservation programmes are not without risk for water companies due to potential incurred costs. For example, if a severe drought occurs, the water company may opt for blanket distribution of water saving appliances resulting in inefficient implementation and high costs per m^3 saved which can be detrimental to the image of water conservation (Turner *et al*., 2007).

The lack of an evidence-base of potential impacts of water conservation measures was identified as a constraint to WDM implementation in Sofia during the knowledge elicitation. Chapter 6, below, examines the use of Bayesian networks for facilitating *in situ* design of WDM programmes, and prior- and post programme evaluation, which includes evaluation of implementation conditions.

The distinction between the *legislation* and *design* stages of water demand management (WDM) implementation was emphasized in Chapter 1. During the design stage the organisations responsible for WDM implementation, i.e. the water utility, local authorities, environment agencies etc., must decide how the demand reduction requirements identified during the legislation stage can be most efficiently achieved using the WDM options specified. This requires further data collection, usually achieved through small scale pilot studies and surveys of citizens attitudes and perceptions (Trumbo & O'Keefe, 2005; Barr & Gilg, 2005) towards water conservation issues, to understand the most effective (i.e. efficient, equitable, sustainable) way to achieve those water savings.

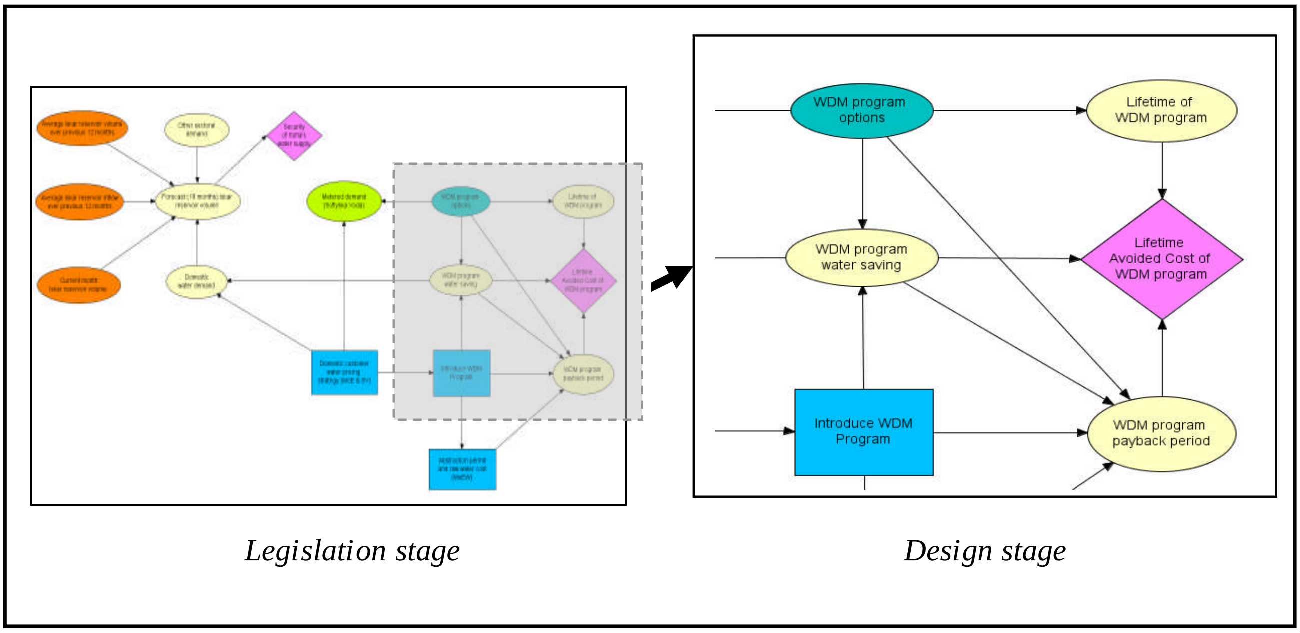


Figure 6.1. *Water conservation programme design addresses uncertainty about implementation conditions*

To demonstrate the link between legislation and water conservation programme design Figure 6.1 (above) shows the economic evaluation components of the conceptual model described in Chapter 5. One of the aims of efficient implementation is to improve the cost per m^3 saved, represented in the WDM programme payback period in Figure 6.1.

As described in Chapter 1, water conservation programmes need to incorporate two basic elements: a *measure* and an *instrument*. A measure is 'what to do' (e.g. increase coverage of water saving appliances) and an instrument is 'how to do it'. To understand how Bns could be used to model the conditionality between implementation conditions and effectiveness of water conservation measures, four models were developed using household survey data collected in Sofia. The issues explored by the four models are summarised in Table 6.1, below.

6.1 Household survey

6.1.1 Survey design

The household survey involved the collection of data using closed (multiple-choice) and open-ended questions. Responses were used to generate conditional probabilities in the four models described in Sections 6.2 to 6.5. The survey elicited information from householders about their household characteristics and demographic indicators as metrics of water demand (i.e. household type, garden, number of occupants, income, perceptions of pressure). The survey also explored householder's perceptions and their behaviour regarding water conservation. To examine citizen's behaviour the Theory of Planned Behaviour (Ajzen, 1991), described below, was used as a prior model structure to inform the content of questions to elicit responses suitable for analysis of constraints, drivers, perceptions, and awareness of water use.

Table 6.1. *Water conservation programme design models*

MODEL NAME	ISSUES ADDRESSED
Behavioural dependencies model (Section 6.2)	▪ Understanding constraints to and drivers of water conservation behaviour
Programme participation forecasting model (Section 6.3)	▪ Forecasting uptake potential at the neighbourhoods scale for different water saving options
Single household water demand and water savings model (Section 6.4)	▪ Forecasting water demand in single households ▪ Forecasting water saving potential in single households ▪ Identifying classes of household with high water saving potential
Model of indicators of high water saving potential (Section 6.5)	▪ Identifying indicators of 'favourable' and 'unfavourable' implementation conditions for introduction of different water saving measures ▪ Estimating the value of carrying out tests prior to implementation

6.1.2 Interviewers

Seven English speaking under-graduate students from Sofia University were trained in household survey interviewing techniques during a one day workshop held in Sofia. Following training the students were involved in piloting the first version of the questionnaire which had been translated into Bulgarian. To check that the meaning in the survey had been maintained during translation, the survey was piloted over two stages, during which each student completed five interviews. Following each piloting stage feedback from the students regarding each question was used to verify, and if necessary amend, the survey. The final (English) version of the Sofia household survey is shown in Appendix R.

6.1.3 Sampling

The students interviewed householders in their places of work and 540 questionnaires were completed. Interviewees were identified by word of mouth, an approach, known as snowball sampling (Rossi *et al*., 1993). An advantage of snow-ball sampling is that it can be cost-effective although it does not provide the researcher control over the profile of respondents.

Of the 540 householders who completed the questionnaire, 343 householders (60%) gave their household income band. The frequency for different income bands among this group was: 37% 'less that 6000 LEV per year', 58% '6000-25000 LEV per year', 5% over '25000 LEV per year'. 82% of respondents lived in multi-family apartments, and the remaining 18% lived in single-households. Other details of the sample including a frequency histogram for household occupancies and existing water saving technology are presented in Appendix M.

The following section describes development and results of the behavioural dependencies model.

6.2 Behavioural dependencies model

The aim of the behavioural dependencies model was to examine constraints to- and drivers of- water conservation behaviour in Sofia. The Theory of Planned Behaviour, Figure 6.2, was used as a theoretical model on which to base questions and response options, which were then used to populate the model.

6.2.1 Method: The Theory of Planned Behaviour

Former research into how awareness and financial incentives drive certain behaviour (e.g. waste recycling, domestic and agricultural water conservation), has utilised existing behavioural models as a foundation for exploration.

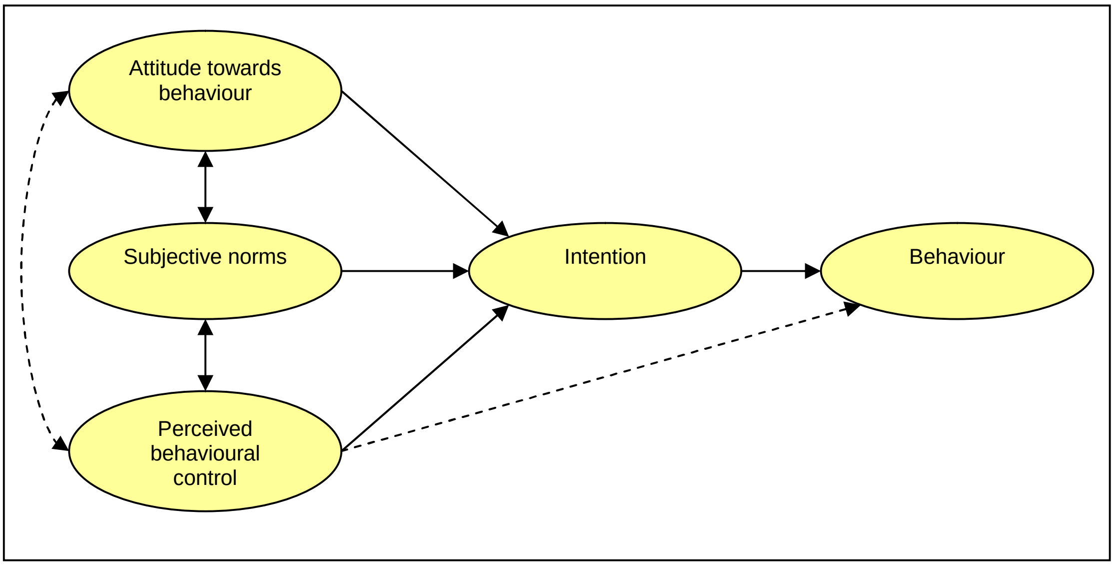


Figure 6.2. *The Theory of Planned Behaviour*

Corral-Verdugo *et al*. (2003) used the NEP–HEP (New Environmental Paradigm – Human Exception Paradigm) scale, developed by Dunlap and Van Liere, to explore resident's attitudes towards water conservation. The Theory of Reasoned Action (Ajzen and Fishbein, 1980) was recently used by researchers exploring domestic water conservation in the USA (Trumbo and O'Keefe, 2005) and waste recycling in the UK (Barr and Gilg, 2005) and results informed policy development in both cases.

The Theory of Planned Behaviour has been used by Lynne *et al*. (1995) to explore farmer's attitudes to water conservation. It distinguishes between three types of beliefs: control, normative and behavioural (Ajzen, 1991). It is an extension of the Theory of Reasoned Action (Ajzen and Fishbein, 1980) made necessary by the original model's limitations in dealing with behaviours over which people have incomplete volitional control. Figure 6.2 (above) depicts the theory in the form of a structural diagram. As in the original theory of reasoned action, a central factor in the Theory of Planned Behaviour is the individual's intention to perform a given behaviour. Intentions are assumed to capture the motivational factors that influence a behaviour; they are indications of how hard people are willing to try, or how much of an effort they are planning to exert in order to perform the behaviour (Ajzen, 1991).

Perceived behavioural control is defined by Ajzen (1991) as "a person's belief as to how easy or difficult performance of the behaviour is likely to be". According to the Theory of Planned Behaviour, among the beliefs that ultimately determine intention and action is a set that deals with the presence or absence of requisite resources and opportunities. The more resources and opportunities individuals think they possess, and the fewer obstacles or impediments they anticipate, the greater should be their perceived control over the behaviour. These beliefs about behavioural control may be based in part on past experience with the behaviour, but they will usually also be influences by second-hand information about the behaviour, by experiences of acquaintances and friends, and by other factors that increase or reduce the perceived difficulty of performing the behaviour in question (Ajzen & Madden, 1986).

The importance of actual behavioural control is self-evident. However, when the Theory of Planned Behaviour was at an early stage of development Ajzen and Madden (1986) raised the point that it is often very difficult to secure an adequate measure of actual control in advance of observing behaviour. They state the reason for this being that many of the factors that can prevent execution of an intended action are accidental in nature and can, by definition, not be anticipated. Nevertheless, further research, which used the Theory of Planned Behaviour, reported by Ajzen (1991) found that "…when the behaviour/situation affords a person complete control over behavioural performance, intentions alone should be sufficient to predict behaviour, as specified by the Theory of Reasoned Action. The addition of perceived behavioural control should become increasingly useful as volitional control over behaviour declines. Both intentions and perceptions of behavioural control can make significant contributions to the prediction of behaviour, but in any given application, one may be more important than the other and, in fact, only one of the two predictors may be needed".

The household survey explored citizen's attitudes, perceived behavioural control, subjective norms, intentions and behaviour towards water saving appliances using questions C2, C3, C5, C7 and A7 in the household survey (Appendix R) and responses were used to develop the Behavioural dependencies model.

6.2.2 Results

Responses to questions C2, C3, C5, C7 and A7 in the household survey were analysed for data dependences using the Hugin software Necessary Path Conditions (NPC) learning algorithm (Steck, 1998) and the data dependencies given different significant thresholds are shown in Figure 6.3, below. A screenshot of the spreadsheet containing responses to the household surveys is also shown in the top right-hand corner of Figure 6.3. Data dependencies, shown in Figure 6.3, found in the

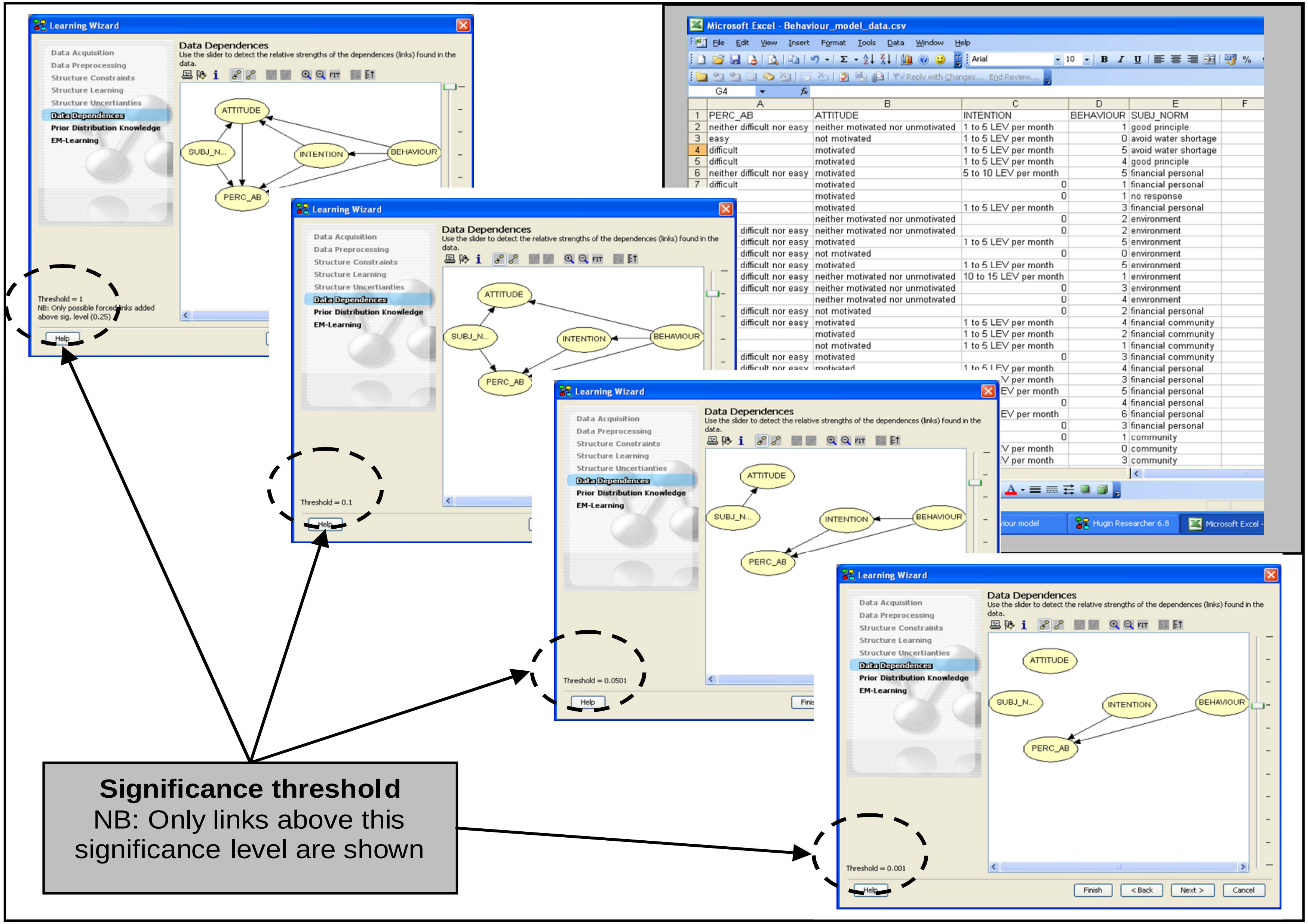
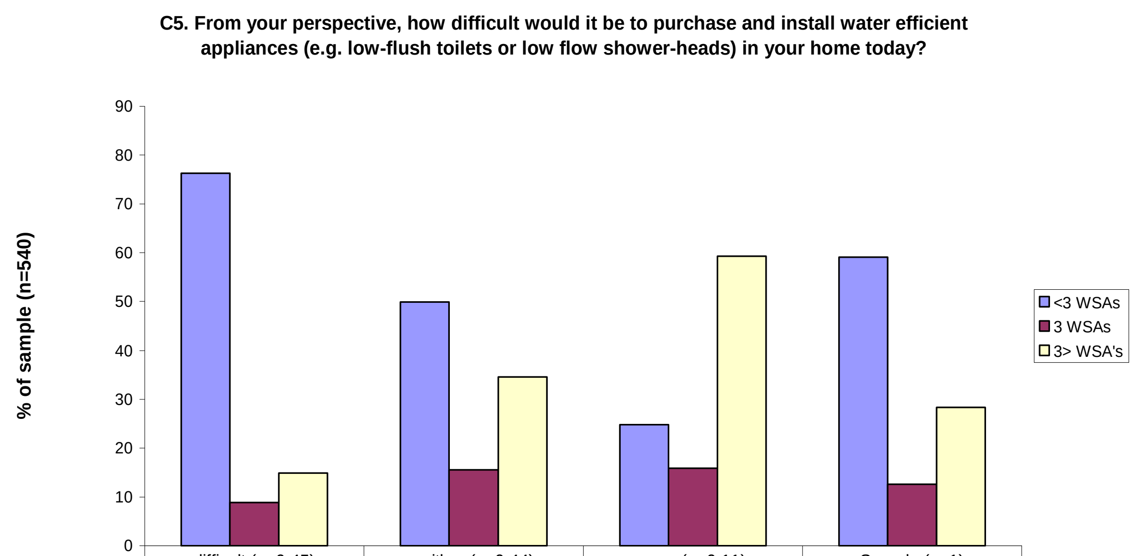


Figure 6.3. *Data dependencies between variables in the behavioural model at different significant thresholds. A screenshot of the spreadsheet database of responses from the 540 social surveys is shown in the top right-hand corner.*

household survey data indicate that for citizens of Sofia: (i) *Behaviour related to water conservation technology in the Sofia case corresponds to the Theory of Planned Behaviour* and (ii) *Perceived behavioural control (pbc) has the strongest influence on intention and behaviour.*

Further analysis involved categorising responses to the question regarding the total number of WSAs into three states: less that 3 WSAs (<3 WSAs), 3 WSAs (3 WSAs) and, more than 3 WSAs (>WSAs). Conditional dependences between variables of the Theory of Planned Behaviour and *behaviour* and p(evidence)-values (i.e. the amount of evidence in the data-set that supports these findings) supporting them, are shown in the histograms in Figure 6.4 (pbc), Figure 6.5 (Intention) and Figure 6.6 (Attitude).

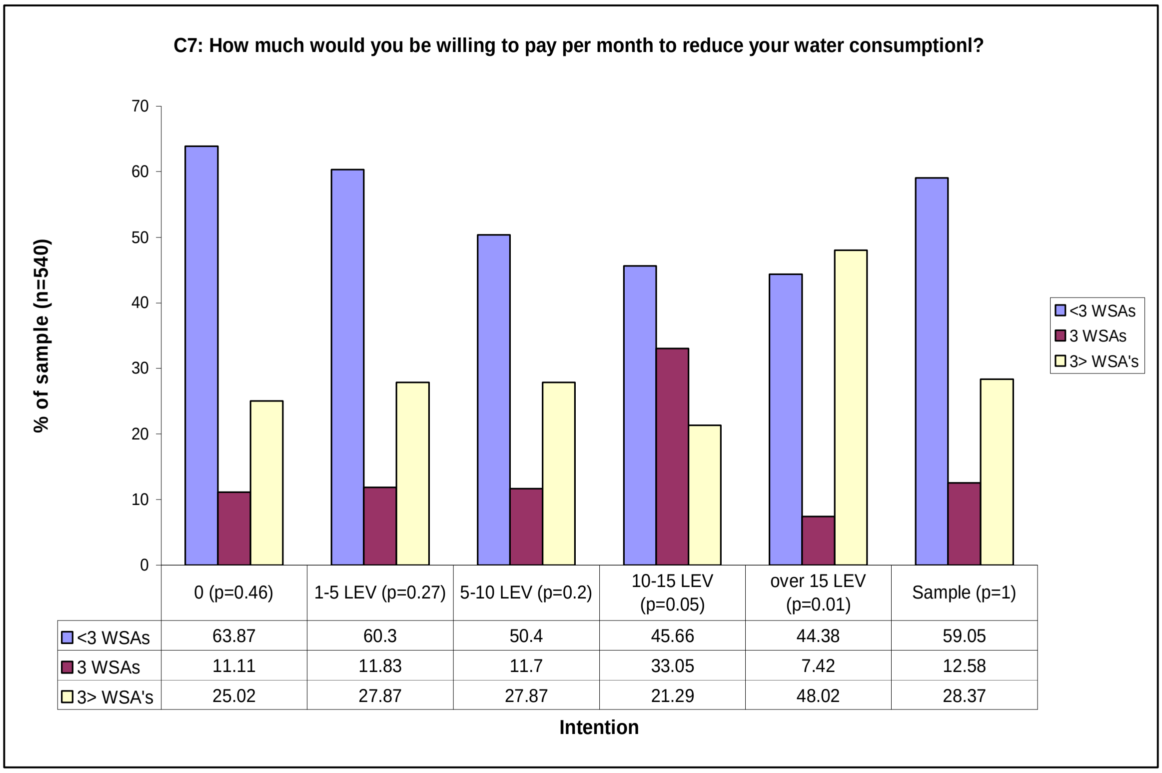
The results show that for the whole sample (*n*=540), 40.95% of respondents had 3 or more WSAs, whilst among survey participants whose response to the question regarding *pbc* was 'easy', 75.18% had 3 or more WSAs installed (*p[evidence]*=0.11). This implies that if people perceive it to be less difficult to install water saving appliance, for example by removing financial and practical constraints (e.g. time and inconvenience for installation), coverage of WSAs could be increase by as much as 35%.



	difficult (p=0.45)	neither (p=0.44)	easy (p=0.11)	Sample (p=1)
<3 WSAs	76.28	49.87	24.81	59.05
3 WSAs	8.84	15.57	15.9	12.58
3> WSA's	14.9	34.57	59.29	28.37

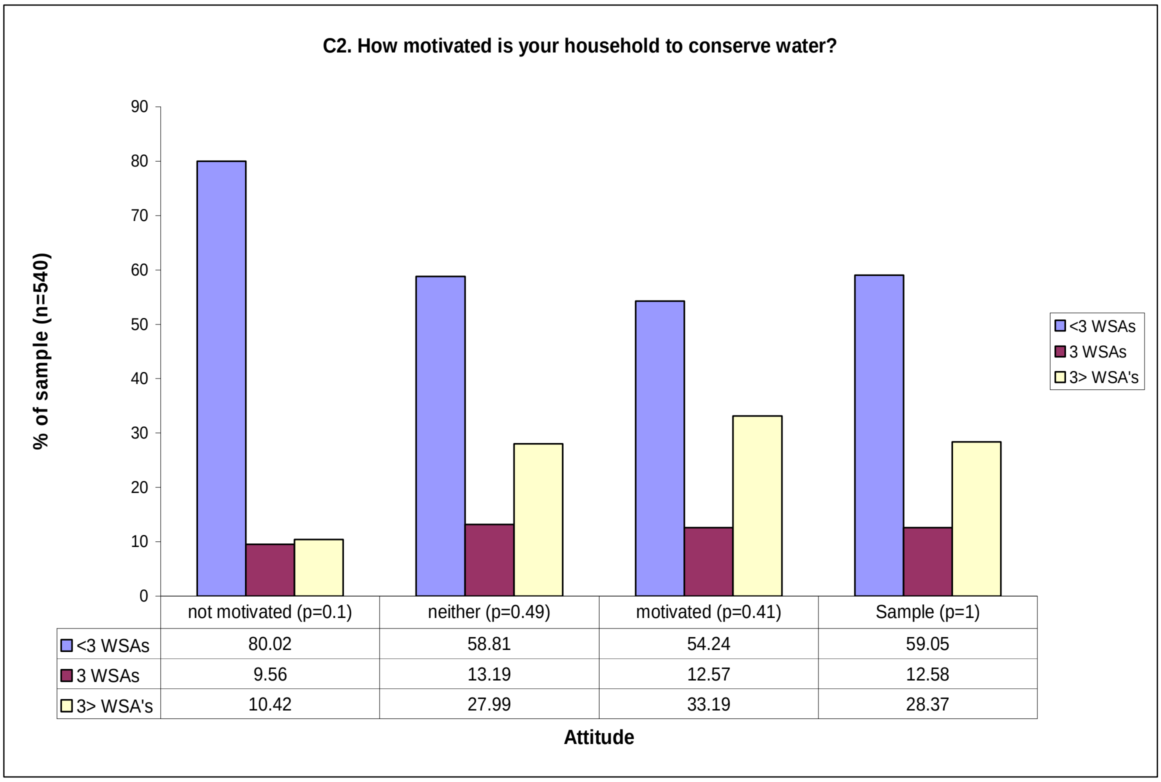
Perceived behavioural control

Figure 6.4. *Perceived behavioural control vs. Behaviour indicated by number of water saving appliances (WSAs) installed in household*



	0 (p=0.46)	1-5 LEV (p=0.27)	5-10 LEV (p=0.2)	10-15 LEV (p=0.05)	over 15 LEV (p=0.01)	Sample (p=1)
<3 WSAs	63.87	60.3	50.4	45.66	44.38	59.05
3 WSAs	11.11	11.83	11.7	33.05	7.42	12.58
3> WSA's	25.02	27.87	27.87	21.29	48.02	28.37

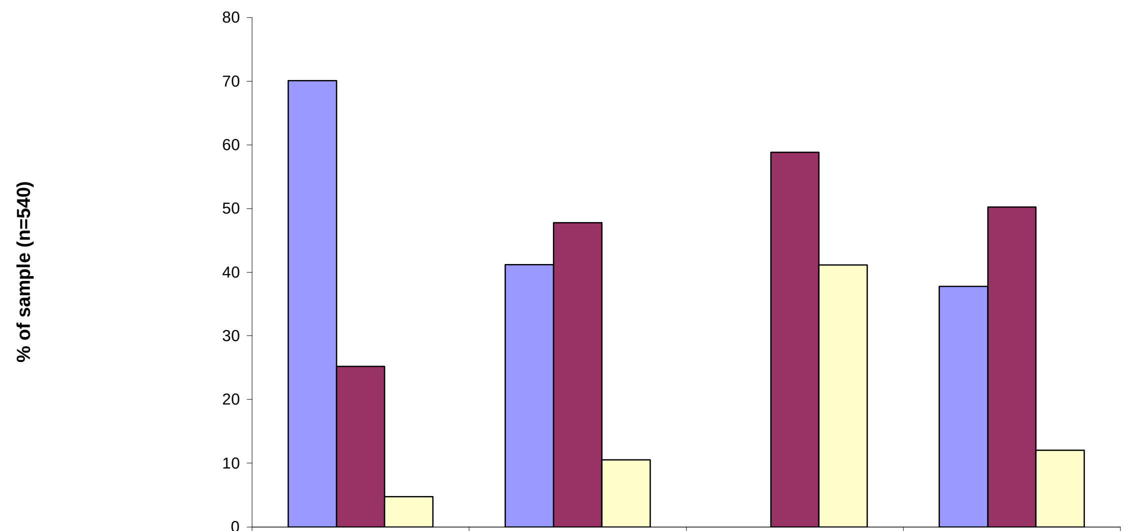
Figure 6.5. *Intention vs. Behaviour indicated by number of water saving appliances (WSAs) installed in household*



	not motivated (p=0.1)	neither (p=0.49)	motivated (p=0.41)	Sample (p=1)
<3 WSAs	80.02	58.81	54.24	59.05
3 WSAs	9.56	13.19	12.57	12.58
3> WSA's	10.42	27.99	33.19	28.37

Figure 6.6. *Attitude vs. Behaviour indicated by number of water saving appliances (WSAs) installed in household*

Analysis of ‘subjective norms’ showed that there was an emphasis on financial reasons for installing WSAs. It was considered that this might infer that *pbc* would vary for different income groups so a version of the model comparing *pbc* and *behaviour* for different income groups was developed and the results are shown in Figure 6.7, below.



	Low income (p=0.22)	Middle income (p=0.35)	High income (p=0.03)	No response (p=0.40)
Difficult	70.08	41.21	0	37.77
Neither difficult nor easy	25.2	47.74	58.82	50.21
Easy	4.72	10.56	41.17	12.02

Figure 6.7. *Distribution of responses for perceived behavioural control among different incomes.*

The above findings indicate that behaviour relating to the adoption of water conservation technology among Sofia’s citizens is characterised by low volitional control, especially among low incomes, and that external assistance is required to improve participation and achieve wider coverage.

To better understand drivers and constraints of water use behaviour a question (C6, Appendix R) was included in the household survey concerning constraints to specific water conservation measures that were mentioned by informed practitioners during the knowledge elicitation. This was an open-ended question and responses regarding constraints for different measures were categorised during the processing of results. The categories for different measures and the distribution of responses are shown in Figure 6.8.

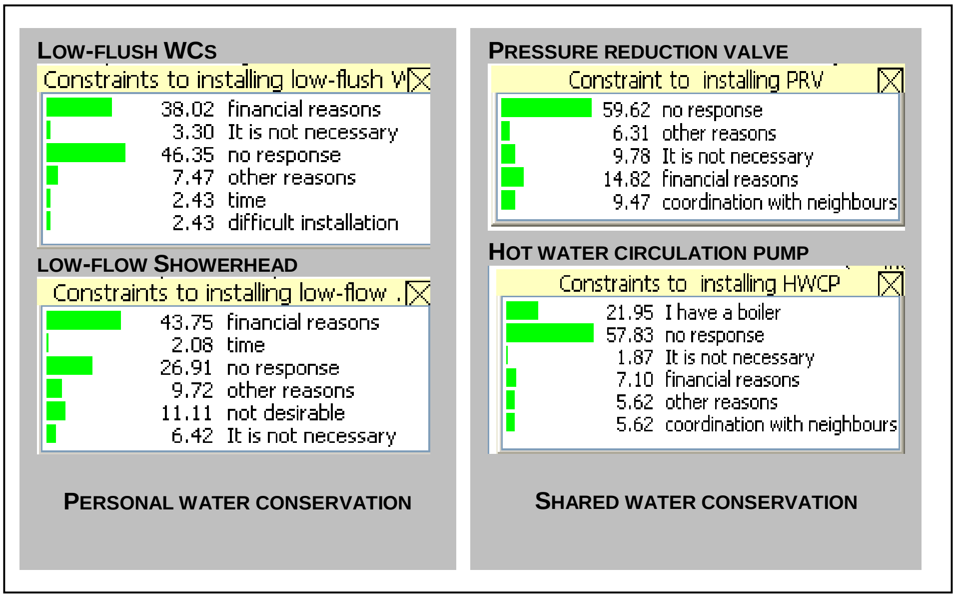


Figure 6.8. *Constraints to introducing specific water conservation measures*[1]

A number of technical constraints to introducing shared water conservation options that were mentioned (e.g. householder having their own boiler for the installation of an HWCP) are shown in Figure 6.8, above. Where the respondent answered 'it is not necessary' for installing pressure reducing valves, this was found to be linked to the existing pressure not being 'too high' (C11, Appendix R). By far the most commonly mentioned constraint, especially for personal water conservation measures, was 'financial reasons'.

The resting state of the behavioural dependencies model was interesting because it showed the frequencies of responses for the sample (n = 540). 26% of people stated that they did not have any water efficient devices. Only 10% of respondents, however, considered it to be 'easy' to purchase or install water saving devices.

Constraints: 'Other reasons' for each option include categories containing less than 2% of the sample. They were as follows:
Other reasons HWCP: Lack of incentive, rented property, lack of information, not desirable, not aware
Other reasons PRV: Time, lack of incentive, technical constraints, rented property, lack of information, not desirable, not required, not aware, not available, low pressure already, water company responsible
Other reasons low-flow shower: lack of information, lack of incentive, rented property, difficult installation, high energy
Other reasons low-flush WC: Not aware, Lack of information, New toilet just installed, Last one broke

Ten percent of respondents stated that they were not motivated to save water. 46% of respondents, however, stated that they would not be willing to make a financial investment in water saving unless there was a financial saving, but this figure dropped to 18% when respondents were told that a 30% saving would be possible on their water bill, supporting the finding that financial reasons are the most important driver of adopting water saving appliances.

The following two sections (Section 6.3 & 6.4) report how Bn models populated with household survey responses were used to describe implementation conditions for introduction of water conservation technology. The idea of the models is that favourable implementation conditions are dependent on per household water saving and uptake potential. For a given population, implementation conditions are described in Bn models using a combination of household characteristics, intention to participate in the programme, and the existing market coverage.

6.3 Forecasting impacts of instruments on programme participation

To understand more clearly why people install water saving appliances in their households, the household survey asked citizens whether each water appliance in their house was a water saving model, whether they had replaced it in the last five years, and what was their reason for replacing their old appliance (A8, Appendix R). The results are used in the forecasting model developed below.

In the following section a method for describing implementation conditions using the uptake potential at the neighbourhood scale using Bns populated with household survey data is described.

6.3.1 Method: components of the 'total market'

Knowledge of the existing coverage of water saving appliances in a neighbourhood is useful because it allows water conservation managers to estimate the remaining households that can potentially participate in a programme.

Weber (1993) suggests that calculation of the 'total market' for a water conservation programme aimed at replacing non-efficient household appliances with efficient models can use the components shown in Box 6.1 (below).

Box 6.1. Components used in calculating the total market for a water conservation programme (Weber, 1993)

Potential market: This is the total population or number of households in a region. Applicable market: Those customers or households who possibly could be affected by the measure. It excludes customers who already employ the measure. In the model, Figure 6.9, the Applicable market includes:

1. All households who answered 'no' to the question: is your water appliance a water efficient model

2. Households who answered 'yes' to is your water appliance a water efficient model but who also answered 'yes' to do you intend to install a new one.

Acceptance rate: this is the portion of the applicable market that will actually fully participate in the conservation measure. This will vary according to the uptake instruments in place. Three different uptake instruments, i.e. efficiency standard, free installation, fully-financed, are represented in the model in Figure 6.9.

Target market: This is the proportion of the applicable market that the user wants to acquire the particular conservation tool. The target market being explored in the model in Figure XX composes of all household with three or more occupants i.e. (>3).

Total market: The total market is defined as the market penetration that results from applying the acceptance rate to the target market. In equation form the total market is the product of a number of participation ratios:

Total market = potential market x applicable market (%) x target market (%) x acceptance rate (%).

The objective of the model in Figure 6.9, below, was to forecast the 'total market' for a specific water conservation measure (low-flush WCs) based on the household survey sample.

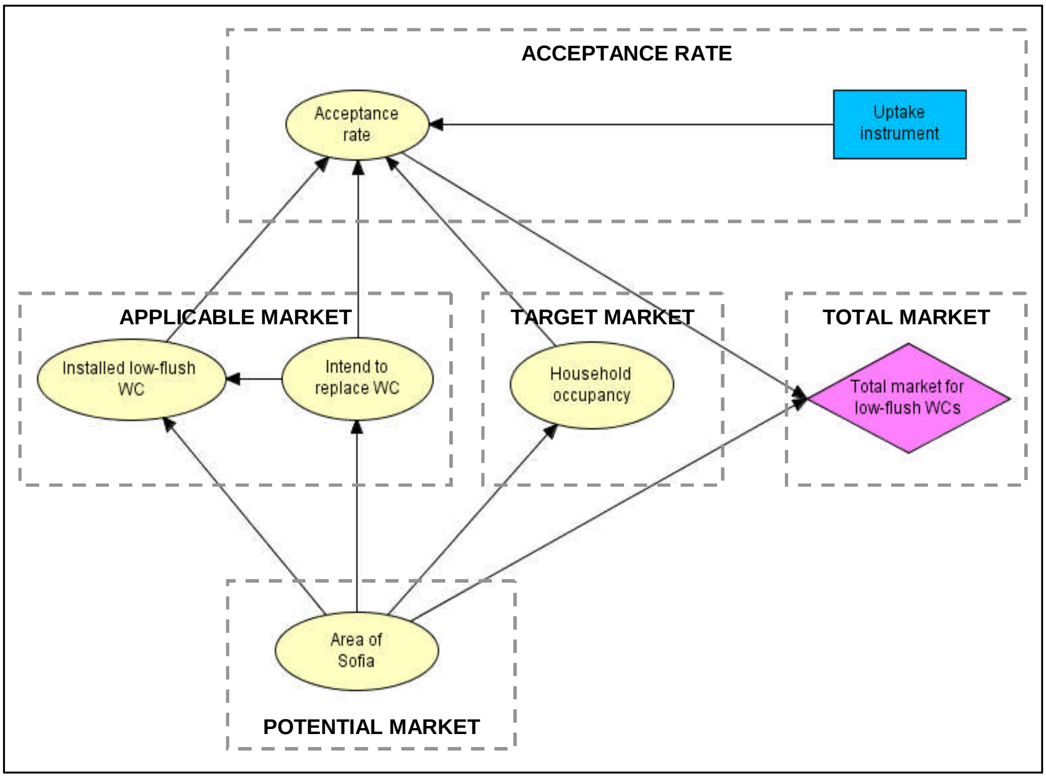


Figure 6.9. *Uptake model showing components of total market*

Responses from the household survey (Appendix R, questions A9, A8, D1) were used to populate the model. For the model shown, the 'target market' includes all households with three or more occupants. The relationship between 'applicable market' and different uptake instruments is described in the 'acceptance rate' node conditional probability table. The only component that requires further data, collected through knowledge elicitation with local experts, is section of the 'acceptance rate' conditional probability table for different instruments. The conditional probabilities for 'acceptance rate' in the version of the model Figure 6.10 (below) are based on estimates from previous studies and are shown in Appendix M0. The 'total market' for low-flush WCs for different neighbourhoods of Sofia using the model in Figure 6.10, are shown in Figure 6.11, below.

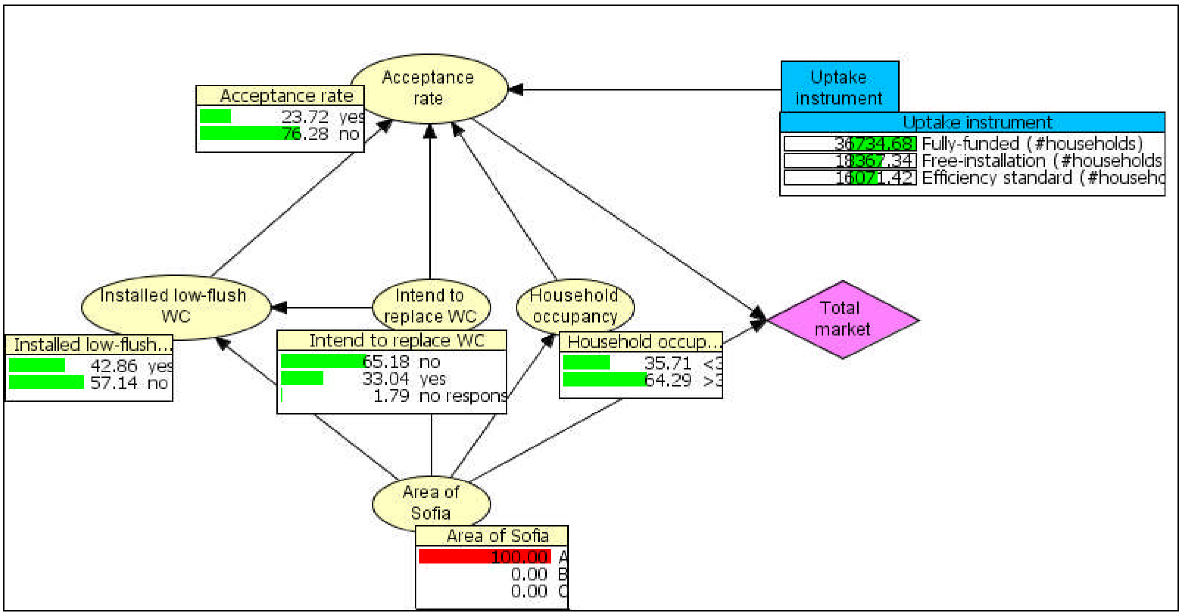


Figure 6.10. *Influence Diagram of Uptake instrument decision*

WDM instrument	AREA OF SOFIA								
	A			B			C		
	Potential market	Total market (pop)	Total market (%)	Potential market	Total market (pop)	Total market (%)	Potential market	Total market (pop)	Total market (%)
Fully-funded	*100,000*	36734	*0.367*	*100,000*	39682	*0.397*	*100,000*	19955	*0.196*
Free-installation	*100,000*	18387	*0.183*	*100,000*	19841	*0.198*	*100,000*	9977	*0.1*
Efficiency standard	*100,000*	16071	*0.161*	*100,000*	17384	*0.174*	*100,000*	7276	*0.073*

Figure 6.11. *'Total market' for low-flush WCs for different areas of Sofia based on different WDM instruments*

The 'target market' needs to be specified prior to constructing the model and the household survey data processed according to the binary states (i.e. household types targeted / household types not targeted) to show that only that specific class of household is being targeted.

The use of the 'total market' approach in Bns demonstrates the importance of using compatible model components to form the model structure. The resulting model structure supports the identification of neighbourhoods with low existing coverage. The 'total market' approach combined with household survey data for the Sofia case addresses a knowledge gap in methods for estimating uptake potential identified in former research (Inman & Jeffrey, 2006). The use of Bns in successfully modelling the total market is promising for their use a support tool to facilitate WDM design.

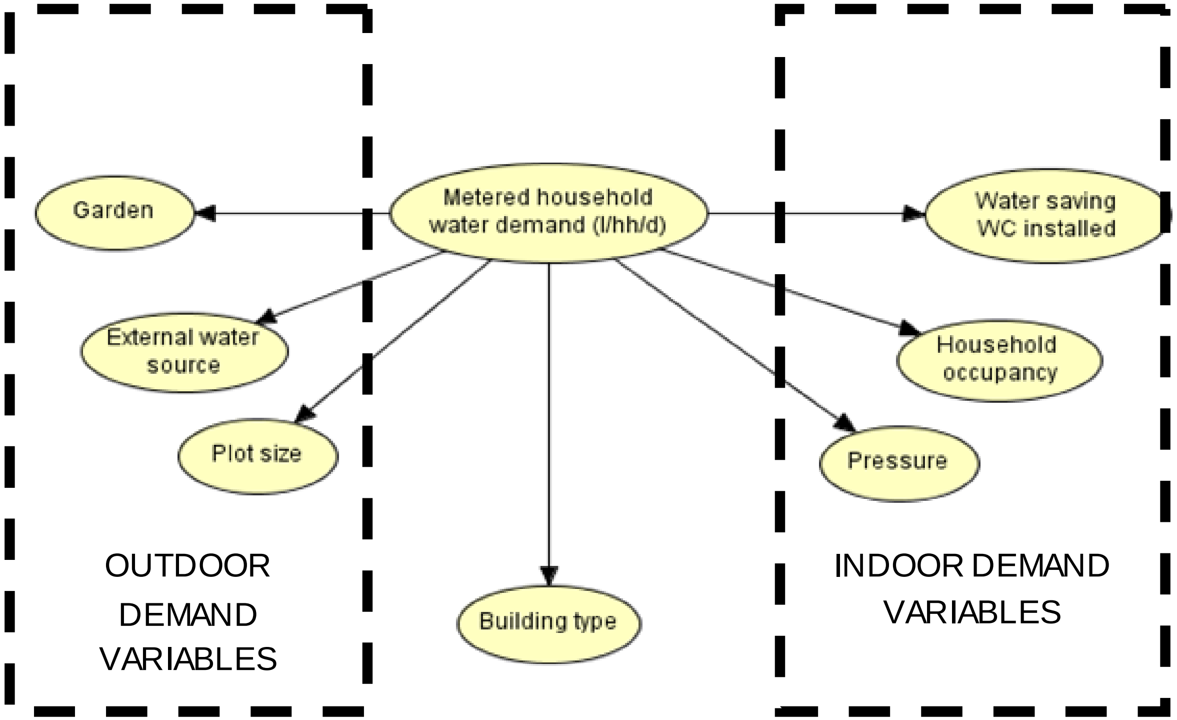
The practical implications are that the current high rate of replacement of household appliances in the Sofia case is an opportunity for achieving increased coverage of water efficient models in households. With the current increase in renovation of old properties and a general increase in affluence in Sofia city a rising replacement rate of household appliances can be expected in the near future. A policy recommendation, therefore, for water conservation programme design is to introduce an efficiency standard on the sale of household water appliances to achieve increased coverage of water saving appliances.

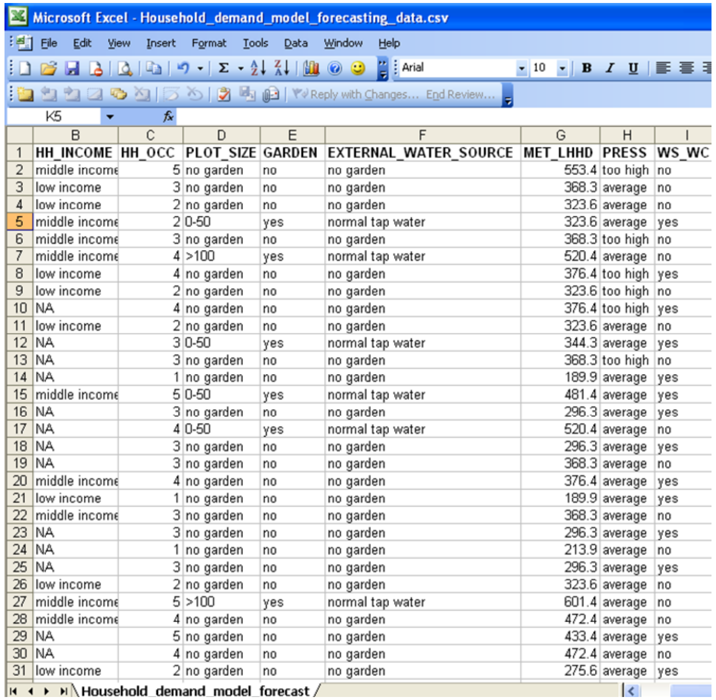
6.4 Forecasting water demand and water savings in individual households

6.4.1 Method: forecasting dependencies between metered use and demand variables

Information for individual household demand variables were collected during the household survey interviews. Metered water demand data was then collected by Sofiyska Voda using personal information provided by interviewees in the social survey. Variables and links included in the probabilistic layer of the forecasting model, showing indoor and outdoor demand variables, are shown in Figure 6.12. A section of the spreadsheet that was used to compute conditional probabilities for the model, showing household survey responses, is also shown.

The water company was able to identify water company accounts for only 40 household out of a possible 200 interviewees who provided their names and addresses. This was a flaw in the research design, specifically in the expectation that it would be possible for the water company to cross-reference the household survey data with metered water demand data using the names and addresses of the interviewee. Future surveys would make use of water company account numbers which would be pre-selected into classes according pre-specified metered demand ranges.





	B	C	D	E	F	G	H	I
1	HH_INCOME	HH_OCC	PLOT_SIZE	GARDEN	EXTERNAL_WATER_SOURCE	MET_LHHD	PRESS	WS_WC
2	middle income	5	no garden	no	no garden	553.4	too high	no
3	low income	3	no garden	no	no garden	368.3	average	no
4	low income	2	no garden	no	no garden	323.6	average	no
5	middle income	2	0-50	yes	normal tap water	323.6	average	yes
6	middle income	3	no garden	no	no garden	368.3	too high	no
7	middle income	4	>100	yes	normal tap water	520.4	average	no
8	low income	4	no garden	no	no garden	376.4	too high	yes
9	low income	2	no garden	no	no garden	323.6	too high	no
10	NA	4	no garden	no	no garden	376.4	too high	yes
11	low income	2	no garden	no	no garden	323.6	average	no
12	NA	3	0-50	yes	normal tap water	344.3	average	yes
13	NA	3	no garden	no	no garden	368.3	too high	no
14	NA	1	no garden	no	no garden	189.9	average	yes
15	middle income	5	0-50	yes	normal tap water	481.4	average	yes
16	NA	3	no garden	no	no garden	296.3	average	yes
17	NA	4	0-50	yes	normal tap water	520.4	average	no
18	NA	3	no garden	no	no garden	296.3	average	yes
19	NA	3	no garden	no	no garden	368.3	average	no
20	middle income	4	no garden	no	no garden	376.4	average	yes
21	low income	1	no garden	no	no garden	189.9	average	yes
22	middle income	3	no garden	no	no garden	368.3	average	no
23	NA	3	no garden	no	no garden	296.3	average	yes
24	NA	1	no garden	no	no garden	213.9	average	no
25	NA	3	no garden	no	no garden	296.3	average	yes
26	low income	2	no garden	no	no garden	323.6	average	no
27	middle income	5	>100	yes	normal tap water	601.4	average	no
28	middle income	4	no garden	no	no garden	472.4	average	no
29	NA	5	no garden	no	no garden	433.4	average	yes
30	NA	4	no garden	no	no garden	472.4	average	no
31	low income	2	no garden	no	no garden	275.6	average	yes

Figure 6.12. *Structure of the probabilistic layer of the forecasting model showing indoor and outdoor water demand variables.*

The interviewee's water company account number would need to be clearly visible on a household survey and sent to citizens by post by the water company. This would ensure that the water company could easily cross-reference returned household surveys with their household metered data, rather than relying on householder's names and addresses which, it turned out, were unreliable criteria for accurately identifying water company accounts.

The quantity of metered data that could be linked to completed surveys was insufficient for developing the forecasting model and led to unacceptable (±30%) confidence intervals (p=<0.05). It was determined, however, that information on variables of household demand that had been collected by Sofiyska Voda could be used to develop a dataset that could then be used to perform structural learning to develop conditional probabilities for the household demand forecasting model.

A study into causes of variable household demand and potential water saving measures and their impacts (WDM Procedure 6 Report, Sofiyska Voda, 2004), completed by researchers at the University of Architecture, Civil Engineering and Geodesy (UACEG) in 2004 on behalf of Sofiyska Voda, as a condition of the EU-ISPA concession agreement provided the majority of information for developing the dataset. The findings in the report that were relevant to developing the household demand forecasting model are described in Appendix O. Based on these findings a dataset of metered demand for the 540 social survey responses was developed in a corresponding column in the spreadsheet containing the household survey data. Using this data-set, structural learning was then used to derive conditional probabilities for the demand forecasting model described below.

6.4.2 Results

The Bn in Figure 6.13, below, shows the resting state conditional probabilities for the demand forecasting model based on the dataset. From a research perspective the resting state conditional probabilities are of interest because reveal how the data in the random sample is distributed between states. Furthermore, by instantiating the model the user can update the distribution for different grouping, for example, comparing

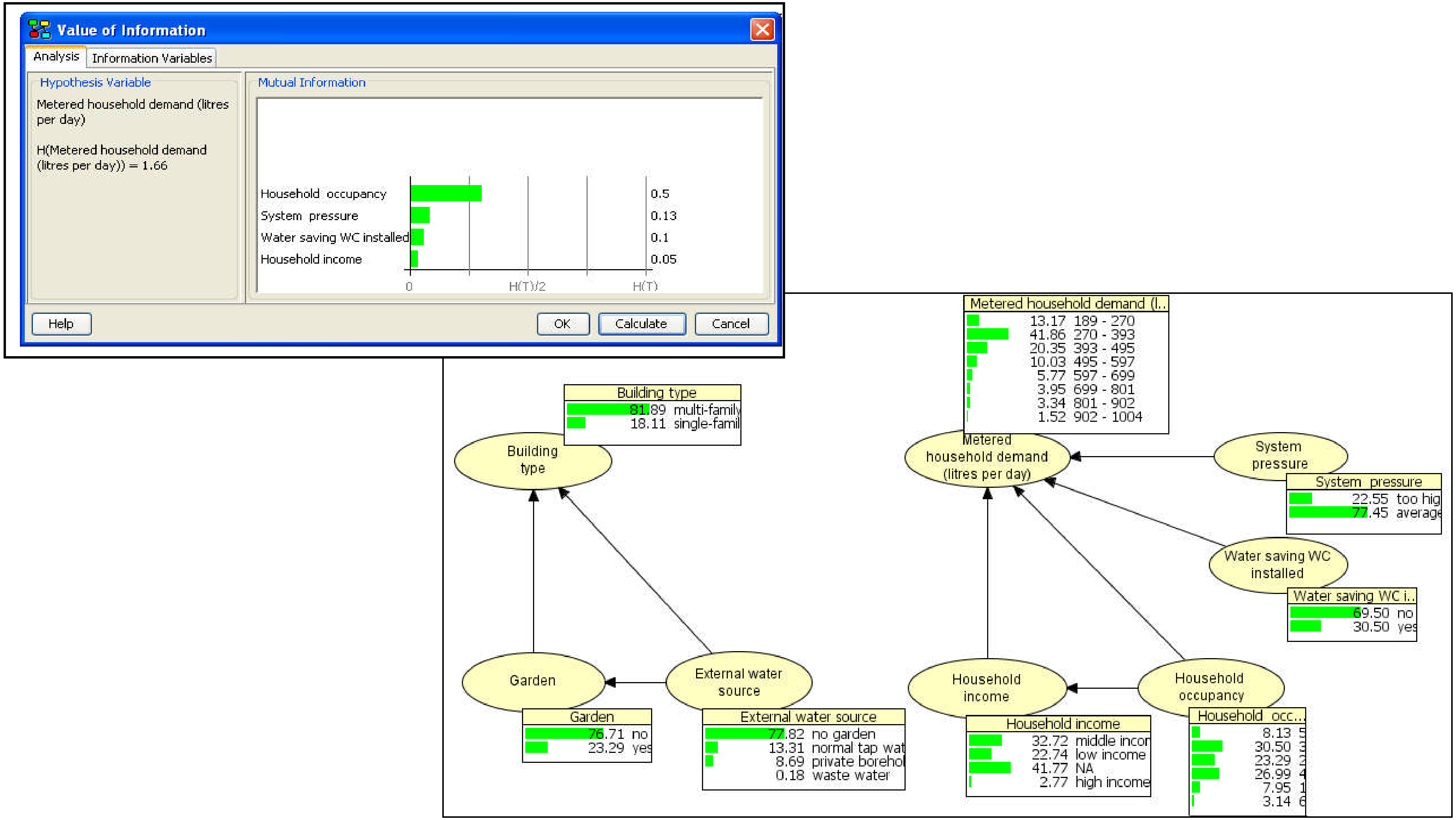


Figure 6.13. *Bayesian network of metered household demand variable, with no evidence, showing only significant links. The dialogue box shows the relative strength of data dependencies.*

occupancy distributions in household with and without water saving WCs or in different household groups. The dialogue box in Figure 6.13 shows the relative strength of data dependencies between metered water demand and indoor demand variables for the data-set.

As the number of demand variables is increased so the parent space for the hypothesis node also increases. As mentioned in Chapter 4 reducing the parent space (determined by the number of child nodes and their states) is desirable to conserve data collection resources. Once the parent space has been reduced (i.e. through parameter sensitivity analysis) a sampling approach can be designed to achieve an equal number of households in each metered household demand range to achieve the required significant levels. As the number of variables (i.e. child nodes) increases, achieving the ideal sample becomes increasingly complex (Rossi *et al*., 1993).

The node labelled metered household demand in Figure 6.13 contains eight states this would imply a sample size of 480 equally distributed among the eight states would achieve required significance levels (i.e. a sample of 60 out of a 100,000 population will give 95% confidence of ± 9.2%). The distribution of household survey responses between different metered demand ranges, as shown in the monitor windows for the node 'metered water demand' in Figure 6.14, was not equal. This was partly due to the snow-ball sampling approach used. The resting state conditional probabilities show that only the first three states in the node labelled metered household demand contain sufficient data to achieve 95% confidence of ± 9.2% and further data collection would be required to achieve the required significance levels for all states in the model. Alternatively missing data can be provided using expert knowledge, and in this way Bns provide method for combining data to address sampling problems.

The above model was applied by informed practitioners during the end-user evaluation, described in Chapter 6, where they used the model to forecast demand and compared the results to a small data-set where actual metered data had been collected.

6.4.3 Household water savings model

The premise of the water savings model developed below is that once the household demand model has been properly calibrated with sufficient data (i.e. household survey and metered demand data) metered demand data alone can be used to forecast the likelihood of demand variables and by attaching water saving potentials to each demand variable, the model can be used for forecasting water savings based on metered data alone. This approach puts an emphasis on metering which, for the Sofia case, where 98% of households are metered.

The Influence Diagram in Figure 6.14, below, shows model structure for the household water savings model. The water saving potential assumption for different states of demand variables and the resulting utility node, which contains the water savings for a single household, are presented and described in Appendix P.

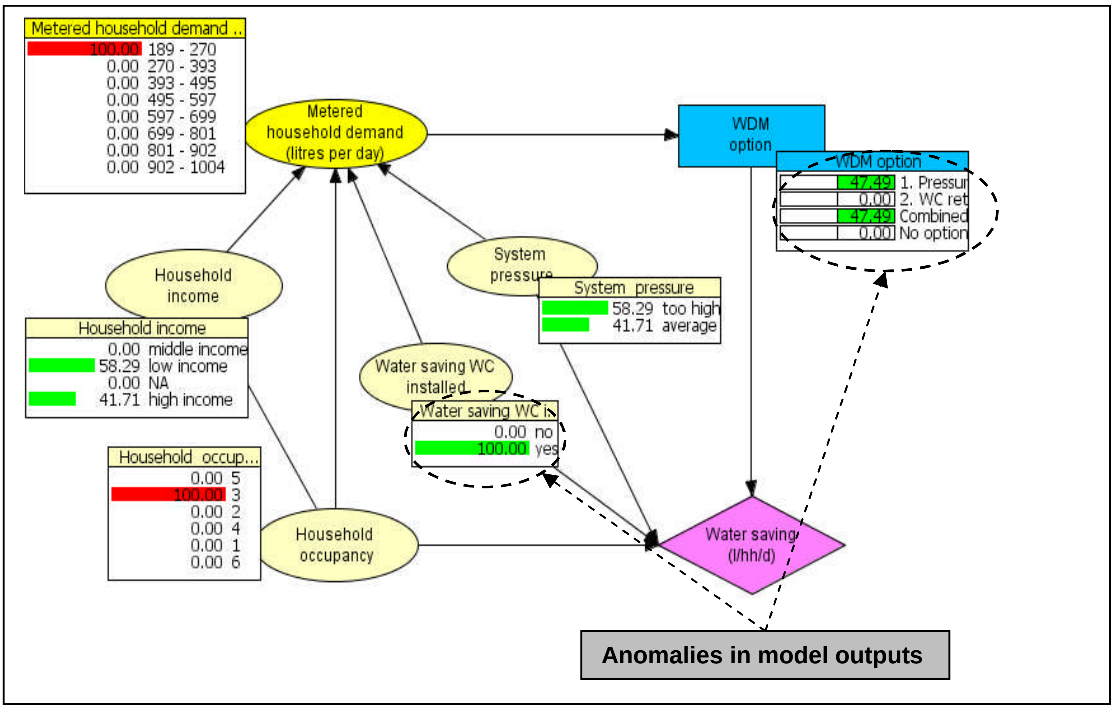


Figure 6.14. *Water savings model structure. Bayesian networks can help to explain model output anomalies in water saving forecasts*

By collecting survey data for different neighbourhoods and adding an additional node called 'neighbourhood' it would theoretically be possible to use the model in Figure 6.14 for targeting of neighbourhoods with high water saving potential.

The graphs in Figure 6.15 to Figure 6.18, below, show the water saving forecast for single households based on: (i) demand variables (i.e. metered demand and occupancy) and (ii) different water saving measures (i.e. press. reduction valves and water saving WCs).

Zero scores for water savings (data anomalies) are due to there being no household survey responses in the data set representing this model instantiation. The ID model can be used to confirm this, as shown in Figure 6.14. If the cause of data anomalies is missing data there are two options. The model can either be reconstructed and knowledge of experts used to replace or fill in gaps in the conditional probability table where the data anomalies arise. Alternatively, the model might signal a requirement to carry out further data collection, e.g. through additional targeted social surveys.

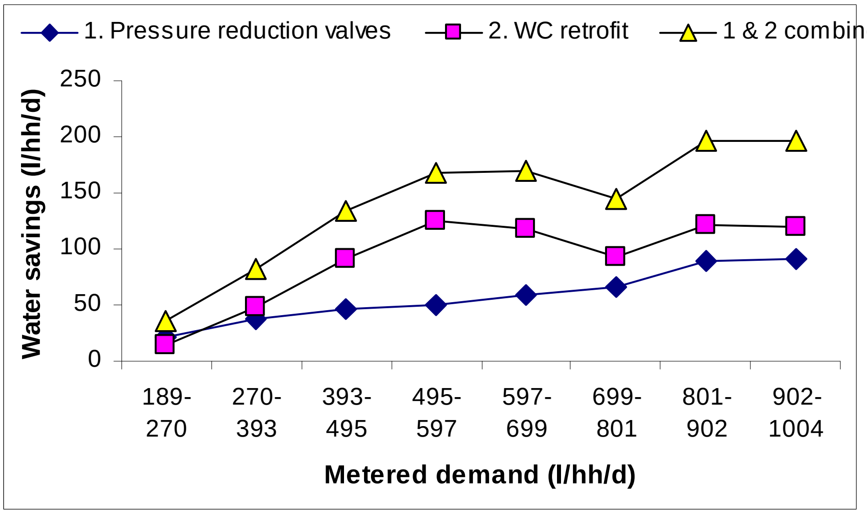


Figure 6.15. *Single household water saving forecasts for pressure reduction valves, WC retrofit, and combined programme using household metered demand as forecasting indicator*

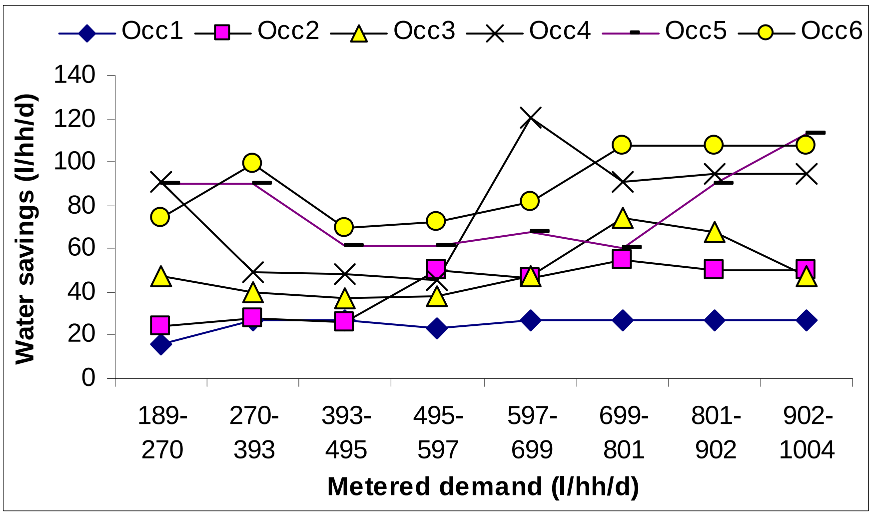


Figure 6.16. *Single household water saving forecasts for Pressure reduction valves only using household metered demand and occupancy as forecasting indicators*

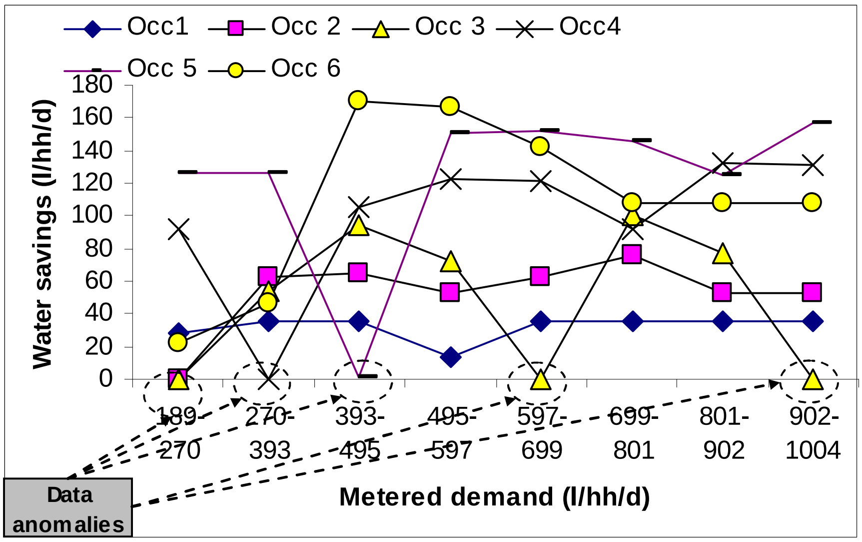


Figure 6.17. *Single household water saving forecasts for WC retrofit only using household metered demand and occupancy as forecasting indicators*

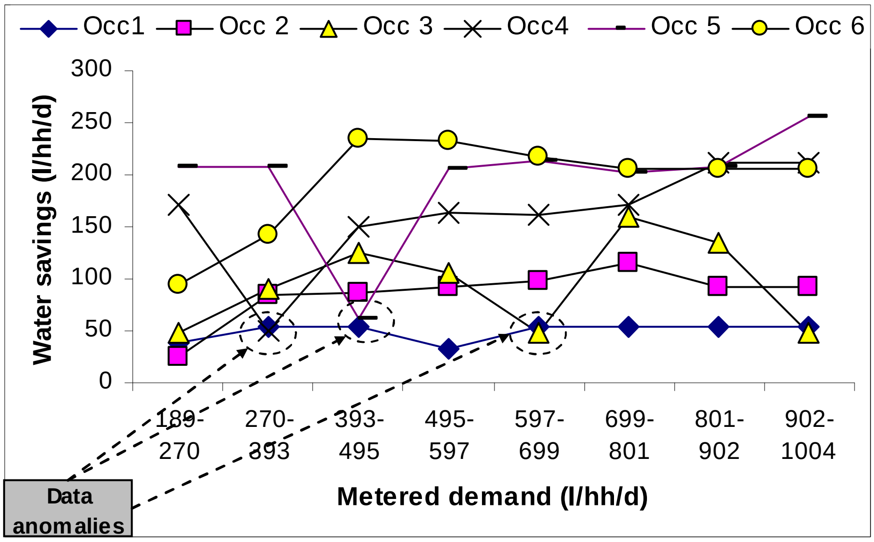


Figure 6.18. *Single household water saving forecasts for combined programme (WC retrofit + Pressure reduction valves) using household metered demand and occupancy as forecasting indicators*

The forecasting models of water demand and water savings in single households shown in Figure 6.13 and Figure 6.14, in combination with the uptake model described in Section 6.3, demonstrate how Bns can be used for describing and evaluating implementation conditions to support programme design.

In the following section a technique known as Value of Information (VOI) analysis is used to estimate the value of carrying out tests prior to implementation of WDM measures?

6.5 Value of data collection to reduce uncertainty about programme effectiveness

The value of information (VOI) is a quantitative measure of the value of knowing the outcome of an uncertainty variable prior to making a decision. When faced with a reasoning or decision making problem, we may have the option to consult additional information sources for further information that may improve the solution. VOI analysis is a tool for analysing the potential usefulness of additional information before the information source is consulted (Kjeurulff & Madsen, 2006).

The following Influence Diagram demonstrates how posterior analysis can be applied to support prior evaluation of implementation conditions for WDM programmes. The models are presented to support further discussion about Bayesian analysis can be applied to support decisions about investment in data collection to improve implementation effectiveness.

6.5.1 Water conservation manager problem

By removing or reducing the uncertainty involved in a decision, new information can increase the expected payoff. For example, if a water company was by some means able to obtain perfectly accurate information about the water saving potential for different WDM measures in all households in a city they could ensure that their water efficiency activities were targeted in such as way as to achieve the lowest possible cost per m^3 saved. A typical decision faced by a water conservation manager might be that they may choose among some actions, but before deciding on the action they also have the option to perform some tests to indicate water saving potential. The question is which tests to perform, if any.

When Bayes' theorem is used to modify a prior probability in the light of new information the result is known as the posterior probability. Posterior analysis using Bayes' theorem is applied in the following example in deciding whether or not to collect data to improve implementation effectiveness of a WDM measure.

A classical approach to addressing problems with multiple decisions is *decision trees* (Goodwin and Wright, 2004). Figure A in Appendix S shows the decision tree for the Bn presented in Figure 6.19, below, for forecasting the water saving potential for low-flush WCs. Prior to constructing the decision tree the water manager must identify a water saving threshold prior to specifying model utilities. For the decision tree in

Appendix S, a water saving threshold is 80 litres per household per day. The probabilities used are for demonstration purposes only and in practice the CPTs could be completed using a combination of household survey data and knowledge elicitation.

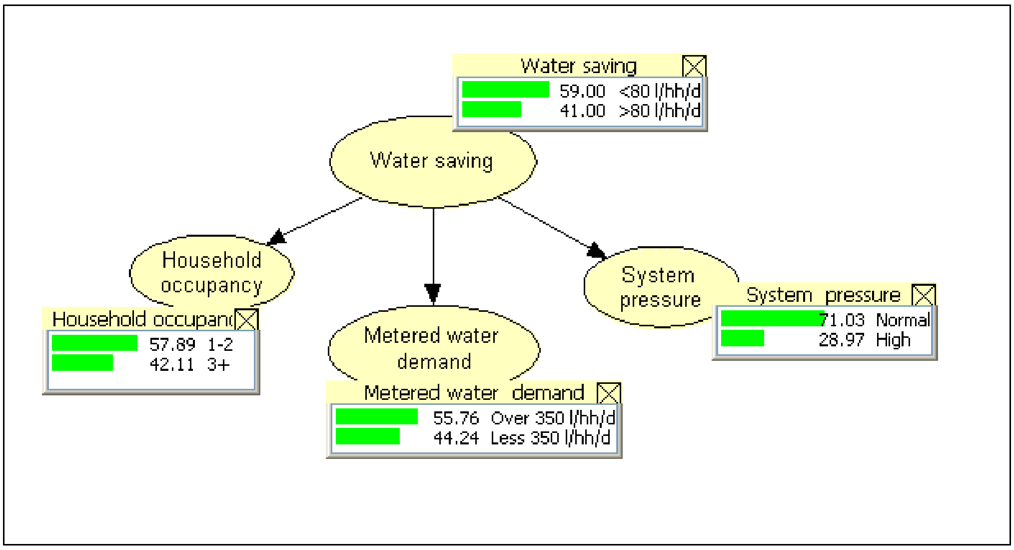


Figure 6.19. *Probabilistic layer for the Influence Diagram of water conservation manager problem*

The three demand variables used for forecasting water savings in the example are households occupancy, metered household demand, and system pressure. To compute the value of collecting information on the three demand variables, a utility and decision node are included in the model and utility functions need to be inserted. The water conservation manager can decide to install the WDM measure now or wait. Utility functions for the model are shown in the top left-hand corner in Figure 6.20, below.

For the method used the utility functions are a combination of the cost of the low-flush WC versus the benefit from water savings. The computed value of information for each demand variable is shown in Figure 6.20. The results show the value of information of each of the selected demand variables relative to the decision. There is one bar for each information variable. The name of the demand variable and the value of information of the variable relative to the decision are associated with each bar. The value displayed for each observation node is the difference between the maximum expected utility of the decision node with and without the node observed before the decision.

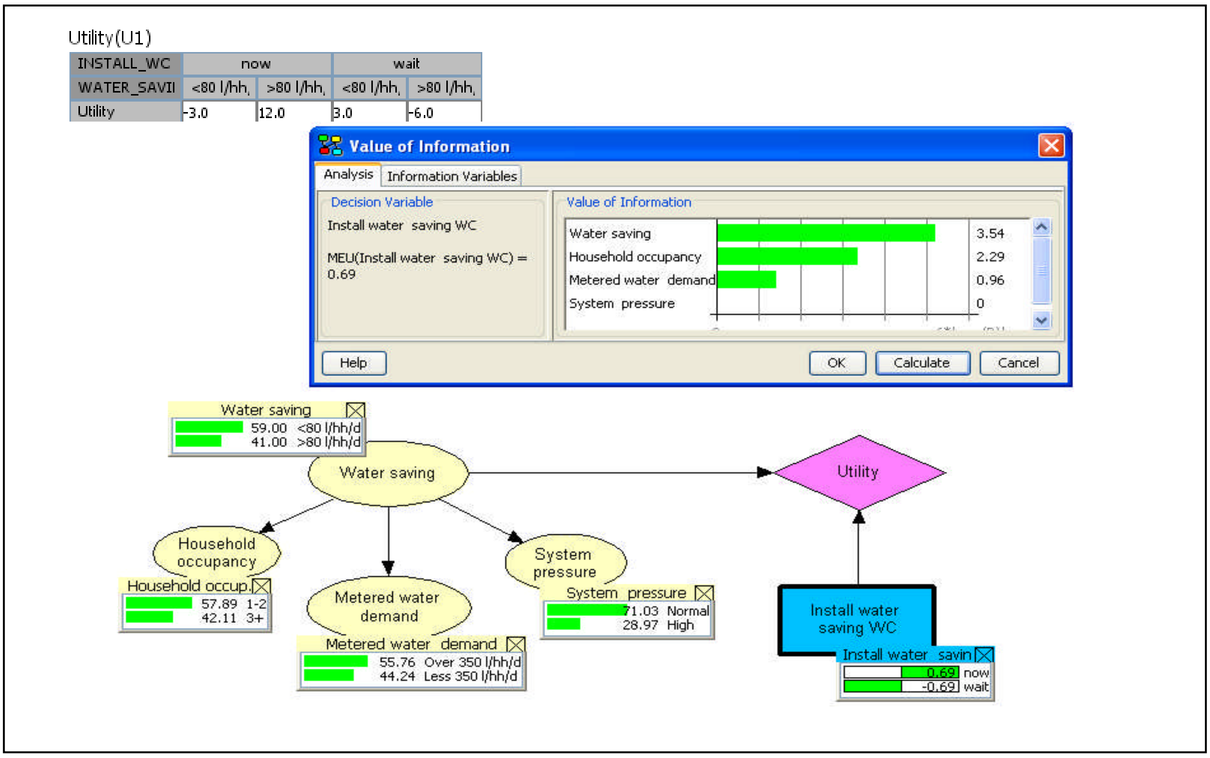


Figure 6.20. *Water conservation manager problem model showing the value of collecting information on different demand variables.*

In theory increasing the target water saving influences the decision to carry out tests because as well as changing the posterior probabilities of water saving, i.e. an updated decision tree would be required, the utility function in the model would be higher due to higher water savings.

VOI analysis supports the user in answering questions about how implementation conditions, target market and the type of water saving technology affect the value of collecting information prior to implementation. Implementation conditions influence the value of collecting data to reduce uncertainty. For example, if the risk of water scarcity increases it might be suggested that this should be reflected in the decision as an increase in the value of saving water. To reflect a changing value of water a node labelled water availability forecast and a corresponding set of utility functions in the utility node labelled avoided costs is included in the Influence Diagram in Figure 6.21, below, to reflect the fact that the value of water changes with its availability. As shown in Figure 6.21, the Hugin software allows the user to insert likelihoods in chance nodes which supports examination of how changes in water availability, represented as changes in the value of saving water, changes the value of data collection for different indicator variables.

Utility(U1)

WATER_AVAI	low				high			
INSTALL_WA	now		wait		now		wait	
WATER_SAVII	<80 l/hh	>80 l/hh	<80 l/hh	>80 l/hh	<80 l/hh	>80 l/hh	<80 l/hh	>80 l/hh
Utility	2.0	15.0	-2.0	-10.0	-5.0	10.0	5.0	-2.0

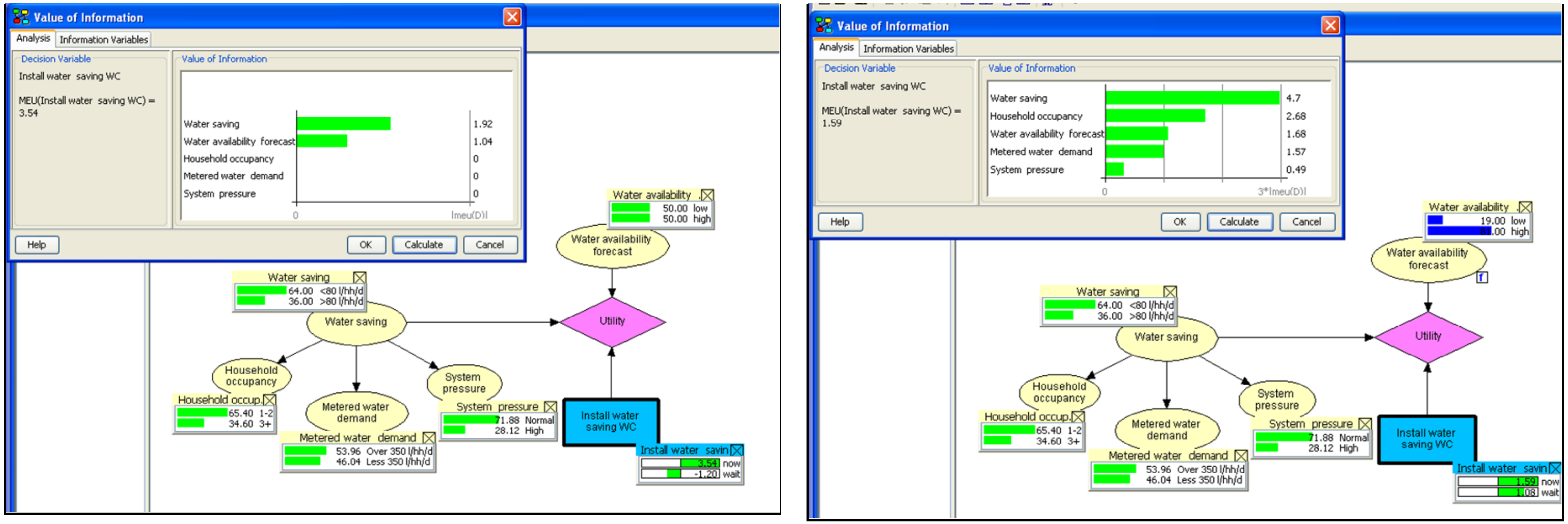


Figure 6.21. *Impact of cost of raw water (security of water supplies) on the value of data collection.*

The following section refers to the model development reported in the above sections as material for a discussion about the applicability of Bns to WDM programme design.

Firstly, practical uses of the four models developed above are identified. Secondly, the need for analogies when developing Bn model structures and how the use of existing approaches might facilitate understanding is discussed. Conclusions summarise the main findings from the modelling work described in this Chapter 6.

6.6 Discussion

6.6.1 Practical implication of WDM design models

6.6.1.1 Behavioural dependencies model (Section 6.2)

Findings from the model in Section 6.2, which used the Theory of Planned Behaviour as a prior mode structure, demonstrates how Bns can be used to support analysis of household survey data. The use of an existing model added credibility and value to the findings because it allowed them to be considered within the context of historical discussions about the Theory of Planned Behaviour. Bns provide a number of techniques for analysing significance of data dependencies between drivers or constraints, and indicators to programme participation. The structural learning from responses to the questionnaire infers that uptake of household water conservation appliances in the context of Sofia conforms to the theory of planned behaviour. Perceived behavioural control (pbc) among citizens in Sofia to adopt WSAs was identified as the chief constraint to programme participation. Financial reasons were the most commonly mentioned *constraint* to adopting water saving technology and financial reasons were also the single most commonly mentioned *driver* (subjective norm) for adopting water saving technology.

Water conservation behaviour in Sofia can be characterised as being subject to low volitional control particularly among low incomes and, therefore, introduction of WDM instruments to improve pbc are recommended. The model indicated that such instruments could increase coverage of WSAs by as much as 35%.

Use of the Theory of Planned Behaviour to structure the behavioural dependencies model demonstrates how making analogies between existing approaches in the problem domain and the modelling approach used supports clarity of meaning of model outputs. This point is returned to in Section 6.6.2, below.

6.6.1.2 Programme participation forecasting model (Section 6.3)

The findings from the model in Section 6.3 support further application of Bns populated with household survey data for evaluating implementation conditions. The model used the 'total market' approach to identify neighbourhoods where coverage of WSAs is currently low and identified large variations in uptake potential between different areas. If outputs of the 'total market' model coincide with high water savings forecasts in the water savings forecasting model, then implementation effort can be focussed on these areas.

Looking forward, the models demonstrate how household surveys could be used to monitor ongoing programme participation rates and presented in Bns to communicate results to a wider policy audience.

Use of the total market approach to structure the programme participation forecasting model is a further example of how making analogies between existing approaches in the problem domain and the modelling approach used supports clarity of meaning of model outputs and is returned to in Section 6.6.2, below.

6.6.1.3 Single household water demand and water savings model (Section 6.4)

The outputs from the models developed in Section 6.4 require further evaluation in terms of accuracy and precision. Measuring accuracy of precision of predictions in the WDM problem domain faces issues of repeatability, and these are discussed in detail in Chapter 8.

The findings from the models developed in Section 6.4 demonstrated how survey data, data from reports, and knowledge of experts can be combined using Bns to address data availability issues in forecasting water savings in household. The graphs in 0 also demonstrate how Bns can be used to evaluate household survey data sets in an iterative process to identifying missing data, and the flexibility of information types (i.e. survey data, data from reports, and knowledge of experts) that Bns support allow some issues of sampling to be addressed.

The 'single household water demand and water savings model' emphasizes the need for metering and the ability of Bns to combine metered data with expert knowledge provides a potential solution where metering coverage is not 100%. It is possible to suggest that different levels of metering coverage have implications for how to go about developing the evidence-base and examples of how Bns might facilitate forecasting water savings under different metering scenarios are given below.

If the area under question is:

(a) *fully-metered* then metered demand data collected from participating households coupled with household survey data regarding demand variables can be used to develop the required data dependencies. The results can be compared to a control group of households with similar or identical characteristics to verify data dependencies. With careful sampling to achieve the required significance levels, this approach is likely to provide the best results.

(b) *partially-metered* it should be possible to included sufficient households in a pilot study to derive data dependencies between demand and water savings. Using household survey data, non-metered households with relevant demand variables (i.e. indicators of high water saving potential) could be identified for inclusion in the programme. Advantages of this approach include reduction in implementation costs (i.e. household survey data is relatively inexpensive to collect compared to fitting meters) and it does not incur the cost of fitting data-loggers to monitor water savings in every household.

(c) *unmetered* the options available are either: (i) to use expert knowledge to populate the conditional probability tables for dependencies between water saving potential and demand variables and collect demand variable frequencies using household surveys or, (ii) to fit a sample of households with data loggers and collect household survey data for these household and learn data dependencies in this way. The costs of installing data-loggers in a sufficient number of households to achieve statistical significance may make such a programme prohibitive. Finally, (iii) use a combination of (i) & (ii) (i.e. expert knowledge and data from loggers).

6.6.1.4 Model of indicators of high water saving potential (Section 6.5)

The model developed in Section 6.5 described the use of Value of Information (VOI) analysis in a test decision concerning data collection to direct implementation effort.

To understand how VOI analysis might be applied in practice to reduce implementation costs, consider the task of a plumber employed by a water company to retro-fit households with WSAs. A random selection process might involve one plumber installing ten low-flush WCs in a day with an average savings of say, 60 litres per household. Alternatively, by identifying relevant indicators of water saving potential and then selecting household based on these indicators prior to retro-fitting, the plumber could be more effective, increasing their rate of installing low-flush WCs to say, 15 households (e.g. due to closer proximity) and increase the average water savings to say 100 litres per day, thus significantly reducing the cost per m^3 saved.

Applicability of VOI analysis for market research have been discussed in former research by Lacava and Tull (1982) and Assmus (1977) who observed that "no other method has demonstrated an equally strong potential for analysing the returns from market research" (Assmus, 1977, p568)

Although Bayes' theorem and VOI analysis appears to be well-suited and as a method for determining the value of new information, both Assmus (1977) and Lacava & Tull (1982) observed that it is seldom practiced. According to Lacava and Tull (1982, p383), reasons for this include *data problems* such as (i) difficulties of qualifying prospective gains and losses resulting from a decision and (ii) difficulties in assessing the probabilities required, and *application problems* including (i) unfamiliarity with how to calculate the expected value of information and (ii) the cost of using the method. If VOI analysis is to be applied to support WDM programme design the above issues need to be addressed to reduce their impacts on receptivity to this potentially useful method; this is an area for future research.

6.6.2 Using existing models when structuring Bayesian network models

Experience of developing Bn models for use in WDM programme design gained during the case study field work in the Upper Iskar highlighted a requirement for being able to find existing models within the domain of application (WDM) to inform the structure of the networks.

Problems of definition in models are acknowledged in research looking to integrate and manipulate relatively simple bio-physical models developed by different developers (Argent, 2004). Questions of ontology and whether the right variables are included in a model are less contentious as theory is typically more mature and well-posed problems more likely to exist (Winder, 2004). It is possible to suggest that the flexibility of Bns, demonstrated in the models in Chapters 4, 5 & 6, and their ability to adopt existing approaches in model structures (e.g. LAC method, Theory of Planned

Behaviour, total market approach), might assist in addressing issues of meaning. If existing approaches used in the problem domain can be readily adopted and represented in the form of a Bn model there should be less ambiguity about the meaning. It is still important to be exact about which question the model is attempting to address but the existence of readily available forms of reference is considered a benefit in achieving clarity and transparency.

6.7 Conclusions

The demonstration models presented in Chapter 6 supported the examination of strengths and weaknesses of Bns relating to two research questions, identified previously in Chapter 1. Findings are presented below.

Research question 6: How does Bayesian network modelling provide support for identifying constraints to- and drivers of- water conservation behaviour?

Bayesian networks support processing and analysing data dependencies in household survey data. Section 6.2 demonstrated that, from a research perspective, structural learning of household survey data provided a means of examining drivers of- and constraints to- citizen participation for different socio-economic groups and also for different household classes. In addition, because expert knowledge can be used to augment survey data (i.e. to update cpts), Bns also provide a potentially useful method to address instances of missing data in household survey data sets, reducing data collection costs.

Weakness of the Bn approach for identifying behavioural drivers are that in order to validate model outputs, social survey design needs to be based on existing and tested model structures, for example the theory of planned behaviour. However, this is a universal issue when validating findings from behavioural models.

Research question 7: How does Bayesian network modelling provide support for identifying indicators of 'favourable' and 'unfavourable' implementation conditions for introduction of different water saving measures?

A number of strengths of Bns for evaluating implementation conditions for WDM were identified from the experience of model development in Chapter 6. For forecasting per capita household demand and water savings, as demonstrated in Section 6.4.2, the profile of a population can be described using chance nodes representing individual demand variables. The further addition of utility and decision nodes then allows those models to be used to forecast household water savings. For forecasting potential participation by citizens in water conservation programmes, the use of conditional probabilities in Bns makes them compatible with the 'total market' approach. The wide range of information types that can be used to develop conditional probabilities in Bns means that they can be used to describe implementation conditions even in areas with low coverage of household meters (see Section 6.6.1.3).

The use of Value of information (VOI) analysis in Bns provides a potentially useful tool for water conservation managers to consider: (i) how the value of data collection is determined by water stress conditions and implementation conditions and (ii) the costs and benefits of collecting more data before proceeding with implementation.

Weaknesses of the Bn approach for evaluating implementation conditions for WDM are that the complexity of the methods used, especially for Value of Information analysis, and the availability of data to populate the models, may constrain the use of the method. Further research is required to see whether the methods demonstrated can be practically useful for water conservation managers in determining data requirements. The use of Bns for forecasting water savings and uptake potential has not been evaluated by practitioners and there wider use in this context would require comparisons with other forecasting methods (e.g. simulation models).

6.7.1 Lessons learned regarding combining household survey and metered demand data for forecasting

Regarding planning of household surveys for forecasting water demand and water savings, if metered data is to be used it is vital to cross-reference each survey with the interviewee's water company account number (i.e. not to use their name and address as this data is unreliable) so that their responses can be cross-referenced with their metered water demand. This puts an onus on the water company to provide such data and to be an active participant in the household survey design. This approach would also support achieving an equal distribution in the sample for each metered demand range represented in the node states in the model.

6.7.2 Recommendation for water conservation programme design in Sofia

Methods for improving the receptivity among citizens including: instruments to facilitate installation such as free-fitting of WSAs, rebates and free-installation for low income families, introduction of efficiency standard to improve availability and take advantage of the current high replacement rate in Sofia, compulsory installation in new-build houses.

Replacement of WCs in households with old toilets is likely to achieve the highest reduction in wastage (i.e. leakage) particularly in neighbourhoods with high pressure.

Chapter 7

End-user evaluation of the use of Bayesian networks to support cross-sectoral planning in water demand management

Introduction

The aim of the field work reported in Chapter 7 was to elicit end-users perceptions of the effectiveness of Bns in cross-sectoral planning for water demand management to answer three research questions:

- Are Bayesian networks perceived to be more or less effective at addressing support requirements for water demand management planning by practitioners from different organisational backgrounds?
- Do Bayesian networks promote learning and the development of common understanding of water demand management issues?
- Do Bayesian networks facilitate decision-making for water demand management?

By collecting end-user's perceptions of the effectiveness of the support tools performance following the workshop using an evaluation instrument, in this case a survey questionnaire, it was possible to examine the above three questions and test the experimental hypotheses shown in Box 7.1 (below).

Box 7.1. Experimental hypotheses that were examined through the end-user evaluation

H1: End-users perceived effectiveness scores from different professions will be significantly different

H2: End-user perceived effectiveness scores for statements related to learning will be higher than scores for other indicators

H3: End-users scores for statements related to decisions stress will be lower when using Bayesian networks

Section 7.1, below, describes how the evaluation instrument used to elicit end-user's perceptions of effectiveness of Bns was designed, and also describes the tasks included in the one-day model testing workshop during which end-users were applied Bns models to three WDM problems. Section 7.2 reports the results if the end-user evaluation and hypothesis testing, supported by comments collected from end-user's regarding their experiences of using the tool. Section 7.3 is a discussion of the evaluation results and areas for future research

7.1 Method

When designing methodologies for Information Systems (IS) evaluation the researcher is faced with a bewildering array of approaches IS research literature (Adams *et al*, 1990). Srinavasan (1985) observes that 'researchers have responded to the shifting emphasis from efficiency to user effectiveness in IS evaluation by focussing either on *usage* or *perceived effectiveness*.' The usage approach uses behaviour, i.e. actual time spend using the system, as a surrogate indicator of IS effectiveness, whilst the perceived effectiveness approach uses measures of effectiveness as perceived by the users of the system.

Researchers have argued both for and against the use of these two approaches to IS evaluation research and reports of the relative success of perceived effectiveness indicators as reliable indicators of IS effectiveness. For example, Ginzberg (1978) argued against the system usage approach by stating that the link between system usage and the quality of decision-making was a weak one, stating that 'if one views the system as a service (instead of a product) that is designed to enable managers to perform more effectively, the extent of use measure would be a very misleading indicator of success.' Based on these assertions, Ginzberg (1981) advocated the perceived effectiveness approach. Furthermore, Srinavasan (1985) carried out research to explore links between system usage and perceived effectiveness, and results emphasized the fact that the two are not always positively associated with each other. Srinivasan concluded that 'practitioners have to realise that lack of strong behavioural indications of system use may not be a negative outcome' and that 'there may very well exist an underlying flurry of problem solving activities' (Srivansan, 1985, p252).

To support the design of an evaluation instrument to measure end-user's perceptions of the effectiveness of Bns in WDM planning a clearly-defined set of perceived effectiveness indicators relevant both to the problem domain, i.e. water demand management, and the method, i.e. Bayesian networks, were identified. The following section describes the perceived effectiveness indicators that were used to inform the design of the instrument and the basis for their selection is discussed.

7.1.1 Perceived effectiveness indicators are specified as a basis for the evaluation instrument

Organisational receptivity refers to end-user's perception of the DSTs effectiveness in terms of their day-to-day work. The inclusion of organisational receptivity as a criterion of perceived effectiveness is based on the belief that high receptivity scores from a range of organisational perspectives, i.e. practitioners, academics and policy makers, would indicate the decision support tool's effectiveness in a collaborative planning context. Adams *et al* (1990) discuss how, when DSTs are viewed as providing decision support within an organisational context, the decision maker becomes a consumer of this support, and his or her attitudes and perceptions become important selection and evaluation measures. Receptivity has been defined by Jeffrey and Seaton (2004) as the extent to which there exists not only a willingness (or disposition) but also an ability (or capability) in different constituencies (individuals, communities, organisations, agencies etc.) to absorb, accept and utilise technology options. Three statements (statements 5, 6 and 7) exploring organisational receptivity were included in the evaluation instrument presented in Appendix T.

Reliance on decisions was included as a criterion of effectiveness to explore how Bns uncertainty and indeterminacy in the WDM problem domain, cited as a constraint to implementation of WDM during the knowledge elicitation presented in Chapter 3. The evaluation instrument used three statements adapted from an evaluation instrument developed by Sanders and Courtney (1985), and Welsh (1980). The three statements (statements 8, 9 & 10) concerning reliance on decisions were included in the evaluation instrument presented in Appendix T.

Technical suitability examines the fit between the technical sophistication of a computer-based system (its capabilities) and user's needs, and the impact of such a fit on system effectiveness (Srinivasan, 1985). Adelman (1992), whose method of evaluation focuses on the suitability of system characteristics to the specific problem, e.g. the adequacy of the selected analytical methods, software development costs, software tests and verification, and adequacy of the knowledge base exerts that 'an analytical method's epistemological basis addresses the assumption made about the data, and perhaps most critically, the rule used to combine data to reach a conclusion.' Adelman continues, giving a number of examples, '… decision-analytic and artificial intelligence methods typically use subjective data (i.e. judgements) whereas simulation and optimisation methods typically use objective, empirical data. Decision-analytic methods use axiomatically based calculation, such as expected value, to combine utility judgements, which themselves are presumed (and elicited) to be consistent with the axioms of rational choice. In contrast, artificial intelligence methods such as those to be found in most expert systems, use heuristics (e.g., if-then rules) to represent how experts supposedly combine subjective data to reach a conclusion. And most simulations and optimisation methods use mathematical formulas to represent the relationships between data and perform calculations necessary to reach a solution on the basis of verifiable proofs' (Adelman, 1992). The models used during the workshop relied on both objective data, i.e. hydrological and social survey data, and subjective data, i.e. expert judgements and data from literature, to populate the models.

Four statements relating to technical suitability (statements 11, 12, 14 & 15) were included in the evaluation instrument in Appendix T.

Strategic planning refers to how the tool integrates different water resource management issues. Although the evaluation activities and workshop modelling tasks did not specifically focus on integration, it was hoped that applying the water balance model and use of the household demand and LAC sub-models would provide opportunities to make analogies of how the tool might be applied to integrate these activities. One statement (statement 13) in the evaluation instrument explored user's perceived effectiveness of the tool in strategic planning.

Transparency refers to the recognition that at any point in time the end-user should have access to the background information needed to understand the models they are working with, the processes represented, and the numbers generated. Without this information, models remain black boxes and learning is excluded (FutureTech, 2002). Ubbels and Verhallen, (2000) evaluated the suitability of tools for specific user groups and decision making phases for collaborative planning processes using characteristics including user friendliness, transparency, flexibility, and the way the effects of possible actions are estimated.

Two statements exploring end-user's perceptions of transparency of the DST (statements 16 & 17) one adapted from an evaluation instrument developed by Sprague and Carlson (1982), and a further one adapted from Jenkins and Ricketts (1979) were included in the evaluation instrument presented in Appendix T.

Learning refers the effectiveness of the support tool in teaching users about the problem domain. Welsch (1980) and Sanders and Courtney (1985) included learning as a dimension to explore how their tool supported dialogue and enquiry with other decision-makers. Watkins and Marsick's Dimensions of the Learning Organization Questionnaire (DLOQ) (Watkins and Marsick 1997; 2003) provided a second source of material to design questions to elicit user's perceptions of the tools effectiveness in providing learning support. Two statements relating to learning (statements 18 & 19) were included in the instrument presented in Appendix T.

Ease of use refers to the ability of the support tool to present information to a decision maker in ways that are clear and familiar, and that permit rapid comprehension and has been included by a number of researchers in evaluating DSTs (Sprague and Carlson, 1982). *Ease of use* is also included in the evaluation instrument as a checking mechanism to indicate if responses to statements regarding the other six criteria of perceived effectiveness were influenced user's experiencing difficulty in applying the tool. Research reported by Sanders and Courtney (1985) showed a negative correlation between difficulty in using DSTs and overall satisfaction with the tool. Srinivasan (1985) also reported that lower perceived effectiveness correlated with time spent using the DST in their study. Both results imply that a correlation may exist for some users between satisfaction and the difficulty in applying the tool for a specific task. One statement was included in the evaluation instrument (statement 20, Appendix T) to elicit user's perceptions of ease of use.

In addition to statements relevant to the perceived effectiveness indicators described above, a number of questions were included in the evaluation survey regarding the informed practitioners perceptions of the existing decision process compared with their experience of using the Bayesian network models during the workshop.

Kottemann and Davis (1991) use the term decisional conflict to refer to the negative affective state experienced by a decision maker as a result of making explicit trade-off judgments among alternatives. There are several studies that give evidence of the decision conflict originating from analytical methods used in decision making processes (e.g., Bettman *et al*., 1993; Luce *et al*., 1999; Scholten, 2002). Janis and Mann (1977) theorize that trade-off conflict is a major source of decisional stress. Aloysius *et al* (2006) measured decisional conflict among users of different types of analytical techniques used in DSTs. They found that some analytic methods used in DSTs, e.g., pair-wise comparisons, require users to make trade-offs leading to greater decisional stress due to the decision conflict, whereas other analytic methods, e.g., those giving output as absolute measurements, result in less decisional conflict.

A large body of evidence exists (Aloysius *et al*, 2006; Shugan, 1980; Bettman *et al*., 1990; Chatterjee and Heath, 1996) linking higher conflict tasks with more cognitive effort for the decision maker, as they attempt to better confront the trade-offs inherent in a multi-attribute problem. As a result users who perceive high levels of decision conflict will also perceive the task to be more effortful.

When decision making tasks are perceived to be higher in effort, decision makers tend to perceive that the results of their decision making are lower in accuracy, due to the increase in perceived decision difficulty (Peterson and Pitz, 1988; Chatterjee and Heath, 1996). It has also been suggested that the higher perceived effort may reflect some limitations in their own ability in the task domain (Reeder *et al*., 2001).

Following on from this body of research the questionnaire first explores individual's perception of *decision conflict, effort* and *confidence* in the existing decision process in Sofia. In the final section of the questionnaire, each end-user is asked about their perceptions of decision conflict, effort and confidence when using the Bayesian network models during the workshop tasks. The results are compared for significance of variance to provide evidence for a discussion about how Bns facilitate these aspects of the decision process.

7.1.2 Eliciting perceived effectiveness scores using the evaluation instrument

The evaluation instrument contained twenty-two, seven-point Likert-scale statements to assess workshop participants perceptions of the effectiveness of Bayesian networks against the indicators described above. Workshop participants were asked to assign a score on the seven-point Likert-scale, ranging from whether they strongly-disagreed to strongly-agreed with each statement.

The full questionnaire is shown in Appendix T. Six statements addressed decision stress, and sixteen statements related to the seven perceived effectiveness indicators. The evaluation survey also included two questions concerning workshop participant's experience and involvement in WDM on a day-to-day basis.

7.1.3 Workshop modelling tasks

A consideration in deciding on tasks to include in the evaluation workshop was the relevance of tasks to workshop participants and evaluation criteria. The expectation was that different models would be of greater or lesser interest to different workshop participants depending on their role in the collaborative planning process. There was, therefore, a requirement to use models that were relevant to different stages, i.e. legislating and design, of the WDM planning process.

The three Bayesian network models that were explored by the attendees at the end-user evaluation have been described in Chapters 4 and 6 (see Figure 7.1, Figure 7.2, and Figure 7.3, below).

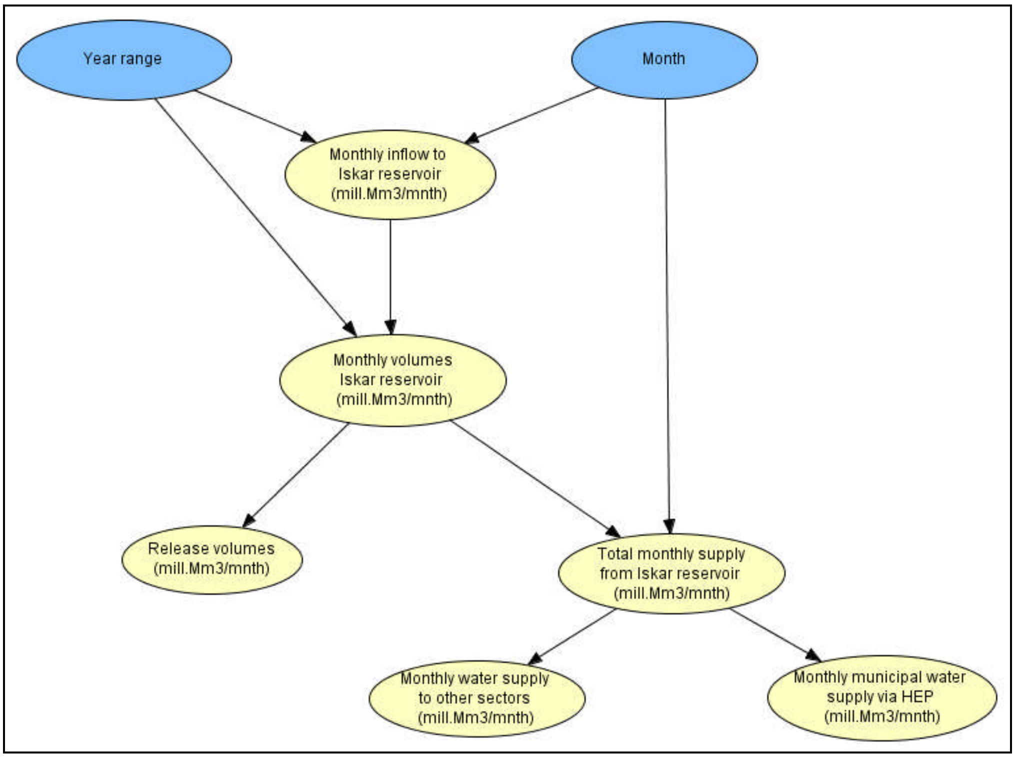


Figure 7.1. *Sub-model 1: Iskar dam water balance model*

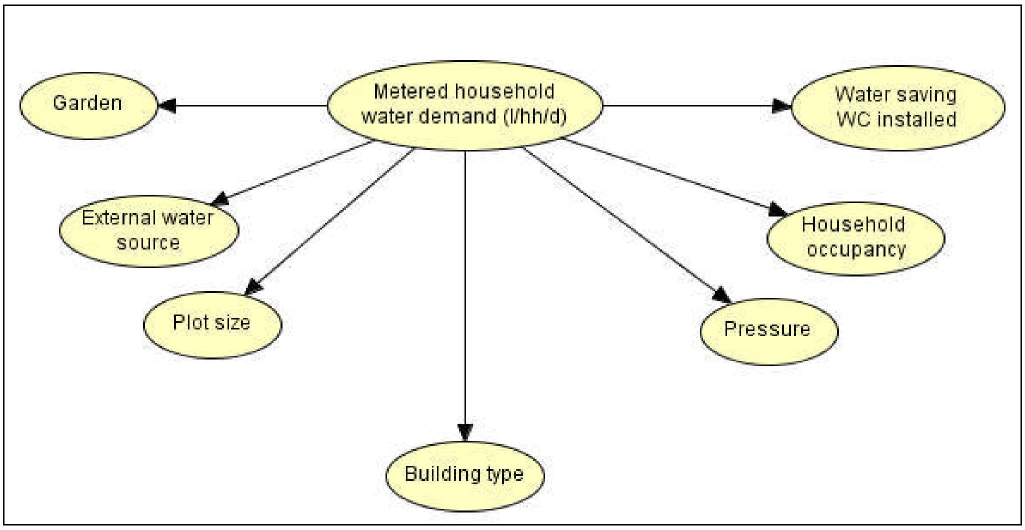


Figure 7.2. *Sub-model 2: Household water demand forecasting model*

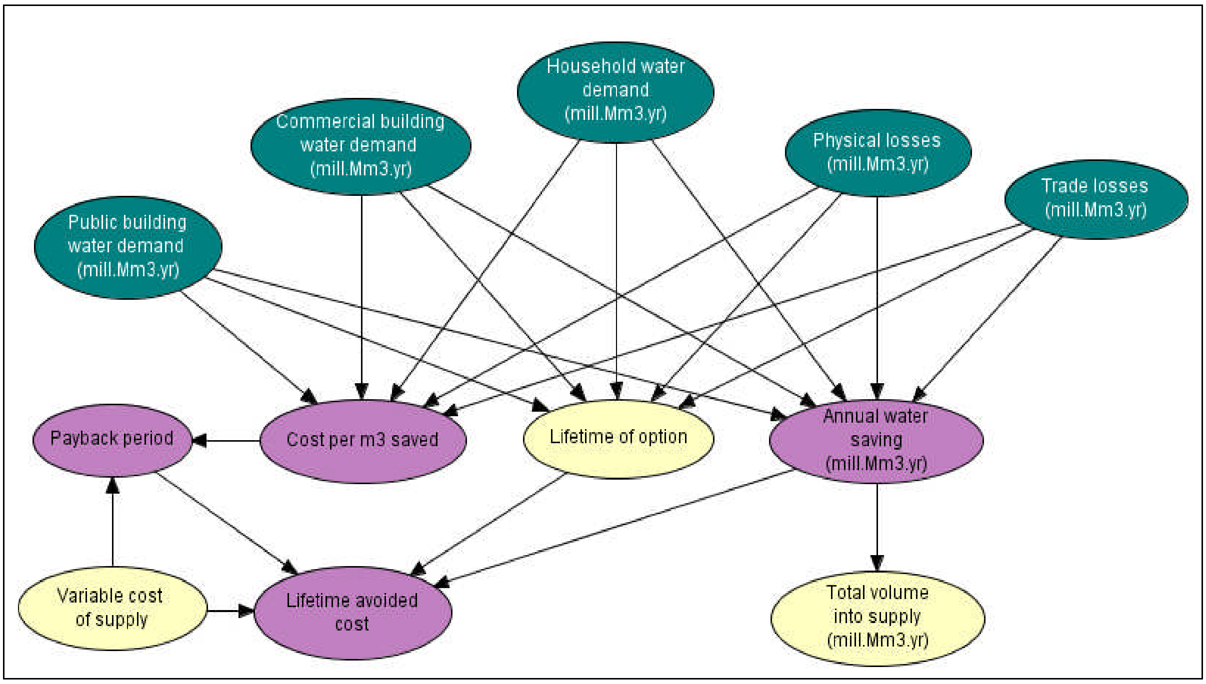


Figure 7.3. *Sub-model 3: Lifetime avoided costs model of economics of water demand management in Sofia*

The end-user evaluation was conducted at the University of Civil Engineering, Architecture and Geodesy in Sofia in July 2007. The evaluation involved a one-day workshop and involved informed practitioners applying Bn models to WDM decision problems in the context of the Upper Iskar river sub-catchment and Sofia city. During the workshop practitioners applied the models, described above, working in pairs on laptop computers and to test each model, carried out a number of decision-making tasks. The agenda for the end-user evaluation workshop and a description of the evaluation workshop tasks presented to each informed practitioner are presented in Appendix U.

7.2 Results

Results from questions regarding workshop participant's experience and involvement in water demand management decision-making are presented in Table 7.1, below. The average number of years experience among the nine individuals was 20.1 years; on average workshop participants spent 34.4% of their working week dealing with water demand management issues.

Table 7.1. *Informed practitioner's experience and time spent dealing with water demand management issues in day-to-day work*

OCCUPATION OF INFORMED PRACTITIONER	EXPERIENCE AND INVOLVEMENT IN WDM	
	EXPERIENCE (YEARS)	TIME COMMITTED TO WATER DEMAND MANAGEMENT ISSUES (%)
Chief of assets department in water Sofia company	21	30
Chief of maintenance department in Sofia water company	3	10
Chief of water department in Ministry of Regional Development and Public Works (MoRDPW)	30	40
Vice Minister of Ministry of Environment and Water (MoEW)	27	70
Professor of water demand management	34	70
Hydrologist at the Bulgarian Academy of Sciences	20	10
Assoc. prof in water infrastructure and building design	21	50
Water infrastructure engineer	21	20
Construction engineer	4	10

Responses to the individual statements for each practitioner are presented in Appendix V, and the histogram in Figure 7.4 (below) presents a summary of the results for all workshop participants. The scores are shown on the *x*-axis on a scale from 1-7. A score of 1-3 indicates disagreement with the statement of perceived effectiveness, a score of 4 or greater indicates increasing agreement with the statement and positive impression of the effectiveness of the tool's performance. The *y*-axis shows the frequency of responses.

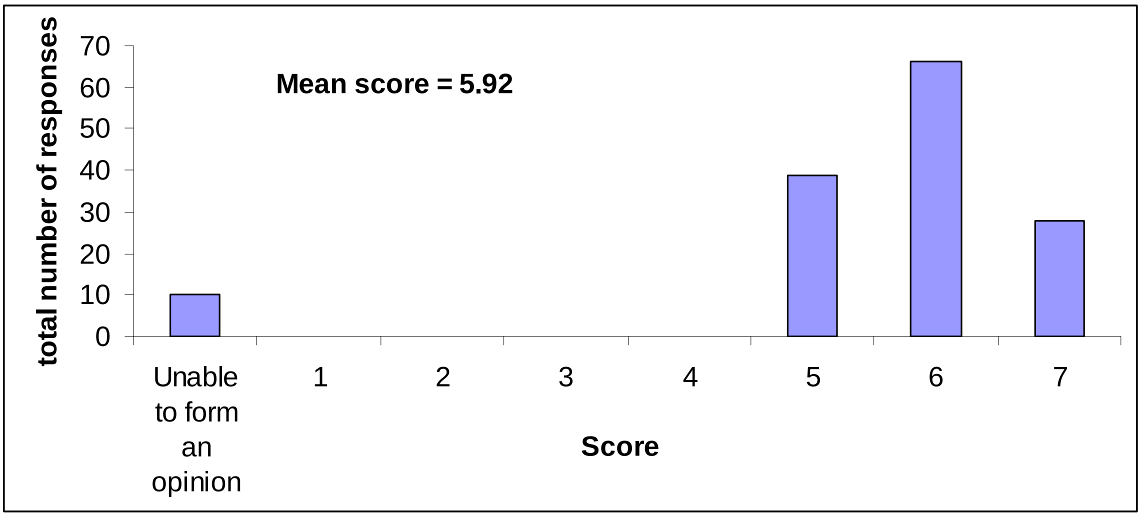


Figure 7.4. *Summary of evaluation results for all workshop participants*

Practitioner's responses were categorised according to profession (policy makers, water company employees, academics, and water engineers) and for the seven dimensions of effectiveness. The histograms in Figure 7.5 to Figure 7.11 (below) show the distribution of responses and mean scores for the seven dimensions of effectiveness for different professions.

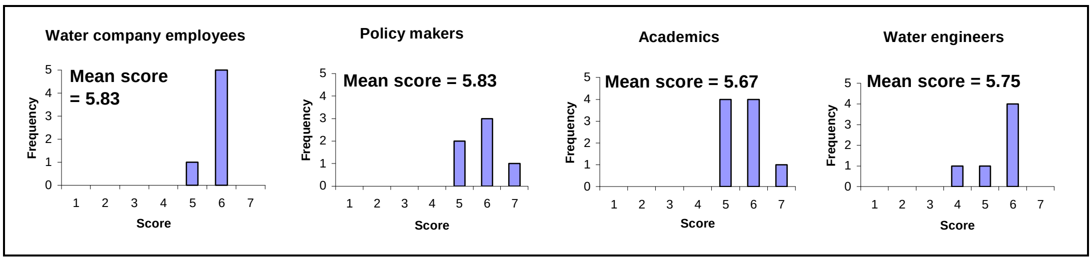


Figure 7.5. *Organisational receptivity scores categorised by profession of workshop participant.*

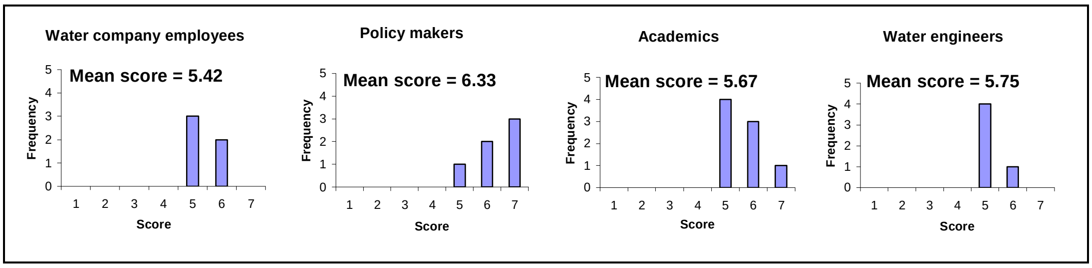


Figure 7.6. *Reliance on decisions scores categorised by profession of workshop participant.*

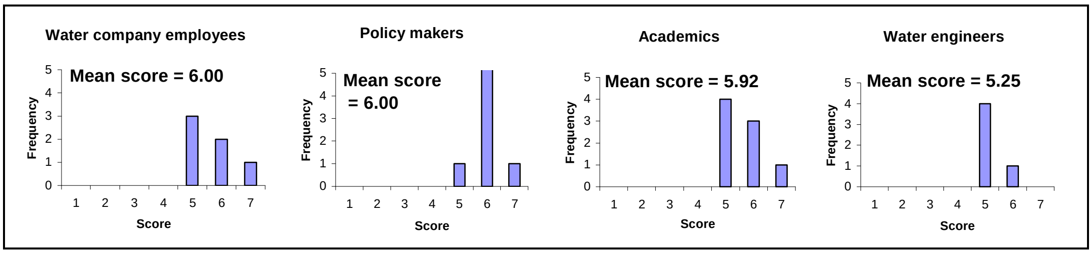


Figure 7.7. *Technical suitability scores categorised by profession of workshop participant.*

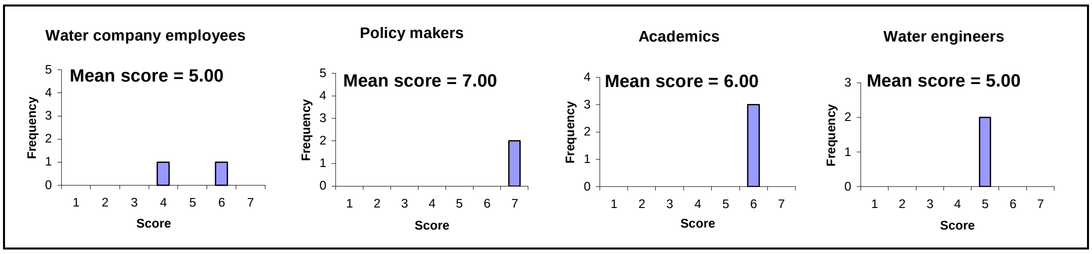


Figure 7.8. *Strategic planning scores categorised by profession of workshop participant.*

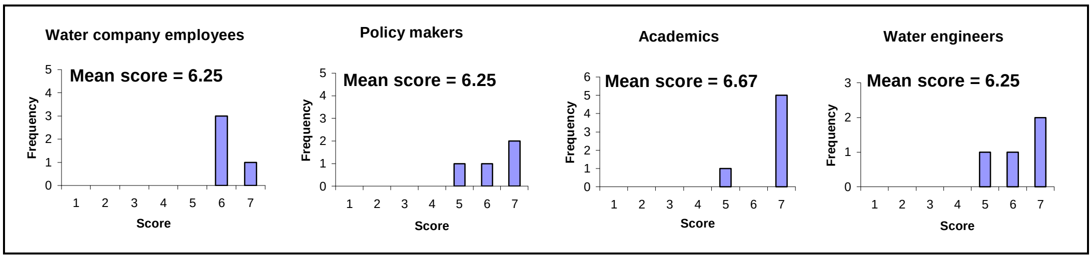


Figure 7.9. *Transparency scores categorised by profession of workshop participant.*

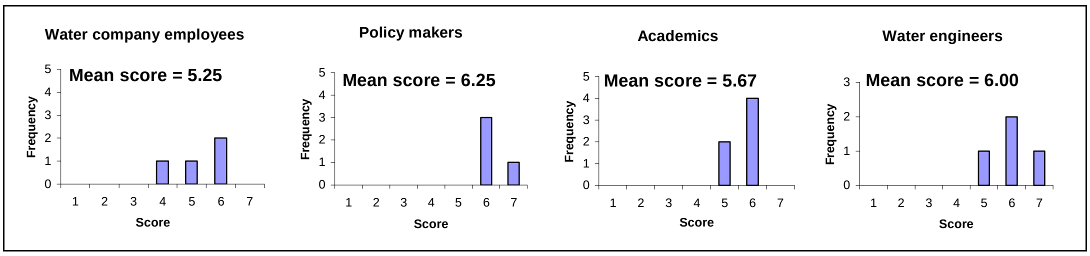


Figure 7.10. *Learning scores categorised by profession of workshop participant.*

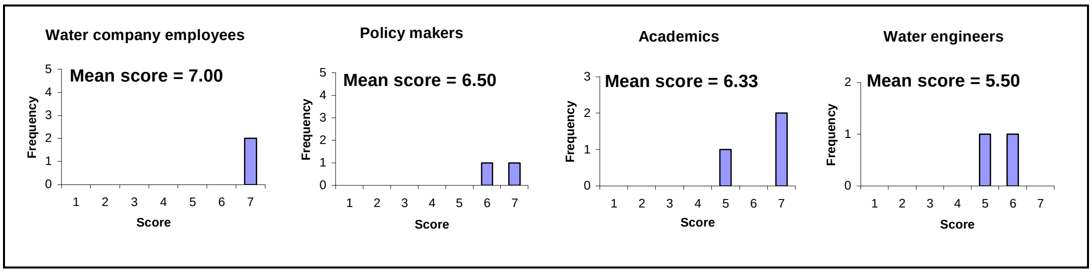


Figure 7.11. *Ease of use scores categorised by profession of workshop participant.*

7.2.1 Are Bayesian networks perceived to be more or less effective at addressing support requirements for water demand management planning by practitioners from different organisational backgrounds?

The following results supported exploration of the above research question:

1. *Organisational receptivity* scores
2. *Technical suitability* scores
3. Mean scores and significance of variance between scores for different professions.

7.2.1.1 Organisation receptivity scores

Average perceived effectiveness scores for *organisational receptivity* for different organisational perspectives ranges from 5.67 – 5.83. Although positive the scores may have been affected by the nature of the models used in the workshop. There was an onus on the workshop participants to make analogies between the models applied in the workshop and specific planning and decision-making tasks that they face in their day-to-day work. As one practitioner from the water company commented, “the software is very interesting because it supports discussion but it is difficult in such a short time to see exactly how it could be applied in my day-to-day work.”

One practitioner from the university enquired about the cost of purchasing the tool for use in the university and said that the cost would not be prohibitive. The Hugin Graphical User Interface also supports Unicode which made it possible to produce all models used during the workshop in the Cyrillic script used in Bulgaria.

Perceived effectiveness scores were highest for organisational receptivity among water company employees and policy makers.

7.2.1.2 Technical suitability scores

Average perceived effectiveness scores for *technical suitability* for different organisational perspectives ranged from 5.25-6.00.

Referring to Submodel 2 (Figure 7.2) one practitioner who had tried to develop method for identifying metering error in households in Sofia proposed that the method could potentially assist in identifying households with faulty meters. For example, high demand, e.g. over 400 litres, in low occupancy households without a garden suggests either that the householders have a number of water intensive appliances, that they have leaking appliances such as an old WC, or that their meter is faulty.

Another practitioner from the university commented that household demand and demand variables might best be represented on an integral curve rather than as discrete frequencies. The reason for using discrete frequencies in Bns is that they are concerned with probabilities which means that ‘quantities’ are always described as ranges between 0 and 1, and must always sum to 1. Discrete frequencies are also required for utility theory, which is not compatible with the use of an integral curve.

Perceived effectiveness scores for technical suitability were lowest among water engineers and highest among policy makers.

7.2.1.3 Significance of variance between perceived effectiveness scores for different professions

A comparison of results for all seven perceived effectiveness indicators for different organisational perspectives showed that policy makers registered highest in five out of the seven indicators. Two-tailed paired t-tests (assuming unequal variances) of evaluation responses *within* profession (i.e. academics vs. academics, policy-makers vs. policy-makers etc) revealed no significant variance. To test whether the null hypothesis “there is no significant difference between perceived effectiveness scores for different organisational perspectives” should be accepted or rejected, analysis of variance (ANOVA) tests of evaluation responses between professions (i.e. academics vs. policy makers, academics vs. water engineers etc) were used. The ANOVA results revealed significant difference ($p<0.05$) between:

1. Policy makers and water engineers
2. Policy makers and water company employees

As there was no significant variance within profession the above ANOVA results *between* professions can be considered significant.

The null hypothesis that "there is no significant difference between perceived effectiveness scores for different organisational perspectives" can therefore be rejected.

To examine this result further paired t-tests for two samples were used to compare each informed practitioner who participated in the end-user evaluation. The results and the mean score for each workshop participant across all seven factors are shown in Figure 7.12, below.

	WE1	WE2	AC1	AC2	AC3	PM1	PM2	WC1	WC2	Mean score
WE1	*n*	*n*	*y* *(p=<0.1)*	*n*	*n*	*y* *(p=<0.05)*	*n*	*n*	*n*	*5.71*
WE2	*n*	*n*	*n*	*n*	*n*	*y* *(p=<0.05)*	*y* *(p=<0.05)*	*n*	*n*	*5.50*
AC1	*y* *(p=<0.1)*	*n*	*n*	*n*	*n*	*n*	*n*	*n*	*n*	*6.07*
AC2	*n*	*n*	*n*	*n*	*n*	*y* *(p=<0.05)*	*n*	*n*	*n*	*5.69*
AC3	*n*	*n*	*n*	*n*	*n*	*y* *(p=<0.05)*	*n*	*n*	*n*	*6.00*
PM1	*y* *(p=<0.05)*	*y* *(p=<0.05)*	*n*	*y* *(p=<0.05)*	*y* *(p=<0.05)*	*n*	*n*	*y* *(p=<0.1)*	*y* *(p=<0.05)*	*6.38*
PM2	*n*	*y (0.05)*	*n*	*n*	*n*	*n*	*n*	*n*	*y* *(p=<0.1)*	*6.00*
WC1	*n*	*n*	*n*	*n*	*n*	*y* *(p=<0.1)*	*n*	*n*	*n*	*6.08*
WC2	*n*	*n*	*n*	*n*	*n*	*y* *(p=<0.05)*	*y* *(p=<0.1)*	*n*	*n*	*5.79*
Mean score	*5.71*	*5.50*	*6.07*	*5.69*	*6.00*	*6.38*	*6.00*	*6.08*	*5.79*	

WE = Water engineer
AC = Academic
PM = Policy maker
WC = Water company employee

n = no significant difference in responses
y = significant difference in responses

Figure 7.12. *Result of two-tailed paired t-test (assuming unequal variances) of significance of variance between nine informed practitioner's perceived effectiveness scores*

The results in Figure 7.12 show that one policy maker's perceived effectiveness scores were significantly different from six other participants whilst the other was significantly different against two other participants. The higher means and the significance of variance between for policy-makers and other professions are interesting in the context of the effectiveness of Bns in communicating research issues to a wider policy audience.

7.2.2 Do Bayesian networks promote learning and the development of common understanding of water demand management issues?

The following results supported exploring the above research question:

1. *Learning* scores
2. *Transparency* scores
3. Significance of variance between *Learning* & *Transparency* scores and other perceived effectiveness indicator scores.

7.2.2.1 Learning scores

Average perceived effectiveness scores for *learning* for different organisational perspectives ranged from 5.25-6.25 and were highest among policy makers.
An observation during the workshop was how the tool facilitated discussion between practitioners from different backgrounds (e.g. policy-makers and academics) about the causes of water stress in the Upper Iskar.

7.2.2.2 Transparency scores

Average perceived effectiveness scores for transparency for different organisational perspectives ranged from 6.25-6.67 and were highest among academics. One practitioner commented that "in other modelling workshop that I have participated in I have always found it difficult to know how the model came to the conclusions it came to; there was no way of knowing what the source data used was and how the outputs were achieved. With this approach it is very easy to see how the model comes to the results that it comes too."

7.2.2.3 Significance of variance between perceived effectiveness indicator scores

To determine whether the null hypothesis that "there is no significant different between end-user's perceived effectiveness scores for statements related to learning compared to other indicators" should be accepted or rejected, paired- t-tests were used. Strategic planning and ease of use were not included in the analysis because each was only represented by a single statement in the evaluation survey. The results of the analysis for the other five perceived effectiveness indicators are shown in Figure 7.13, below.

The results show that the highest mean score among the five indicators of perceived effectiveness was registered for statements referring to transparency, and paired t-test results showed that transparency scores varied significantly (p=<0.05) from all other perceived effectiveness criteria.

	Organisational receptivity	***Reliance on decisions***	***Technical suitability***	***Transparency***	***Learning***	**MEAN**
Organisational receptivity	n	n	n	y (p=<0.05)	n	5.76
Reliance on decisions	n	n	n	y (p=<0.05)	n	5.78
Technical suitability	n	n	n	y (p=<0.05)	n	5.78
Transparency	y (p=<0.05)	y (p=<0.05)	y (p=<0.05)	n	y (p=<0.05)	6.39
Learning	n	n	n	y (p=<0.05)	n	5.78
Mean score	5.76	5.78	5.8	6.39	5.78	

Figure 7.13. *Result of two-tailed paired t-test (assuming unequal variances) of significance of variance between Learning & Transparency scores and other perceived effectiveness indicator scores (p=<0.05)*

The null hypothesis that "there is no significant different between end-user's perceived effectiveness scores for statements related to learning compared to other indicators" can therefore be accepted. The results, however, reveal that the same null hypothesis for transparency can be rejected, so the hypothesis that "there is no significant difference between end-user's perceived effectiveness scores for statements related to transparency compared to other indicators".can be rejected

7.2.3 Do Bayesian networks facilitate decision-making for water demand management?

The following results supported exploration of the above research question:

1. *Strategic planning* scores
2. *Reliance on decision* scores
3. Significance of variance between prior- and post- workshop *decision conflict, effort* and *confidence* scores

7.2.3.1 Strategic planning scores

Average perceived effectiveness scores for strategic planning for different organisational perspectives ranged from 5.00-7.00 and were highest among policy makers. These results are based on a single statement in the questionnaire and are, therefore, somewhat less reliable than those for other perceived indicator variables.

7.2.3.2 Reliance on decision scores

Average perceived effectiveness scores for reliance on decisions for different organisational perspectives ranged from 5.42-6.33. Reliance on decision scores were lowest among water company employees and highest among policy makers.

7.2.3.3 Significance of variance between prior- and post- workshop *decision conflict, effort* and *confidence* scores

To determine whether to accept or reject the null hypothesis that "there is no significant difference between perceived effectiveness scores for statements related to decision stress when using and not using Bayesian networks", average scores for the three decision stress criteria for all workshop participants were analysed and the results are shown Table 7.2, below.

Table 7.2. *Paired-sample t-test results between prior- and post- workshop scores for decision stress criteria*

DECISION STRESS CRITERION	PRIOR-WORKSHOP	POST-WORKSHOP	DIFFERENCE USING BNS	P(T<=T) TWO-TAIL	SIGNIFICANT (P=<0.05)
Conflict*	1.33	1.00	+0.33	0.78	NO
Effort*	-1.40	1.33	-3.13	0.004	YES
Confidence*	-0.20	1.13	+1.33	0.11	NO

*Response options as follows:

Conflict: High = -3, low = +3

Effort: Much effort = -3, little effort = +3

Confidence: Not confident = -3, very confident = +3

Decision conflict scores were marginally higher when using the tool than when not using the tool, results were not statistically significant, so <u>the null hypothesis that "there is no significant difference between perceived effectiveness scores for</u>

statements related to decision conflict when using and not using Bayesian networks" can be accepted. Aloysius *et al* (2006) found that higher decision conflict can result where decision-makers are required to make trade-offs between options, and it might be suggested that the lack of deterministic nodes in Bns, which forces the user to make judgement decision based on probabilities, can be a cause of higher decision conflict.

Decision effort scores were lower using the support tool and a test for difference between the sample results (using a paired-sample t-test) was significant (p=<0.05). The null hypothesis that "there is no significant difference between perceived effectiveness scores for statements related to decision effort when using and not using Bayesian networks" can therefore be rejected, and the results indicate that decision-making effort is reduced by using the Bayesian network tool.

Decision confidence scores were marginally higher when using the tool, although results were not significant. The null hypothesis that "there is no significant difference between perceived effectiveness scores for statements related to decision confidence when using and not using Bayesian networks" can be accepted. During the workshop there was discussion about the models outputs regarding whether current demand levels could be maintained given a repeat of the conditions that led to the 1994-1995 drought, and the general consensus, based on the water balance model and current demand data, was that demand would not be maintained.

The following discussion first considers how receptivity to Bayesian networks might be affected by the availability of skilled personnel. Former research which showed that DSTs are particularly applicable to unstructured decision environments, and evidence from the end-user evaluation, provides the basis for a discussion about Bns as a resource to improve adaptive and institutional capacity.

7.3 Discussion

Receptivity theory (Seaton & Cordey-Hayes, 1993; Trott *et al*., 1995; Jeffrey & Seaton, 2004; McIntosh *et al*, 2007) refers to the ability (or capability) to absorb, accept and utilise a new technology or innovation. The high scores from the evaluation, especially for technical suitability, transparency and learning, indicate that Bns are effective in facilitating planning processes where individuals with different disciplinary backgrounds or from different organisations, are required to collaborate.

However, the requirement for seasoned modellers to facilitate the use of Bns is identified below as a possible constraint to their wider use.

7.3.1 Receptivity: availability of experienced model developers

Porter (1986) observed that statistical literacy, like reading and writing, is indispensable for an educated citizenship in a functioning democracy, and the dissemination of statistical information in the 19th and 20th centuries has been linked to the rise of democracies in the Western world. Unlike reading and writing, however, statistical literacy – the art of drawing reasonable inferences from such numbers – is rarely taught (e.g. Garfield & Ahlgren, 1988; Shaugnessy, 1992; Sedlemeier and Gigerenzer, 2001) and the result of this has been termed "innumeracy" (Paulos, 1988).

Methods for teaching of Bayesian reasoning have been investigated and reported in former research. For example Gigerenzer & Hoffrage (1995) and Sedlmeier & Gigerenzer (2001) examined the idea that "natural frequencies, rather than probabilities shown as percentages, seem to correspond to the format of information that humans have encountered throughout most of evolutionary development" (Gigerenzer & Hoffrage, 1995). Varis and Kuikka (1999) found positive responses from students applying policy models developed for natural resources management in Finland. Their research supports the idea that a 'learning-by-doing' approach to learning about Bayesian approaches using computer-based modelling tools would be successful and the wide availability of ready-to-use software that allows Bn models to be developed and used on a PC would support this approach. It is suggested that teaching of Bayesian approaches will need to be more widely incorporated into school and university courses, possibly focussing on disciplines such as natural resources management, if there use in environmental planning and management is to be more widespread.

7.3.2 Need for structuring in complex planning environments

During the knowledge elicitation presented in Chapter 3 informed practitioners described current WDM policy in Bulgaria as being fragmented and uncoordinated and it might be suggested that one role for Bns lies in providing structure to the planning process. Researchers have consistently indicated that organizational context, i.e. the effect of rules, procedures, and formal policies, is a crucial area of concern for decision support tool (DST) evaluation (Sanders and Courtney, 1985). Ginzberg (1980) has suggested that decision systems have a greater chance for success in organizational units facing unstable environments. Roland (1980, p8) states the case appropriately: "If the organizational task is composed of well-structured problems, there will be minimal need for a DSS". Evidence to support these suggestions can be found in empirical research. For example, Cheney and Dickson (1982) found that computer-based information systems increased the degree of stability in the user's decision environment, but had little impact on reducing the degree of complexity. Implications from a study by Sanders and Courtney (1985) add support to Cheney and Dickson's study in finding that environments previously perceived as unstructured may become more "structured" during the DSS development process and they assert that "this supports the assertion that the greater level of *a priori* unstructuredness, the more successful the DSS becomes".

Successful introduction of WDM calls upon institutional and adaptive resources, referred to by Turton (1999) as "secondary resources", who describes them as "the changes that need to take place within the society, in order to meet the challenge of increased water scarcity. The change is generally some form of secondary water management strategy, namely demand-side management, that comes into play at a point in time when the first phase of supply-side management faces a crisis and is unable to mobilise more water by the application of traditional supply-side solutions" (Turton, 1999, p13).

Although the role of Bns in structuring decision or planning processes was not tested during the evaluation, the positive results and evidence that they alleviated stress in water management decisions by reducing 'decision effort', supports the suggestion that Bns provide support by providing structure to the WDM planning process making it easier to comprehend. The suggestion is that if DSTs can be developed from generic models of WDM 'problems', such as the models developed in Chapters 5 & 6, they would provide a valuable source of adaptive and institutional capacity by structuring the implementation process, that could be transferred to other river basins.

7.4 Conclusions

Even though evaluation has been stated as one of the principle stages in planning and decision process theory, it is noted that significant evaluation of process attributes and results of participatory modelling experiences remains an underdeveloped practice that will need to be significantly improved in future (Bellamy *et al*., 2001). The evaluation described in Chapter 7 was, as far as we are aware, the first formal evaluation of the use of Bns in IWRM or demand management. As such, the results contribute to the body of knowledge about their applicability to this problem domain. In addition, the approach used contributes to Information Systems evaluation research methods to inform the design of future evaluations.

The modelling approach performed particularly well in terms of technical suitability, transparency and learning for all workshop participants. Policy makers perceived effectiveness scores were significantly (p=<0.05) higher than water engineers and water company employees. It is possible to suggest that the transparency of Bns and their effectiveness in promoting learning may make them compatible with policy-maker's knowledge requirements which would make them a useful tool for addressing science-policy interfaces.

Average organisational receptivity scores by profession were all in a very narrow band between 5.67 and 5.83 indicating moderate to strong agreement with the statements regarding the applicability of Bns to their work. Workshop participants perceived that making decisions with the support of the Bayesian network models was significantly (p=<0.05) less effortful than without them.

The relevance of tasks and evaluation criteria to workshop participants may have influenced the scores. For example, the information requirements for a water engineer or water company employee are different from those of a policy maker. These differences in information requirement may also explain some of the variability in evaluation scores.

The relative unfamiliarity of the informed practitioners with Bayesian networks and the limitation of the evaluation workshop being held over a single day, meant that it was not possible to examine some of the more detailed questions about compatibility between the method (i.e. Bns) and the problem domain (i.e. WDM). This influenced the subject and wording of the statements in the evaluation instrument which might be criticised, and would bring into question the validity of the evaluation results. However, the evaluation results are positive in encouraging further application and research into the use of Bns to facilitate implementation of WDM strategies.

Chapter 8

Lessons and directions for the use of Bayesian network modelling in water demand management implementation

Introduction

In Chapter 8 the findings of the case study fieldwork are discussed in the context of how Bayesian network modelling addresses issues of validity and legitimacy. A philosophical debate on how to conduct Information Systems (IS) research, i.e. positivism vs. interpretivism, has been the focus of much recent attention (Robey, 1996; Klein and March, 1995; Weber, 2003). Hevner *et al*. (2004, p75) write that "… the major emphasis of this debate in IS research lies in the epistemologies of research; that is, somewhere some truth exists and somehow that truth can be extracted, explicated and codified." The behavioural-science paradigm seeks to find 'what is true'. In contrast, the design-science paradigm seeks to create 'what is effective'.

Determining what is 'true' and, at the same time, what is perceived to be 'effective' in terms of support tool performance are central issues that overlap with historical debates (e.g. Rosenhead, 1989; Boulaire, 1992; Landry *et al*., 1996) about the importance of validity and legitimacy in IS research. The debate has generally pitched one against the other in a hierarchy, e.g. knowing 'what is effective' is dependent on knowing 'what is true', whilst recognising that what is perceived to be immediately 'true' can sometimes be affected by individual's judgements about what is 'effective'. For water demand management, where there is an emphasis on forecasting to design the future management of river basins, a further dimension arises because the aim of any research in this area is judging what *will be* effective in the future which is dependent on knowing what *will be* true. It might be suggested that this is why there is an emphasis on the need to manage risk and uncertainty in the WDM problem domain.

The discussion in Section 8.1 uses the results of the case study fieldwork as evidence of how Bayesian modelling addresses the parallel need for validation and legitimisation of models. Section 8.2 refers to the evaluation results as a basis for a discussion about the potential pay-off of using Bns from different stakeholder perspectives. In Section 8.3 lessons are drawn from the case study fieldwork to support a discussion about legitimisation in the context of a country in the midst of economic and social transition.

It should be pointed out that the discussions below are not an attempt to gauge the validity or legitimacy of the Bn models developed during the case study fieldwork but rather to draw lessons from the research about how attributes of Bayesian modelling address validation and legitimisation issues, thereby supporting integration of science and practice.

8.1 Bayesian modelling to facilitate validation and legitimisation of the water demand management decisions

8.1.1 Validation

Model validation is an essential step in the modelling process to build-up confidence in the current model or to allow selection of alternative models or model parameters (Tedeschi, 2005). Because the WDM problem domain is characterised by complexity and non-repeatability of events problems arise when attempting to evaluate the validity of model outputs in terms of their accuracy and precision. As discussed below, some of the problems that arise are a result of factors associated with WDM implementation, whereas others are due to a combination of the problem domain and the modelling / analytical method used.

8.1.1.1 Accuracy and precision

Accuracy measures how closely model-predicted values are to the true values, whereas precision measures how closely individual model-predicted values are to each other. In other words, accuracy is the model's ability to predict the right values and precision is the ability of the model to predict similar values consistently. Figure 8.1 (below) from Tedeschi (2005, p5) illustrates the difference between accuracy and precision using the analogy of target practice.

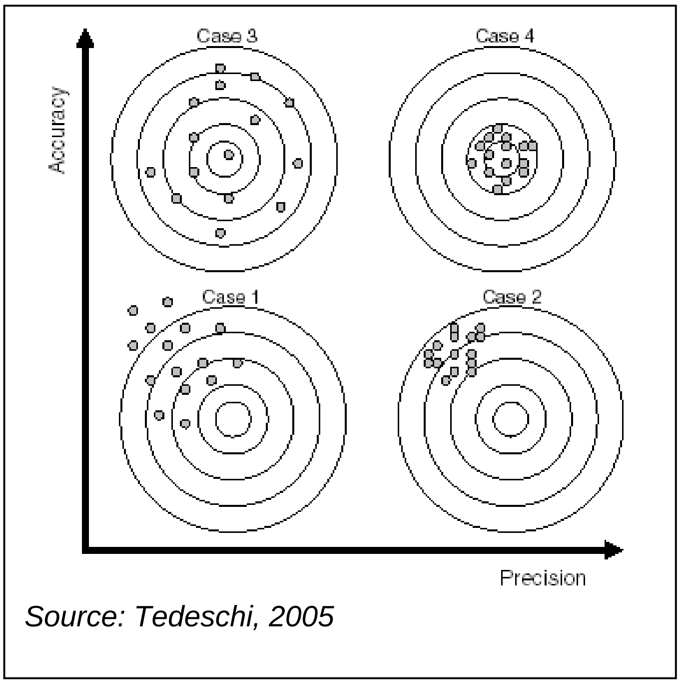


Figure 8.1. *Schematic of accuracy versus precision: Case 1 is inaccurate and imprecise, case 2 is inaccurate and precise, case 3 is accurate and imprecise, and case 4 is accurate and precise*

Testing a model usually involves comparison of predicted outputs with a real world ‘control’ sample. For implementation WDM strategies non-repeatability of events limits how models can be tested both at the legislation and design stages. For example, during the design stage testing the accuracy and precision of the household water demand or water saving forecasting model presented in Chapter 6, Section 6.4, is challenging but could be achieved using a control sample, as has been demonstrated in former studies described in Chapter 1, Section 1.2.2.1 (e.g. Turner *et al*., 2005). However, testing the uptake forecasting model presented in Chapter 6, Section 6.3, is more problematic because implementation conditions, i.e. household/ demand variables profiles for a population will never be repeated.

For the legislation stage, problems of forecasting water availability (i.e. reservoir level forecasts) can be partially addressed by using historical data and hydrological modelling, as discussed in Chapters 4 & 5, although the rare or one-off nature of droughts means that such forecasting models are still difficult to validate. Developing models for forecasting bulk water savings and the costs and benefits arising from these savings faces major problems of non-repeatability because implementation of WDM strategies in a city is a one-off event. However, the premise of the 'design' models in Chapter 6 is that disaggregating uptake and water savings to the neighbourhood scale will provide information to support the detailed implementation of measures and the design of relevant uptake mechanisms.

Model testing is commonly used to prove the rightness of a model and the tests are typically presented as evidence to promote their acceptance and usability. However as a number of authors have commented (Sterman, 2002; Tedeschi, 2005; van den Hove, 2007) the understanding and acceptance of the wrongness and weaknesses of a model strengthens the modelling process, making it more resilient and powerful in all aspects during the development, evaluation, and revision phases. Rather than ignoring the fact that a model may fail, design evaluations to identify and incorporate the failures of a model strengthen the learning process. Sterman (2002) points out that in systems thinking, the understanding that models are wrong and acceptance of the limitations of our knowledge is essential in creating an environment in which we can learn about the complexity of systems. The findings of the technical evaluation that Bns offer support for identifying research priorities and evaluating confidence in data, and the findings of the end-user evaluation regarding their transparency for analysing strengths and weights of causal relationships both demonstrate their potential as an interface for communicating research issues such as uncertainty and data availability to a wider audience.

In the following section the importance of data and information processing for validation in complex problem domains such as water demand management is discussed. The suitability of Bns for supporting validation tasks is reviewed citing examples of how Bayesian modelling was applied during the case study fieldwork.

8.1.1.2 Complexity and uncertainty

Uncertainty is considered to be a property of the environment resulting from two powerful forces: complexity and the rate of change. Complexity refers to the number and diversity of the elements in an environment and the rate of change refers to how rapidly these elements and the interactions between them change (Sahota, 2004). Duncan, (1972) showed that what affects organisations is not the environment so much as the decision maker's perceptions of how uncertain the environment is; these concepts are summarised in Figure 8.2, below.

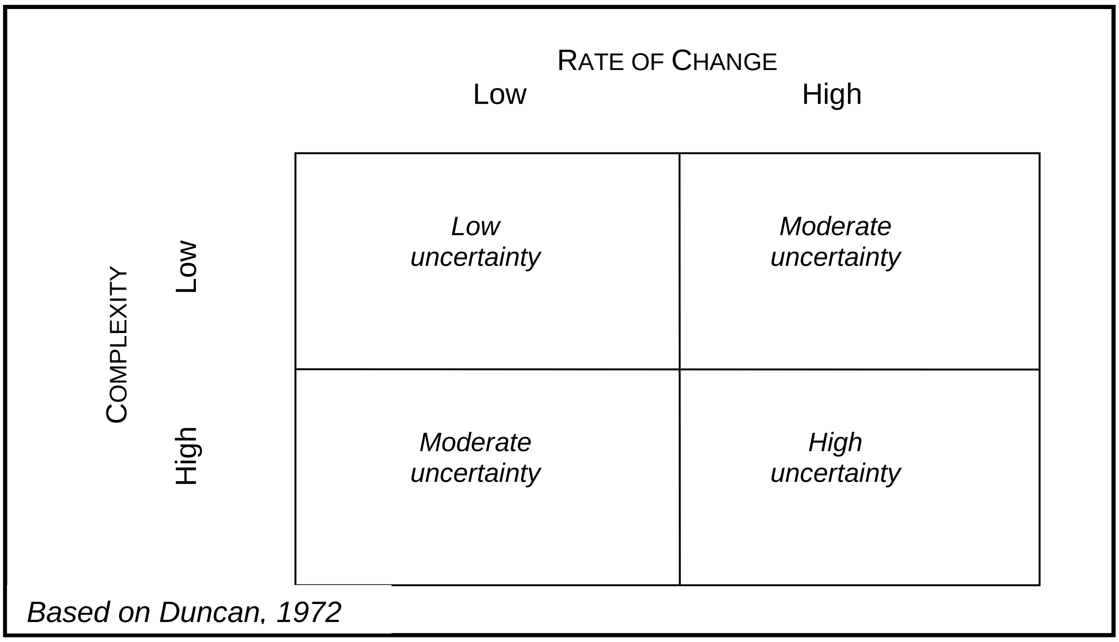


Figure 8.2. *Environmental uncertainty is defined by the amount of complexity and the rate of change in the organisation's environment*

Contemporary organisational theorists recognize that uncertainty lies not in the environment but in the individuals who consider the environment when they make organisational decisions. This viewpoint has come to become associated with the information perspective in organisation theory (Aldrich and Mindlin, 1978) which argues that managers or policy makers feel uncertain when they perceive the environment to be unpredictable and this occurs when they lack the information they need to make sound decisions. The concepts that encompass the information perspective of uncertainty are presented in Figure 8.3, below.

When managers perceive environments as stable and as having minimal complexity, they find that the information they need is both known and available, and as a result experience low levels of uncertainty (Hatch, 1997). When environments are perceived to have high complexity or to be rapidly changing, managers confront either too much information or the challenge of keeping up with changing information. In the case of high uncertainty, managers perceive a highly complex and changing environment and will face an overwhelming amount of information but they will not know which to attend to due to constantly changing circumstances.

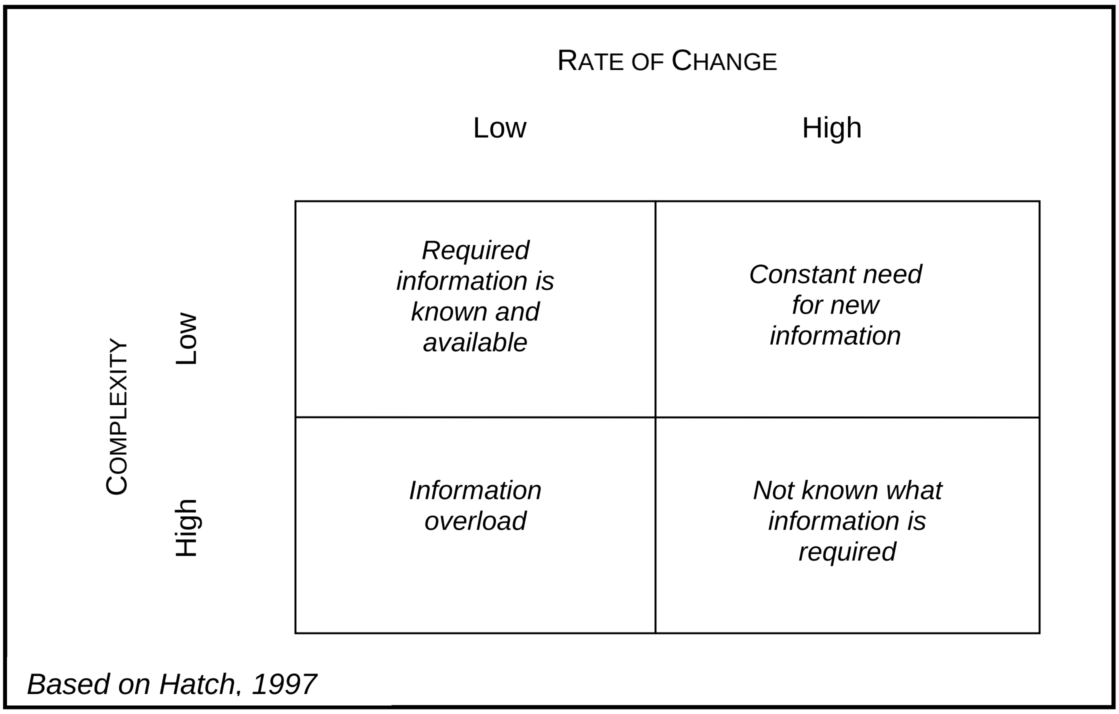


Figure 8.3. *Links between conditions in the perceived environment, uncertainty, and information*

For WDM the 'environment' not only refers to the natural system in terms of water availability (i.e. meteorology, hydrology), but also the human system which includes numerous actors (i.e. individuals & their households) who make up the implementation conditions on which decision are based. The large number of actors makes the range of potential classes of 'water users' very large, leading to complexity in collecting information. Bayesian modelling methods for addressing these issues, which relate to complexity of collecting and processing information and evaluating the resulting models in terms of uncertainty and statistical significance, were demonstrated in Chapter 6.

The slow-onset nature of drought, as demonstrated in the water balance model in Section 4.1, Chapter 4, may imply that the rate of change in Figure 8.2 for WDM planners is low. There are, however, other issues that need to be considered (e.g. timing of implementation, existence of preparedness strategies, and the risk attitude of the water managers / policy makers) that require a holistic approach to the modelling process. Box 8.1 lists Bayesian analysis was used during the case study fieldwork to support validation.

Box 8.1. Bayesian analytical methods that support model validation

1. Structural learning:

a) Data-based structural learning: Quantifying the strength of dependencies between variables in a data-set

b) Knowledge-based structural learning: Using expert knowledge to provide structure to decision models

2. Sensitivity analysis:

a) Reducing complexity by identifying and excluding variables that do not require treatment for uncertainty

b) Prioritising research and data collection priorities by identifying variables that are subject to greater uncertainty

3. Model instantiation:

a) Exploring what-if scenarios

b) Examining the utility of human interventions (Influence Diagrams)

c) Supporting discussion about the 'value of truth' of model outputs by providing a transparent interface that presents the statistical significance of different model instantiations

4. Value of information analysis:

a) Examining the value of collecting data under different conditions

Having examined the importance of validation, the following section differentiates between legitimisation and validation prior to further discussion about challenges to legitimisation and integration of Bayesian networks.

8.1.2 Legitimisation

Legitimacy is a highly desirable attribute of human activities that provides an efficient way to maintain, adapt or change an entity or a system (Landry *et al*., 1996). Broadly speaking, legitimisation refers to the perceived acceptability among stakeholders within an existing social network or organisation to a change. An important distinction between validation and legitimisation is that whereas validation refers to verification according to the 'laws' or 'canons' of science, legitimacy refers to verification according to society as a whole, which, depending on the subject, might include: politicians, managers, commercial enterprises, the general public, etc.

A number of authors (Rosenhead, 1989; Boulaire, 1992; Landry *et al*., 1996) have focussed on legitimacy of models in terms of how they enable or constrain thought and action among their users. Rosenhead (1989) suggest that “it is generally their flexibility that makes models more enabling than restrictive”. The enabling side of models directly leads to what Landry *et al*. (1996) refer to as their *instrumental* mode (i.e. use for understanding, thinking and suggesting action).

Models are also constraining devices. As suggested by Poggi (1965), and many others after him (Benson, 1977; Pondy and Mitroff, 1979; Astley and Van de Ven, 1983; Weick, 1984), any modelling method is not only a way of seeing but also a way of not seeing. Indeed, each model bears with it a set of simplifying assumptions and hypotheses about the phenomenon under investigation. It imposes a perspective that limits the way of looking at the phenomenon, and consequently of acting on it, while other assumptions, hypotheses and perspectives could have been advocated and used with different results (Landry *et al*., 1996). Furthermore, the more sophisticated a model is, e.g., mathematically, the less it is likely to be used directly in organizations: it is language that is the common currency of organizational life (Eden, 1989) and organizational problem solving (Eden, 1986). Being dependent on Operational Research (OR) specialists also makes those actors partially lose their autonomy (Landry *et al*., 1996). Therefore, model use creates dependency and uncertainty: models are threatening and risky to use.

Landry *et al*. (1996) refer to two modes of use where models can be perceived as constraining devices: (i) the *underground mode* (i.e. instruments through which the need for personal feeling of consistency, morality and potency has to be accommodated) and (ii) *symbolic mode* (i.e. instruments through which the need for restoring external coherence (bargaining, compromise, consensus) has to be accommodated).

The payoff from using computer-based support tools, which refers both to the return on investment in terms of resources spent in developing them and the expected output, provides an indication of their potential for adoption. However, measuring the payoff or the expected payoffs in an organisational context is difficult and therefore payoffs are frequently unrealized (Alavi & Joachimsthaler, 1992; Finlay and Forghani, 1998). Meador *et al*. (1986) point out that perhaps the evaluation of an organizational support tool that serves multiple managers and functions is much more challenging than a personal support tool.

For tools aimed at providing support in cross-sectoral planning, payoffs are likely to be equally difficult to measure. The end-user evaluation results of perceived effectiveness scores are considered below as suitable surrogates or predictors of support tool payoff and provide a basis for continuing the discussion about legitimisation from the perspective of the public, politics and management, and science.

8.2 Applicability of Bayesian networks from different organisational perspectives

The Water Framework Directive (WFD) 2000/ 60/EC established a framework for community action in the field of water policy. The key objective of the directive is to achieve, by 2015, a ‘‘good water status’’ for all European surface and underground waters. One of the five main instruments that will be used to reach this objective is Public Participation (PP). The main article of the WFD concerning PP (Article 14) states:

‘‘Member States shall encourage the active involvement of all interested parties in the implementation of this Directive, in particular in the production, review and updating of the river basin management plans.’’

Public participation is generally defined as a process by which citizens, as individuals or collectively, are engaged in planning or decisions that impacts their livelihoods or environment (Maurel *et al*., 2007). Several benefits, but also drawbacks, can be expected from PP, as described in a recent synthesis (Drafting Group, 2002; Mostert, 2003). This synthesis shows that PP is necessary but has to be organised in order to make it work, especially in terms of the types of outcomes expected and which elements of ‘the public’ to involve. Different types of participation that refer to different levels of involvement are commonly conceptualised as Arnstein’s ladder of participation (Arnstein, 1969). Article 14 of the WFD recognises the need for three types of participation in river basin planning: information supply; consultation (plans and options are made available for comments); and active involvement (Maurel *et al*., 2007).

The discussion below identifies information supply as the main area where Bayesian modelling can facilitate participation. Their transparency and effectiveness in promoting dialogue and discussion, as elicited through the end-user evaluation, along with high perceived effectiveness scores across the four organisational perspectives represented in the evaluation, are referred to as evidence of their suitability for supporting negotiation and participation.

8.2.1 Public

Maurel *et al*. (2007) classify Information and Communication (IC) tools into two types for the size of group they are designed to facilitate. The first type corresponds to *small working groups* whilst the second corresponds to the *general public*. For the general public Maurel *et al*. (2007) comment that “such interactions (i.e. with the general public) are typically achieved via mailings and the world-wide web.”

The use of Bns for analysing household survey data reported in Chapter 6 demonstrates their effectiveness in representing the views of the general public through a common interface. Although the different versions of the behavioural dependencies model have not yet been tested and evaluated by the informed practitoners in the Sofia case study, the results from the end-user evaluation imply that there is no reason why Bns would not also be suitable for the disseminating household survey results about public perceptions and attitudes to water conservation to a wider audience. Such models would provide practitioners and policy-makers with information to support the design of mechanisms to increase participation in water conservation programmes (e.g. the need to address issues such as perceived behavioural control).

8.2.2 Management

Spencer (1962) remarked that in the absence of uncertainty, the co-ordination role of management would become superfluous in all but the initial phases of a project. Whilst adopting a simplified view of the management function this comment highlights the fundamental role that uncertainty plays in organisational control. The evidence from the case study field work indicates that for implementation of WDM strategies, Bns can provide valuable support to managers and policy makers in their ‘co-ordination role’ by reducing decision ‘effort’. It is suggested below that Bns reduce decision effort by facilitating the task of information collection, structuring and dissemination within and between organisations involved in WDM planning and implementation.

It might be suggested that the adoption of decisions support tools (DSTs) within an organisation to facilitate standard operating procedures (SOPs) is the strongest indicator of their legitimacy at the organisational level because in this way they can have a significant impact on decision making processes and on the output of any decision support tool/process. SOPs are a means to removing variations in work performance caused by people completing the same work processes in different ways (Stup, 2004). They describe the steps that people should use to complete a process by providing a detailed description of commonly used procedures. Whilst they provide direction, improve communication, reduce training time, and improve work consistency, SOPs can also create barriers to using support tools due to improper and inappropriate SOPs that includes fear of “stepping outside the boundary”. Participative development, which involves design and legitimisation of DSTs specifically to support SOPs, has been applied in former research by Stup (2004) and requires that everyone affected by the SOP (the stakeholders) to contribute to the development and integration of the DST (Stup, 2004).

At present in Sofia, as in most other major cities in Europe, there is no single agency responsible for co-ordinating and overseeing implementation of WDM. A result is that there is no representative within the social / organisation network taking on the role and ‘championing’ WDM. Whilst evidence from the knowledge elicitation and end-user evaluation demonstrates that there is willingness and concern at all levels about the risk of water scarcity and the need for demand management, the absence of an agency focussed on co-ordinating activities means that the implementation process has tended to be reactive to changing conditions, rather than being pro-active.

Under the right conditions, standard operating procedures (SOPs) for WDM are likely to be adopted by either the water company or, if such a body exists, an agency such as the one proposed above. Evidence from the technical and end-user evaluations indicate that Bayesian network modelling can be an effective tool for prioritising data collection, to support processing of information, and presentation of that information to practitioners and policy-makers for both WDM legislation and design. It is proposed that further development and integration of the models developed in Chapters 4, 5 & 6 into work practices would reduce uncertainty about how to plan and implement WDM in terms of legislation and design at the management level, and could conceivably be used in learning and training SOPs.

Barriers to the receptivity to Bayesian network support tools in organisations were discussed in Section 7.3.1. Another potential barrier to their adoption in organisations is the complexity of collecting and validating data to populate models. The structure that the use of support tools might place on the planning process and the potential loss of autonomy for policy-makers, managers etc, also raises issues of legitimacy that, it is suggested, might constrain full-integration of Bayesian networks into the planning process. This last issue is discussed in more detail in Section 8.3 below. The following section considers the pay-off of using Bns from the perspective of policy-makers.

8.2.3 Politics

The term “water stress” has in recent years been adopted to describe the numerous water management challenges facing human populations. The word ‘stress’ has numerous meanings. In physics, stress is used interchangeably with pressure. In psychology, ‘stress’ is used to describe states such as worry, confusion, conflict, and panic (OED). There is an onus on policy-makers to set the conditions for reducing water stress. Setting the right legislation to permit demand management to take place at the individual and the organisational level is an example that has been referred to throughout this thesis. Starting from scratch, however, the task of gathering the right information to examine the inherent uncertainties faced during implementation of WDM strategies may make this task overwhelming for policy-makers, and is an important issue that needs to be addressed to reduce water stress.

Goodwin and Wright (2004, p373) have shown that, in an organisational context, inertia in strategic planning is a common response to an increase in perceived environment threat, and in such a state an organisation will be less capable of thinking creatively about strategic decisions (Goodwin and Wright, 2004). Under such circumstances better access to relevant information would provide an important resource for policy-makers allowing them to think more creatively about how to introduce mechanisms to enable all stakeholders involved in the management of water resources to adapt their water use behaviour according to the prevailing conditions of water availability. Strong dependencies between water saving ‘behaviour’ and ‘perceived behavioural control’ in the behavioural dependencies model in Section 6.2, Chapter 6, are interesting in this regard because they are evidence that, at the individual / household scale, enabling water saving behaviour to take place requires legislative action (e.g. efficiency standards, design norms, rebates on technology and its installation etc). If the same dependencies regarding the role of governance in enabling water conservation behaviour are reflected at the organisational level then it is imperative that policy makers in regions of water stress have all relevant information available to them.

The availability of information and the ability to process this information into knowledge that can be used to inform decisions are important factors in an individual's ability to perform their work and to make effective decisions. If an individual waits until they have all the information that they need to make a decision, however, the window of opportunity for their action to be effective may pass.

As described in Chapter 4, finding a balance between having too little and too much information is one of the tasks of Bayesian modelling. Box 8.1 (above) lists examples of how Bns provided support in facilitating validation of the information collected during the case study field work and its use in informing decisions. The positive perceived effectiveness scores from the policy-makers involved in the end-user evaluation lend evidence to their need for structured information and the support provided by Bns. The transparency of Bayesian network models, their handling of uncertainties and risk, and their graphical representation makes them applicable for communicating information and supporting dialogue and discussion.

Application of Bns in a policy context requires the ongoing support of an experienced IS researcher. The section below discusses how the use of Bns and the interaction between policy-makers and researchers has the potential to address a number of science-policy interfaces.

8.2.4 Science-policy interfaces

In Chapter 1, Section 1.3.2, six science-policy interfaces relevant to the WDM problem domain were identified from a review by van den Hove (2007) and these are presented again below in Box 8.2.

Box 8.2. Science-policy interfaces relevant to the WDM problem domain

1. To bring about communication and debate about assumptions, choices and uncertainties, and about the limits of scientific knowledge
2. To allow for articulation of different types of knowledge: scientific, local, indigenous, political, moral and institutional knowledge.
3. To provide room for a transparent negotiation among standpoints (participatory processes).
4. To allow for balancing issue- and curiosity-driven science and their articulation in knowledge for decision-making processes
5. To include a reflection on research priorities and research organisation

6. To allow for genuine trans-disciplinary articulation between social and natural sciences

The theoretical problems arising from the above science-policy interfaces that are discussed below are presented in the schematic in Figure 8.4, below.

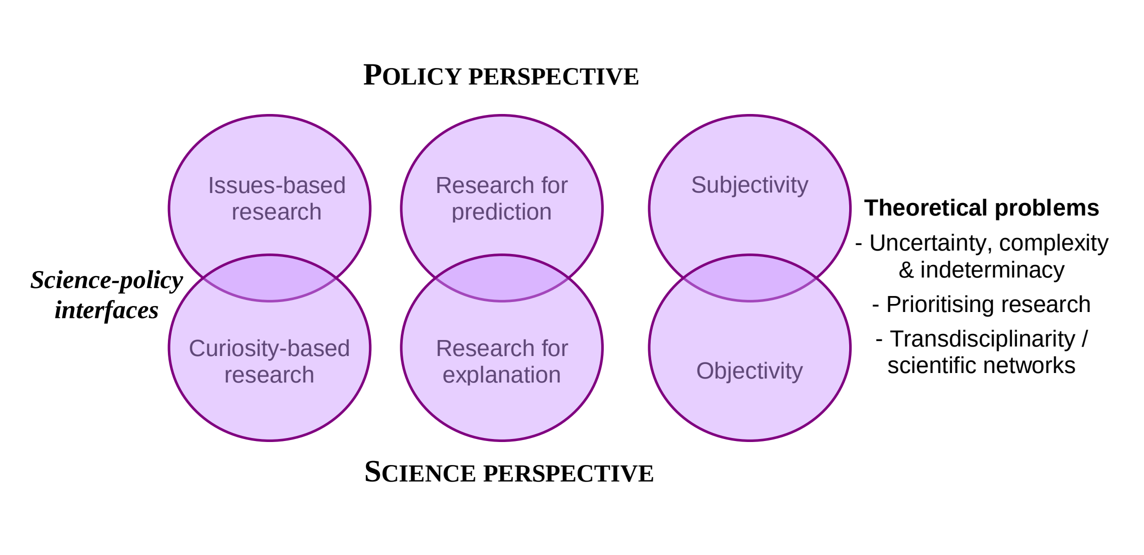


Figure 8.4. *Bayesian modelling addresses theoretical problems arising from science-policy interfaces in water demand management*

The following is a discussion about how the development and evaluation of Bns, as described in Chapter 3 to Chapter 7, has potential to address the above theoretical problems arising from the science-policy interfaces in the WDM problem domain.

8.2.4.1 Uncertainty, complexity and indeterminacy

Accepting the limitations of scientific knowledge and the value of transparency in representing the resulting uncertainties in models, which refers to the first science-policy interface in Box 8.2, was discussed in the context of model validation in Section 8.1.1. Van den Hove (2007, p817) describes how, "…contrary to some a priori fears of relativism that are often found in both scientific and policy communities, such transparency and explicit statement of boundaries does not weaken the power of science—or maybe only some undue power—but can correspond to a reinforcement of scientific quality." Limits to knowledge are also associated with the meaning of research as input to policy-making and relates to the complexity, uncertainty and indeterminacy that arises when explaining and predicting human interaction with natural systems (O'Connor, 1999).

For water demand management where a range of individuals and organisations with varying stakes are involved it is desirable for researchers to be able to communicate complex issues regarding causes of uncertainty and data collection through a common interactive interface. Proving the validity of some models for prediction is likely to remain problematic where the decision in question is non-repeatable. There are, however, areas where Bayesian modelling can be useful, driven by the scientific community, to provide an interface for communicating and discussing causes of uncertainty and the limitations of knowledge to a wider policy audience, so that measures can be put in place, awareness can be raised, or data collection can be targeted accordingly. Evidence from the end-user evaluation supports this and provides an impetus for further research into the use of Bns in communicating these issues.

8.2.4.2 Prioritising research

The process of decision analysis that is required to develop Bayesian models provides a number of identifiable opportunities for prioritising research.

Knowledge elicitation is the first point of contact between science, policy and practice and provides the model developer with information to construct prior models of the problem domain. In Chapter 3, Section 3.3.2, the value of the knowledge elicitation activity in allowing for balancing of issue- and curiosity-driven science and their articulation in knowledge for decision-making processes (see the 4th science-policy interface in Box 8.2) was discussed.

Sensitivity analysis, demonstrated and discussed in Chapter 4, Section 4.4.2, supports identification of model parameters whose probabilities are distributed over a large number of variables or whose state has a strong influence on the hypothesis variable. Sensitivity analysis can also be applied to models that have been constructed and populated using expert knowledge to prioritising focal areas for research and data collection. Alternatively, construction of the prior model with experts can provide a forum for discussion about research priorities.

In addition to the roles that knowledge elicitation and sensitivity analysis can play in prioritising research, it is possible to suggest that the transformation of Bayesian network models constructed using only chance nodes into Influence Diagrams that incorporate decision and utility nodes provides further opportunities for balancing and prioritising research activities. A Bayesian network constructed using only chance nodes, can be considered to be a none-subjective representation of the world. By transforming the Bn model into an Influence Diagram (i.e. adding utility and decision nodes) subjective values (utility functions) are applied to the world being in a particular state, and human interventions are introduced. This step in the model building cycle also finds analogies between the integration of research and policy models, discussed in Section 2.1.1.

8.2.4.3 Transdisciplinarity

Research to support implementation of WDM strategies requires the use of methods drawn from physical and social science disciplines (i.e. hydrology, economics, and policy research). Bns lend themselves to a wide range of data types and representation of qualitative and quantitative variables, and their flexibility demonstrated in the models developed and reported in Chapters 4, 5 & 6, support their candidacy for use in research domains that attempt to address a broad range of issues from social science, policy and planning. Examples where Bns were used to analyse dependencies between indicators from different disciplines from Chapters 5 & 6 include:

- Human interventions > environmental indicators
- Human interventions > decision variables (e.g. LAC sub-model)
- Environmental indicators > sustainability (e.g. forecasting sub-model)
- Household demand variables > water conservation programme design requirements (e.g. household demand and water savings forecasting models)
- Perceptions > intention > behaviour (e.g. behavioural dependencies model)

Further research is required to fully understand how Bayesian network modelling can address science-policy interfaces, and it is probable that their full potential will only be realised in combination with other modelling approaches.

The following section uses the results of case study field work to support a discussion about how legitimacy of Bayesian networks is likely to be different for different stages of their integration and that this affects the likelihood of their future use, described in terms of challenges to legitimisation. The discussion has wider-implication for the development and integration of computer-based supports tools in general.

8.3 Integration of computer-based support tools in self-organised systems

Sahota (2004) writes that where the developers of support tools do not take into consideration new organisational forms such as exisiting informal networks, and related changes in decision making processes, constraints can arise to their adoption. In a similar vein McIntosh *et al*., (2007, p641) observe that "ongoing model and support tool development and research in the environmental sciences appears focussed primarily on technical, often software-oriented concerns" and that "little attention is being paid to the contextual issues that accompany the use of support tools, except as motivating factors (e.g. improving the applicability of science to management at minimal cost)."

The section below first describes the concept of informal networks and their importance in self-organising systems. The importance of informal networks in the Upper Iskar and Sofia case study and possible causes of their emergence in recent years is discussed. Suggestions of how the existence of informal networks might have influenced the end-evaluation results are proposed and lessons are drawn about how support tools such as Bns might best be integrated in future to facilitate the integration of science and practice.

8.3.1 Knowledge transfer and informal networks

Networks are organizational configurations that perform two functions: co-ordination and transmission. They consist of 'nodes', 'connections' and 'intensities of transfer' all of which are important for the generation and transfer of knowledge. Research organizations are part of the network that can facilitate regional development and the question of how to organize the transfer of information and knowledge has been the focus of much recent research (e.g. Willems and de Lange, 2007; van den Hove, 2007).

Lambooy (2004) provides a helpful distinction between data, information and knowledge. "Knowledge is different from data and information: data are unstructured facts, information consists of structured data, and knowledge is the capability to judge, to use information for defining problems and for solving problems. Sometimes, it can be codified in books, patents, or programs ('codified knowledge'). Data and information are given meaning by interpretation and their contexts. Data and information are relatively easy to transfer, even to other countries" (Lambooy, 2004, p644). Boekema *et al*., (2000) defines knowledge as being more often connected with people, especially when it is not yet codified (sometimes called 'tacit knowledge'). In that case, embeddedness is particularly important and can be connected with the governance structure of knowledge creation.

Simon (1962) once contended that 'Nature loves hierarchy.' He emphasized that, in the end, organizations often develop in the direction of a certain stability and hierarchy. Economists emphasize that interaction and co-operation among market parties are primarily based on utility motives, to be measured by prices, quantities, and frequencies. More recently, Transaction Cost Economics (TCE) has led to the emergence of a further mode of co-ordination or market structure which conceives of 'networks' as a third, or hybrid, alternative mode besides markets and hierarchies (Williamson, 1996).

In economic theory, the market is seen as the natural venue for relations; it uses prices and volumes as indicators for making decisions about allocation. Establishing relations may mean having to build non-market relations or embedded relations, and in this process, it is sometimes necessary to become friends or at least to have a meal together, write letters to each other, and to get some knowledge of the background of the relation (Lambooy, 2004). The 'content' of those relations cannot be confined to prices and quantities only: they are richer and encompass trust, experience, and history. Sociologists have defined such relations as 'informal networks' (Scott, 1991; Wellman, 1983). Because they direct the flow of information, power, and status in organizations informal networks are seen as an important social resource (Campbell, *et al*., 1986; Lin, *et al*., 1981).

Organizations are not only consciously devised structures, they can also be conceived of as a result of self-organization. Hayek (1937, 1973) introduced the concept of 'self-organization' in the approach to economic complexity. His idea was that the economic system consists of heterogeneous individuals, with different levels of cognitive ability, who cannot be 'co-ordinated', or 'controlled', by centralized commands. He argued that 'self-organization' was a better method of co-ordinating the multitude of individual decisions and situations than central planning. Both markets and institutions are expressions of self-organization. Hayek approaches 'self-organization' as 'spontaneous order' (Hayek, 1973, p36). Camazine defines it as follows: 'Self-organization is a process in which patterns at the global level of a system emerge solely from numerous interactions among the lower-level components of the system.” Moreover the rules specifying interactions among the systems components are executed using only local information, without reference to the global pattern’ (Camazine *et al*., 2001, p8).”

The social sciences often connect the concept of self-organisation with a learning process (Lambooy, 2004). Learning leads to changing relations of persons and firms with the environment. The members of the relevant group and organizations accumulate knowledge, which in turn can lead to the making of different decisions and adaptive behaviour. Myrdal (1956) called this feedback process ‘cumulative causation’. The process of development ‘finds its way’ through many individual decisions made without consultation. The individual members of the group or region act together without knowing exactly what the final results will be. Hayek (1937, 1973) emphasized that the cognitive competencies of individual actors are heterogeneous and limited, but that nevertheless the final results can be better than when governments or other planning bodies decided what to do.”

The concepts of informal networks and self-organisation described above are considered below with reference to the Sofia case from two perspectives: (i) Bulgaria being in a state of (economic and political) transition (ii) the water sector in Bulgaria currently being considered for privatisation.

8.3.2 Informal networks and self-organisation in Bulgaria

The general health and connectivity of informal networks has a significant impact on strategy execution and organisational effectiveness (Cross *et al*., 2002). Studies into social capital in Sofia (Danchev, 2005) provide insights into the current state of informal networks in the Upper Iskar region. Social capital is described by Danchev (2005, p25) as “feedback playing the role of a homeostatic mechanism of keeping the sustainability of economic systems in dynamics”. The study examined two basic measures of social capital (the level of confidence (trust) among the members of society and the level of integration (consensus in ranking the social preferences)) by means of a survey. Results indicated that at present both levels are in a relatively good state in the micro aspect, but in the macro aspect the level of integration is not high. The author refers to the slow reforms in the legal system in Bulgaria by several governments as evidence of the need to develop social capital at the organisational level. Commenting on results of the study, Danchev (2005) proposes that until social capital restores its feedback power, the economic reforms, the accession to the EU and all utmost social aims will move to realization painfully slowly and with a great loss of social energy. Furthermore, Danchev recommends that "joint efforts to facilitate cooperation and mutual discussion about the problems are a precondition to start useful initiatives for more comprehensive study of the social capital–sustainable development link. This is one of the crucial elements in the search to find the quickest ways to more effectively integrate the Balkans not only with the rest of the European region, but as well with the rest of the civilized and developed world" (Danchev, 2005 p36).

As mentioned in Chapter 3, the Sofia water company – Sofiyska Voda – has recently been privatised under a 25-year concession contract. It is suggested that privatisation of the water utility can be seen as 'self-organisation' on the macro-scale that has created new networks between the water utility, the water regulator and other ministries, and potentially also with the EBRD and the EU. This is the context within which water demand management implementation now takes place in Sofia. From the perspective of integrating science and practice and the use of computer-based DSTs it has implications for support tool integration or, more accurately, support tool legitimisation. For example, Howarth (1999) comments that, "for private enterprises, the financial profit motive is a strong driver of efficiency, and regulatory mechanisms should ideally be aligned accordingly". The profit motive needs to be addressed in any new regulation that is part of the decision process. This has implications from an IS research perspective, to consider whether such motives, or drivers, can and should be integrated into decision support models.

Landry *et al* (1996) describe such issues in terms of an 'organisational contract' and point out that the implications of a model on the organisational contract are important in determining perceptions of models as enabling or constraining devices. The conclusion might be that IS specialists should focus on ensuring legitimisation of models in the *instrumental* mode (i.e. promoting understanding, thinking and suggesting actions), making it useful and acceptable as an enabling device, whilst leaving room for further development and integration of the model as a negotiation tool later on (i.e. its use in the *underground* and *symbolic* modes). Reflecting on the case study field work reported in Chapter 3 to Chapter 7, it is possible to find evidence to support this approach to support tool integration as discussed below.

8.3.3 *Links between stages of support tool integration and challenges to legitimisation*

Firstly, the models used during the end-user evaluation represented information about historical water availability, water demand, and the economics of WDM. The function of the models was biased towards the *instrumental* mode (i.e. promoting understanding, thinking and suggesting actions) and authors (Boulaire, 1992; Landry *et al*, 1996) have suggested that in this mode models are perceived as enabling devices and pose less of a challenge to legitimisation. The positive results of the end-user evaluation provide empirical evidence to support this view.

Secondly, the models used during the end-user evaluation did not make any assumptions about the planning process in the Upper Iskar study. In this regard they did not challenge the existing organisational contract, relationships, historical networks of trust, or hierarchies. It is possible to perceive how evaluation and use of the conceptual model presented in Chapter 5 might involve a move towards the *underground* and *symbolic* modes of use and would thus increase the challenges to legitimisation, not only of the conceptual model structure, but more importantly, of the modelling technique being used and its adoption as a tool to support the process of decision analysis and integration of science and practice. The diagram in Figure 8.5, below, illustrates the above ideas about how model evaluation is linked to legitimisation and how, in turn, legitimisation is linked to the challenges to model integration.

It is understandable that the integration of DSTs to support cross-sectoral planning in water management, where the gravity of decisions can have major implications for organisational operational procedures as well as wider social, economic and environmental systems, should be constrained by a perception among planners, policy-makers and managers that the use of DSTs might undermine the trust, experience, history, and ultimately the robustness of the existing network. This is a very human issue.

		This study		*Future application*		
Stage in model integration process		Developing evaluating exploratory / diagnostic models	Implementing exploratory / diagnostic models	Developing / evaluating decision models (Influence Diagrams)	Implementing decision models	Supporting standard operational procedures (SOPS)
Legitimisation issues	**Support tool mode**	Instrumental		Underground / Symbolic		Instrumental / underground / symbolic
	Enabling / constraining	Enabling		Constraining		Enabling / constraining
Challenge to legitimacy		Low	Low	High	High	Medium

Figure 8.5. *Perceived challenges to integration of Bayesian networks indicated by the results of this study*

The above discussion regarding challenges to legitimisation of the use of Bayesian networks in water management imply that, from a scientific perspective, the emphasis should be always on the support provided in terms of how they facilitate decision analysis and 'thinking about the problem', as well as supporting communication between practitioners and researcher, and the positive results of the end-user evaluation support this view. The integration of support tools requires integration into the existing social and organisational network; it takes time to build up trust as well as knowledge about information requirements. In order for IS researchers to be able to carry out evaluation of the effectiveness of support tools in all modes shown in Figure 8.5, the timing of research projects may need to be re-evaluated to allow for the necessary integration to take place, and also to investigate how continuity can be achieved at the end of the project.

Chapter 9

Conclusion, practical implications and future research

Introduction

The aim of this thesis has been to evaluate the effectiveness of Bayesian networks in facilitating implementation of water demand management (WDM) strategies through their application in an ongoing cross-sectoral planning process in a water-stressed region in Europe. Like a number of other parts of the world, the city of Sofia in Bulgaria has suffered from chronic water shortages in recent decades. Since the 1970s, government officials in Sofia have advocated several controversial projects in the region including the construction of a massive complex of dams, channels and diversion structures, to transfer water from the Rila mountains to meet the city's needs. With the supply threshold being regularly exceeded and all accessible water resources being accounted for there is inevitably a more pressing need to look to demand-side approaches. However, despite escalating pressure on water resources in the Sofia region in recent years, the water utility, local and national governments and the public have made relatively limited advances in reducing domestic water demand, which currently accounts for around 70% of total water abstracted from the Upper Iskar River.

Chapter 1 of this thesis highlighted a distinction between two stages of WDM implementation: *legislation* and *design*. For the legislation stage of WDM implementation three aspects that require support were identified: (i) forecasting and backcasting, (ii) prior- and post- evaluation, and (iii) managing risk and uncertainty. Two support tool requirements for the design stage of WDM implementation were also identified in Chapter 1: (i) using household demand variables to forecast water saving potential and demand, and (ii) understanding and modelling of how implementation conditions affect programme effectiveness.

The knowledge elicitation activity in Chapter 3 supported framing of seven context specific research questions, presented in Chapter 1, Table 1.4 that were explored through the technical evaluation chapters (Chapters 4, 5 & 6). Chapter 7 reported an end-user evaluation of the use of Bns to facilitate implementation of WDM strategies and the results were used to examine three research hypotheses. The following section presents a summary of the results from the exploration of research questions and hypothesis, as well as further methodological contributions to knowledge.

9.1 New contributions to knowledge

The case study fieldwork presented in this thesis went beyond a desk study of the applicability of Bayesian network modelling and involved an end-user evaluation of Bns in an ongoing cross-sectoral planning process. Together, the technical and end-user evaluations provided evidence to explore seven research questions (Table 1.4), and three research hypotheses, and the results are summarised below.

Research question 1: How does Bayesian network modelling provide support for analysing uncertainty in water supply and demand forecasts?

Strengths of Bns for water supply and demand forecasting were identified from the model development reported in Chapter 4. The visual representation in Bns (using nodes and directed links) makes it easy to demonstrate how a system functions as demonstrated in the water balance model in Section 4.1. In Section 4.2.2, structural learning and parameter sensitivity analysis were applied to hydrological data collected from the Iskar dam between 1966 and 2000, and the results were used to develop a forecasting model of future water availability. In practice, the resulting model (Figure 4.5) supports exploration of scenarios to identify risks of low water availability. The forecasting model also demonstrates how Bns can be used to model over a single time-step. In Chapter 5 the forecasting sub-model was included as part of larger conceptual model for supporting water management policy decisions in the Upper Iskar.

A further strength of Bns is the wide range of data types (see below) that can be used to populate conditional probability tables (cpts). This addresses some of the issues of data availability often encounters in forecasting and backcasting. Four types of information that can be used to populate cpts in Bns were identified. These are:

- Raw data collected by direct measurement (e.g. River flow or reservoir levels, population measured by census, income measured by accounting).
- Information collected from regional reports (e.g. from water companies, environment agencies, research institutions) of water demand and supply.

- Raw data collected through stakeholder elicitation (e.g. stakeholder perceptions of water availability, population and income).
- Output from process-based models calibrated using raw data collected by direct measurement.

Because historical hydrological data rarely include all possible scenarios of water demand (i.e. all possible demand management scenarios) when constructing Bn models it will be desirable to use outputs from other hydrological models. However, this is a universal problem with collecting data for hydrological modelling and the facility to use expert knowledge in Bns in combination with actual data has potential advantages.

Research question 2: How does Bayesian network modelling provide support for economic analysis of impacts of demand management programmes?

The strengths of using Bayesian networks for analysing causes of uncertainty in economic evaluations of demand management options were examined in Chapter 4, Section 4.5.1. The lifetime avoided costs (LAC) method described in Section 4.5.1 is only one of many methods that could potentially be used to support economic evaluations of demand management. In Section 4.5.2.1 the LAC method was used to support structuring of a Bn model and demonstrates how Bayesian networks support identification strengths and weights of variables that, when instantiated, constraint the uncertainty about potential programme impacts. This makes it possible to understand how human actions (adaptive policies) will lead to more certainty about implementation effectiveness. Regarding the use of knowledge elicitation to support model development, the use of supply curves, as reported in Turner *et al.,* (2003), will be a helpful approach for structuring future knowledge elicitation activities. An example of a supply curve is given in Appendix K.

Research question 3: How does Bayesian network modelling provide support for developing preparedness strategies?

Strengths of Bn modelling to support the development of preparedness strategies were identified from the experience of model development reported in Chapter 5. Forward and backward propagation of conditional probabilities in Bns means that, once constructed, a Bn model can potentially be used to support both forecasting and backcasting studies. However, to avoid misunderstanding or discussions becoming unfocussed, the objective of the model needs to be clearly stated during the early stages of model development.

Once the network has been constructed, model instantiation makes it possible to quickly evaluate the impact of a range of future scenarios. This, along with their visual representation, which makes it easy for the user to gain a quick understanding of how the system works, makes Bns a potentially valuable too for supporting development of preparedness strategies.

Weaknesses of using the Bn approach for supporting preparedness strategies identified from model development are that although modelling over time-steps is possible with Bns, it increases model complexity. If the length of a time-step needs to be changed, all cpts in the model need to re-specified, which can be very time-consuming, and former research (Jensen, 2001) recommends that for modelling over multiple time-steps, the Bn model for each time-step should only include a minimum number of nodes (e.g. 3-5).

Research question 4: How does Bayesian network modelling provide support for decisions involving multiple organisations?

Bayesian modelling, and specifically Influence Diagrams (IDs), were demonstrated to provide potentially useful characteristics for supporting decisions involving multiple organisations. The ID in Figure 5.2 effectively represents the causal relationships and inter-dependency in a multi-organisational decision process involving three interconnected decisions. The sequential structure of IDs together with a suitable model instantiation procedure allows the user to see how each policy mechanism effectively determines who pays for demand reduction.

Weaknesses of using Bns for decisions involving more than one organisation include the complexity of modelling over more than one time-step already mentioned above.

Research question 5: How does Bayesian network modelling address issues of structural uncertainty in the planning process?

Using Bayesian networks, it is easy to demonstrate the way in which a system functions through the use of nodes and directed links. This is relevant not only to physical flows, as demonstrated in the water balance model in Figure 4.1, but also to information flow as demonstrated in the conceptual model in Figure 5.2. The Bn model in Figure 5.2 is valuable as an artefact of the WDM implementation process. It is a viable output of the research that supports dissemination of knowledge about indicators and cause-effect relationships between them, to support implementation of demand management strategies in other river basins. Once populated, parameter sensitivity analysis allows each cause-effect relationship in a prior model to be analysed for uncertainty so as to determine its candidacy for inclusions in the final model.

A weakness identified relating to research question 5 is that in large networks there is a danger of having too much information to take in and an instantiation procedure is therefore required in order to avoid subsequent analysis becoming unfocussed.

The demonstration models presented in Chapter 6 supported the examination of strengths and weaknesses of Bns relating to two research questions, identified previously in Chapter 3, Table 3.5.

Research question 6: How does Bayesian network modelling provide support for identifying constraints to- and drivers of- water conservation behaviour?

Bayesian networks support processing and analysis of household survey data. Section 6.2 demonstrated that, from a research perspective, structural learning of household survey data provided a means of examining drivers of- and constraints to-citizen participation in water conservation programmes. In addition, because expert knowledge can be used to augment survey data (i.e. to update cpts), Bns can also address instances of missing data in household survey data sets, potentially reducing data collection costs.

Weakness of the Bn approach for identifying behavioural drivers are that in order to validate model outputs, social survey design needs to be based on existing and tested model structures, for example the theory of planned behaviour. However, this is a universal issue when validating findings from behavioural models.

Research question 7: How does Bayesian network modelling provide support for identifying indicators of ‘favourable’ and ‘unfavourable’ implementation conditions for introduction of different water saving measures?

A number of strengths of Bns for evaluating implementation conditions for WDM were identified from the experience of model development in Chapter 6. For forecasting per capita household demand and water savings, as demonstrated in Section 6.4.2, the profile of a population can be described using chance nodes representing individual demand variables. The further addition of utility and decision nodes then allows those models to be used to forecast household water savings. For forecasting potential participation by citizens in water conservation programmes, the use of conditional probabilities in Bns makes them compatible with the ‘total market’ approach. The wide range of information types that can be used to develop conditional probabilities in Bns means that they can be used to describe implementation conditions even in areas with low coverage of household meters (see Section 6.6.1.3).

The use of Value of information (VOI) analysis in Bns provides a potentially useful tool for water conservation managers to consider: (i) how the value of data collection is determined by water stress conditions and implementation conditions and (ii) the costs and benefits of collecting more data before proceeding with implementation.

Weaknesses of the Bn approach for evaluating implementation conditions for WDM are that the complexity of the methods used for Value of Information analysis and the availability of data to populate the models may constrain the use of the method. Further research is required to see whether this method can be practically useful for water conservation managers in determining data requirements. The use of Bns for forecasting water saving and uptake potential has not been evaluated by practitioners and there wider use in this context would require comparisons with other forecasting methods (e.g. simulation models).

In Section 1.3 of Chapter 1, cross-sectoral planning was identified as a further support tool requirement for WDM implementation and the technical and end-user evaluation results provided evidence of the effectiveness of Bns in this context. Firstly, the technical evaluation in Chapter 5 demonstrated how modelling the decision process as a decision stream and aggregating utilities in Influence Diagrams supports decisions involving multiple organisations by modelling the effect that policy mechanisms have on who pays for WDM implementation. Secondly, the end-user evaluation in Chapter 7 examined three hypotheses relating to the use of Bns in participatory planning for WDM implementation in Sofia. The results showed that Bns were effective across the range of evaluation indicators used, with average scores for the ten practitioners ranging from 5.76 to 6.39 (on a seven-point scale) for the seven indicators of perceived effectiveness, and the results for *transparency* were significantly ($p=<0.05$) higher. Among the four organisational perspectives represented in the evaluation workshop policy makers perceived effectiveness scores across the seven indicators were significantly ($p=<0.05$) higher. Decision effort for WDM implementation was significantly ($p=<0.05$) lower when using the tool during the workshop.

Even though evaluation has been stated as one of the principle stages in planning and decision process theory, it is noted that significant evaluation of participatory modelling experiences remains an underdeveloped practice (Bellamy *et al*., 2001). The end-user evaluation reported in Chapter 7 composes a new approach to the literature on participatory modelling in water management and is, as far as we are aware, the first formal evaluation of the use of Bns in IWRM or demand management. As such, the results contribute to the body of knowledge about their applicability to this problem domain. In addition, the approach used contributes to Information Systems evaluation research methods to inform the design of future evaluations.

9.2 Study limitations

There are a number of limitations to this study, which have been discussed throughout this thesis, and are considered further here. This study provides empirical evidence of perceived effectiveness of Bayesian networks from just one urban European case study. It is acknowledged that the support tool requirements will differ for different contexts (e.g. privately vs. publicly owned water utilities) and this may affect the technical suitability of Bns within a specific context. It is also recognised that perceived effectiveness of Bns by end-users may be dependent on a number of factors such as: the risk attitudes of practitioners, the competence of the model developer (s) and workshop facilitators, the perceived effectiveness criteria used.

The relative unfamiliarity of the informed practitioners with Bayesian networks meant that it was not possible to examine some of the more detailed questions about compatibility between the method (i.e. Bns) and the problem domain (i.e. WDM). Although the evaluation results are positive, further application and evaluation into the effectiveness of Bns to WDM planning and IWRM is required.

9.3 Future research questions

The results of this study have led to further questions and areas of interest relating to the application of Bayesian networks in demand management and wider water resources planning. Despite the thesis's contributions to knowledge and understanding of the technical suitability and end-user's perceptions of the effectiveness of Bayesian networks, numerous knowledge gaps still exist in addition to those associated with other aspects of water demand management (e.g. institutional arrangements, policy) which were outside the scope of this study. The major research needs that are directly related to the scope of this thesis topic are discussed below.

The end-user evaluation focussed on the use of Bayesian networks as a tool for facilitating cross-sectoral planning and the technical evaluation gave a more detailed demonstration of how Bayesian networks and Influence Diagrams (IDs) can be applied. However, further evaluation by end-users (i.e. policy-makers, water company employees and academics) is required to evaluate the effectiveness of Bns and IDs in facilitating specific issues at the legislation and design stages presented in Chapters 4, 5 & 6.

If Influence Diagrams are to be applied, methods for eliciting utility functions will need to be developed and evaluated, and it is suggested that the knowledge elicitation methods in Appendix H might form the basis for such evaluation research. Furthermore, components of the ‘full cost’ method, described in Appendix Q, will be helpful for designing knowledge elicitation activities for collecting expert’s opinions about utilities that are relevant to the water demand management problem domain (e.g. security of water supplies).

Results of the technical evaluation suggest that for some tasks, populating Bayesian network models will require outputs from other models. Combining Bns with other modelling approaches is an area for future research and three modelling approaches that, in combination, could increase the potential applicability of Bayesian networks in water demand management include:

- System Dynamics modelling for detailed hydrological forecasts
- Mathematical programming or optimal control for calculating utility functions
- Geographical Information Systems for supporting presentation of model results regarding implementation conditions at the design stage of WDM implementation

Drivers and constraints to the adoption of computer-based support tools for water management is an area that has received increasing attention in recent years. A shortage of experienced model developers was identified as a potential constraint in Section 7.3.1, and the absence of a focal point for co-ordinating WDM was identified as a further constraint in Section 8.2.2. In Chapter 8 (Figure 8.5) challenges to integrating Bayesian networks were identified and challenges to validation and legitimisation were discussed. Further evaluation research of the use of Bayesian networks Influence Diagrams to specific problems within individual organisations is required to develop a better understanding of their potential intra and inter-organisational uses.

9.4 Practical implications

Recent outputs of European Commission-funded research into the decision support tools and modelling requirements for facilitating implementation of the Water Framework Directive (WFD) have recommended that the use of models to support the WFD requires not only identification of appropriate models but also technical, and end-user, decision support mechanisms. This involves “the integration of science within policy and enhanced methods of communication and understanding among scientists, decision-makers and stakeholders” (Irvine *et al.,* 2002, p14). Two fundamental requirements for the application of decisions support tools and models to the implementation of the WFD is how models can help understand and identify risks to water-bodies and how they can help define and target monitoring (Irvine *et al.,* 2002).

From a practitioner’s perspective (e.g. water company employee / engineer) the value of any computer-based support tool lies in its resulting utility in terms of how it provides a means to achieve economic efficiency, whilst for policy-makers the research in this thesis provides evidence that the value of computer-based support tools lies in their capacity to communicate knowledge and information on which to base future governance decisions. Churchman (1971) maintained that a general methodology has its status because of its success in use, but that every future use of the methodology would adapt, test and evaluate with a view to improvement. The research presented in this thesis has demonstrated the application of Bns to a number of aspects of WDM implementation and provides a limited evaluation of their usefulness in cross-sectoral planning and the practical implications arising from the results are detailed in Table 9.1 on the previous page.

Table 9.1. *Practical implications arising from the results of this study*

Perspective	No	Recommendation	Implication
Policy makers	1	Bayesian networks support communication about the structure of knowledge and information by representing strengths and weights of causal relationships.	
	2	Bayesian networks provide support for identifying research priorities in water management by providing an interface to discuss uncertainties of scientific knowledge.	Bns provide an effective platform for negotiation between policy and science / practice that can lead to better understanding about the economic and organisational conditions required for implementing demand management.
	3	Bns provide support for considering the economic feasibility of demand management whilst making transparent the inherent risks and uncertainties	
Practitioners (water utility employees)	4	Bns provide an approach to analysing dependencies between metered household water demand data and demand variables. The approach, demonstrated in Chapter 6, shows potential for use in calculating household water saving potential at the household and neighbourhood scale, thus supporting feasibility studies	The demonstration of the use of Bns in Chapters 6 supports their application to support economic feasibility studies. The ability to combine expert knowledge with empirical data means that they can be used in areas where there is low coverage of meters, and this would lead to reduced data collection costs.
	5	The combined analysis of household survey and metered demand data provides a potentially useful method for supporting water conservation managers in efficient planning and targeting of WDM programmes.	
	6	The ability to combine expert knowledge with empirical data in Bns has potential to increase their usefulness in areas with low metering coverage.	

The positive perceptions of informed practitioners in the Upper Iskar case study and the results of the technical evaluation demonstrate that Bns are an effective tool for validating research outputs for subsequent use in water resource planning. Their effectiveness as an explanatory tool for facilitating dialogue and for providing an interface between stakeholders and also between science and practice was demonstrated through the end-user evaluation. Their effectiveness as a tool to provide support for analysis of social surveys was demonstrated and provides an impetus for further application by researchers in this area. However, knowledge gaps still exist as to how they can be used to communicate outputs from other modelling approaches to a policy audience and it is proposed that this is the most promising topic for future researchers interested in their application.

The results of the fieldwork presented in this thesis suggest that further application and evaluation of Bayesian network modelling will provide benefits by allowing scientific research, particularly in domains characterised by uncertainty, to be communicated to a wider audience. In this way Bayesian networks can be a useful tool for supporting sustainable management of water resources.

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Appendix A UK Water Demand Management Study

First Report
Mapping Expert Knowledge
April 2007

David Inman
Cranfield University, UK

1. Introduction

The aim of the study reported below is to develop and evaluate a computer-based tool for supporting policy decisions involving water demand management implementation. The drought that affected areas of south east England during the summer of 2006 led a number of water suppliers to introduce drought orders that included minor restrictions on public water use. This came at a time when a number of public discussions were taking place regarding the efficient management of UK water resources. The discussions led to a number proposals from different parties, such as schemes to augment existing supplies, e.g. through reservoir construction, desalination, water transfer, and others to manage demand, e.g. through wastage reduction, water efficiency, and water conservation etc.

Contemporary approaches to dealing with water scarcity can be found in the literature (e.g. Turton, 1999; Wilhite, 2005). Unsurprisingly, the major debates and advances in managing water scarcity can be found in regions with a history of meeting the challenges of water scarcity.

In the 1990s, Spain experienced the most severe water crises of any European country (Ituarte and Giasante, 2000). Commenting on the crisis that resulted from the drought, Ituarte and Giasante (2000) highlight a number of factors that, in combination, led to the Spanish system being vulnerable to drought. One of their main conclusions is that the hydraulic model, which is based on the systematic increase of water regulation capacity, expressed in deterministic values, discouraged the perception of residual risk, leading to reactive, as opposed to pro-active, drought policy. The model promoted the expansion of water demands, leading to the subsequent reproduction and even enhancement of vulnerability. Economic, technological, demographic or climatic uncertainty scenarios were almost completely absent in this context, and drought risk and uncertainty were disguised in average figures presented in a deterministic manner which, they suggest, was misleading.

The Spanish case highlights the way that representation in models used in decision-making can influence the way that policy-makers incorporate uncertainty and elements of risk into their decisions. In the current study we will evaluate the use of a probabilistic decision support tool (DST) based on Bayesian belief networks (BBNs).

This document reports findings from an expert consultation held during August and September 2006. The 10 experts who participated in the consultation each hold a decision-making role within organisations involved in water demand management (WDM) policy development in England and Wales. The consultation, which was recorded, explored the current decision processes affecting water demand management implementation in England and Wales. Analysis involved transcription of digital recordings and coding and mapping of causal statements. The results, summarised below, have been used to guide the development of evidence-based reasoning models using BBN modelling software. The effectiveness of the models and BBN approach in supporting WDM strategy design will be tested during a workshop in June 2007.

The report has a number of aims:

a reference document for decision makers involved in demand-side management policy design and implementation in the UK
an advisory document for the development of decision support tools to facilitate WDM planning
a preparatory document for the modelling workshop to be held at Cranfield University during June 2007.
Recap of expert consultation
The consultation followed a problem-solving approach (De Bono, 2000) with the following set of topics:
Identify perceptions of the risk of water deficit
Identify demand-side options for reducing risks
Identify the impacts of these options
Identify constraints to implementation of the options
Identify how these constraints might be overcome
Each participant has received their transcribed responses, elicited during the consultation, separate to this document, and the results reported below reflect the responses from all 10 experts.

2. Results

Perceptions of risk of water deficit

Expert perceptions of the risk of a water deficit occurring in the UK over the next 30 years were captured by asking experts to draw a line on a graph. The axes on the graph represented the likelihood of supply interruptions, and reduced economic productivity resulting from drought, affecting the UK both regionally and nationally over the next 30 years.
At the regional scale results revealed a high level of variation in perceptions of future drought risks, with a gradual increase in risk over the 30 year forecast period. At the national scale perceptions of drought risk also varied indicating variability in expert opinions.
The implications at the regional scale are that risk of drought will vary between regions and this can be explained by the different pressures, e.g. climate, socio-economic development, etc, mentioned by experts within their regions. However, at the national scale we might expect less variability because England is considered as one region. This was not found to be the case, and experts' perceptions of risk of drought and its impacts varied widely over the 30 year period.
The benefits of WDM are partially dependent upon the extent to which demand reduction will alleviate the effects of drought. The results suggest that a computer-based decision support tool that provides economic analyses should represent this uncertainty surrounding future water supply scenarios.

Demand-side options and their impacts

A list of WDM options elicited during the expert consultation is shown in Table 1. The list informed the selection of tools for inclusion in the modelling workshop.

Table 1 WDM options elicited during the expert consultation

Long-term options		
Building regulations	Outdoor flow restrictors	White goods retrofits
Water efficiency regulations	Leak detection systems	Indoor flow restrictors
Metering	Customer supply-pipe replacement	School education
Tariff structures	Optimisation of plumbing network	Info on bills
Rainwater harvesting	Bathroom retrofits	Media campaigns
Greywater-re-use	Pressure reduction	

Short-term options		
Education – behaviour	Self retrofit of bathroom fittings	Media campaigns
Outdoor use restrictions	Water butts	Xeriscaping
Householder bathroom / kitchen audit	Actual retrofits of bathroom fittings	

Experts were generally reluctant to allocate specific savings for particular WDM options because of the uncertainty in predicting the impact of a single or combined option, and the potential variation in the time-scale of these impacts.

key Constraints to WDM implementation

Three key constraints were identified during the expert consultation:

Lack of an evidence base for the selection of water efficiency options in the UK context

Economic methods currently used for evaluating demand management measures bias larger supply-side schemes such as transfers, and this is partly due to the limited number of factors included in the calculations

Regulatory fragmentation

The following three sections report expert perceptions of how these factors are influential under current conditions. Quotes from the experts are used but, to maintain confidentiality, the names are not provided.

Developing the evidence-base

In the UK, developing an evidence-base to support WDM decision-making was cited as a priority by most experts. The following quotes from individuals involved in the study summarise the current needs.

'… we can't demonstrate the benefits of water efficiency until we've done the pilots, so it's a chicken and egg situation' Respondent I

'…the lack of an evidence-base is one of the main causes of the uncoordinated and fragmented state of water efficiency implementation, because it leads to uncertainty about the economics of water efficiency options' Respondent B

'Regional specific conditions cause complexity in design of water efficiency policies at the national scale' Respondent A

The effectiveness of BBNs in facilitating the development of an evidence-base for WDM options will be explored during the workshop to which you are being invited. A detailed plan for the workshop is described in Section 3 of this report.

Economics of WDM

The economic methods use for comparing supply and demand-side approaches were mentioned by a number of experts as being a constraint on the WDM decision-making process. According to one expert

'With the EBSD (Economics of Supply and Demand) / LCP (Least cost planning) approach, demand management options don't get a look in' Respondent F

In addition to the economic methods used, factors that affect the economic efficiency of WDM options are not fully understood at present. One illustrative example given during the expert consultation, relevant to implementing retrofits, is given below:

'…the people who are doing the fitting will be on a day rate, so that's the major cost, the cost of a plumber. So, if the plumber does ten in a day instead of three in a day, there's a big difference. If you can maximise the number of houses they visit, the number of things they're retro-fitting, and the number of litres per household saved, you're reducing your cost per litre. So, you need to do whatever you can to reduce the cost per litre. That's your key cost centre, it's your key variable. There's the cost of the appliance, and then the labour costs. So, you need to increase the productivity.

So ideally, you want to find somewhere that you can park the van and go door to door and knock off twenty of these things in the day' Respondent I

The economic methods used to evaluate WDM options, and the influencing factors included when calculating costs and benefits, inevitably determine the utility associated with of a specific option. A number of Bayesian methods for identifying important factors (e.g. payback period, drought intensity, demographic factors) to include in utility models will be tested during the workshop.

Regulatory fragmentation

Regulatory fragmentation was mentioned by a number of experts as being linked to the two problems already described above. As one expert put it:

' … the lack of an evidence-base is one of the main causes of the uncoordinated and fragmented state of water efficiency implementation, because it leads to uncertainty about the economics of water efficiency options' Respondent I

Different views and interests, and their impacts on the decision process are possibly best summed up by the following three observations:

' … whilst the organisational framework may be fragmented, that is necessary really. Sometimes, in the media you may see this antagonism between the EA and Ofwat, but that's quite healthy. Different parties are vying for different outcomes. The EA are looking at the environment whilst Ofwat are looking out for the customer, seeing that the customer doesn't pay more than they need to. Maybe they could work better together. But it's healthy because rather than having one organisation steam-rolling through, there are the two putting their arguments across and Defra at the top and hopefully that way, they find a better way forward' Respondent B

' … regulatory constraints … as opposed to institutional, technical, market (economic), and cultural constraints … are the key constraining factor at the moment. The problem is that with the large number of bodies, what you do tend to find is that you don't actually get clear regulation at times. So I don't think you need to change the institutional set up, but rather the regulations need to be joined up, although I do think institutions play a big part. What you do get is a lot of different view sets in the regulations and that is where a problem arises' Respondent E

And with regard to Water Company proposals for funding to support water efficiency:

' … the water companies really aren't sure what to submit. So, Defra, Ofwat and the EA need to lay down a common framework, a way for Water Companies to structure their Water Efficiency proposals. It needs to be almost … "this is what we want".' Respondent I

Decision support tools can facilitate better understanding between organisations through information storage, processing and presentation. One aim of the workshop will be to understand how BBNs might facilitate better understanding between organisations.

Influence diagrams

A number of causal maps were developed from expert's responses to the questions. The influence diagram in Figure 1 summarises expert perceptions as to the current constraints and requirements for WDM implementation in the UK.

The following section describes the workshop plan for evaluating the effectiveness of BBNs in support WDM decisions.

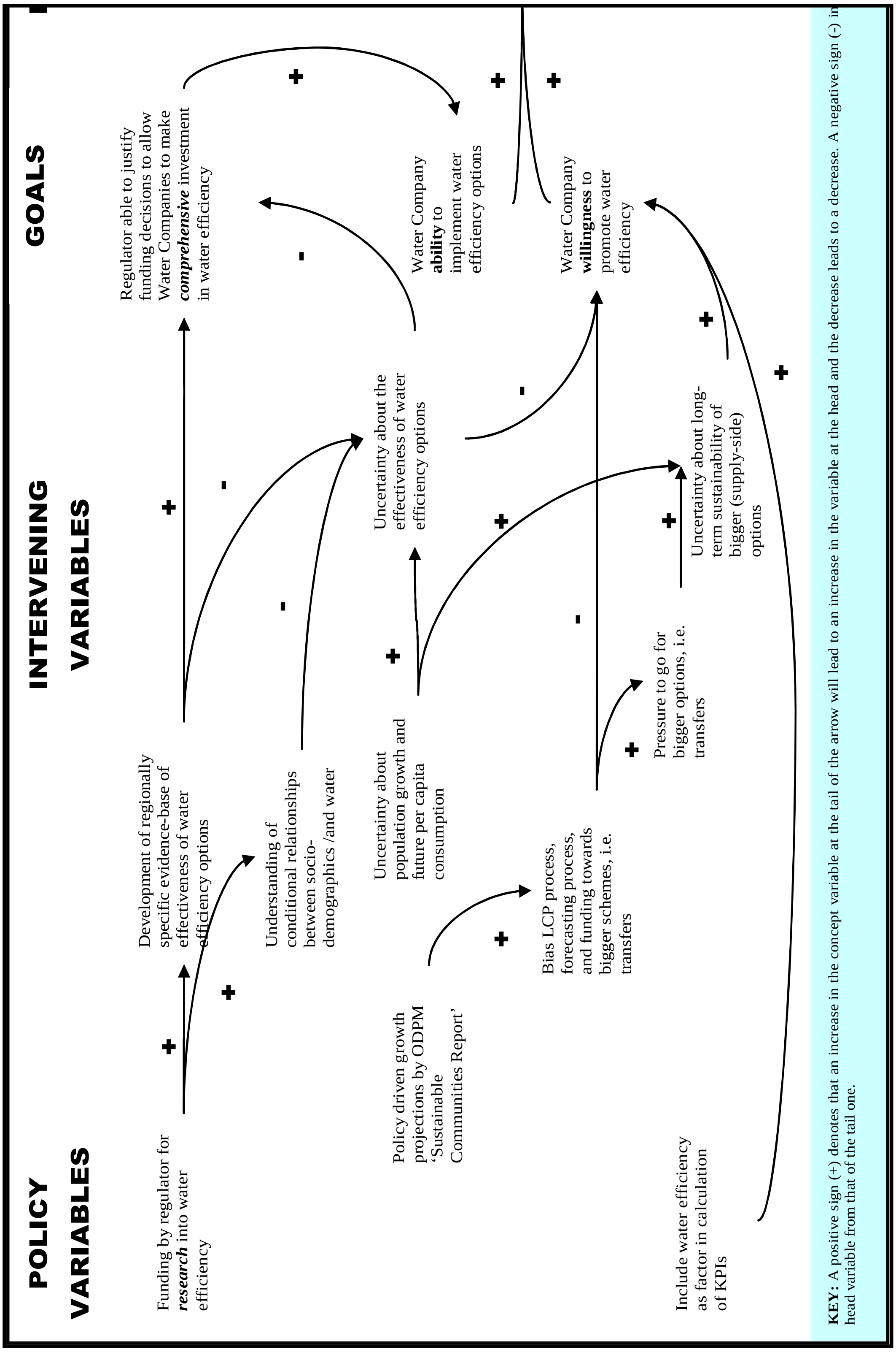


Figure 1 A composite influence diagram of constraints and opportunities as perceived by 10 experts

Appendix B Table of reviewed modelling platforms

#	Model Name	Key features	Reference
1	STELLA	Stocks and flows model to build consensus in the context of risk assessment, non-point source pollution control, and wetlands mitigation/restoration	Costanza and Ru
2	VENSIM	Stocks and flows model developed to promote stakeholder participation. Generates output after calibration which shows the effect of different conservation measures. Cannot combine parameters.	Stave, 2003
3	Water management under scarcity model utilising Bayesian and Dependency Networks	Utilises conditional probability tables to introduce parent variables which represent known interactions between elements of water management	Bromley et al, 20
4	DST for the identification of sustainable treatment options	A decision support tool which uses sustainability indicators and 'weighted sums' to promote participatory involvement.	Balkema *et al,* 20
5	WEAP – Water Evaluation and Planning model	WEAP places demand side options on an equal footing with supply side options to investigate 'what if' scenarios	Levite & Sally, 20
8	WDF-ANN model - Water Demand Forecasting Artificial Neural Network	Uses artificial neural networks and econometric to generate output such as the effect of pricing on household water use.	Liu et al, 2003
9	CALVIN model	An economic optimisation model which allows for constraints, e.g. policy and environmental issues, to be taken into account.	Jenkins et al, 200
10	Wixams model	Allows strategic analysis of options for sustainable water management in the context of scale of application and climate scenrios	Labaien, 2003
11	Watsup – Water Supply Network Simulation Modelling System	Allows the simulation of a water supply network in which large a number of modules can connected to simulate a typical supply chain.	Murray & Murray,
12	ENERGY demand models	Combines different household characteristics with the presence of different types of micro-components. Able to forecast the impact of introducing demand-side management techniques with long-term forecasting	Michalick et al, 1 Michalick et al, 1
13	IWR-MAIN - Institute for Water Resources - Municipal and Industrial Needs	A model for predicting water demand and the effect of water conservation measures. Requires a high level of disaggregation of end uses to permit all necessary determinations to estimating water savings of various programmes.	Baumann et al, 1
15	Aquacycle	Developed to provide a holistic view of an urban water system, allowing water supply, wastewater disposal, and storm water drainage to be considered within a single modelling framework.	Mitchell et al, 200
16	Combined water conservation using storage reservoir model	Model created to predict water saving potential of water conservation measures which make use of storage reservoirs	Dixon et al, 1999. Villareal & Dixon,
17	Integrative reuse systems model	This model is aimed at defining an "objective function" (an expression of the cost) to be optimised subject to a series of technological, environmental, social and operational constraints	Oron, 1996.
18	UVQ—Urban Volume and Quantity model	Uses the structure of the Aquacycle model (see above) but has an added facility to monitor the feasibility of using recycled water for groundwater recharge	Eiswirth et al, 200
19	A model for industrial reuse	GIS based model for optimising industrial reuse systems	Nobel, 1998.
20	WAWTTAR: A wastewater reuse potential model capable of analysis at the national scale.	Analyses the trade-off between wastewater reuse supplies and demand,	Gearheart, 1999

Appendix C Review of Bayesian networks software packages

The following table compares the technical specifications of BN software. Definitions of the column heading are given below. Technical details which restrict the suitability of software packages for the current research tool are signalled by shaded cells.

TABLE 1. Comparison of Bayesian Network Platforms

Name	Authors	Src	API	Exec	Cts	GUI	Params	Struct	Utility	Free	Undir	Inference	Comments
Analytica	Lumina	N	Y	W,M	G	Y	N	N	Y	$	D	sampling	spread sheet compatible
Bassist	U. Helsinki	C++	Y	U	G	N	Y	N	N	0	D	MH	Generates C++ for MCMC.
Bayda	U. Helsinki	Java	Y	WUM	G	Y	Y	N	N	0	D	?	Bayesian Naive Bayes classifier.
BNT	Murphy (U.C.Berkeley)	Matlab/C	Y	WUM	G	N	Y	Y	Y	0	D,U	Many	Also handles dynamic models, like HMMs and Kalman filters.
Genie	U. Pittsburgh	N	WU	WU	D	W	N	N	Y	0	D	Jtree	-
Hugin Expert	Hugin	N	Y	W	G	W	Y	CI	Y	$ (free demo)	CG	Jtree	-
Java Bayes	Cozman (CMU)	Java	Y	WUM	D	Y	N	N	Y	0	D	Varelim, jtree	-
MSBNx	Microsoft	N	Y	W	D	W	N	N	Y	0	D	Jtree	-
Netica	Norsys	N	WUM	W	G	W	Y	N	Y	$ (free demo)	D	jtree	-
Web Weaver	Xiang (U.Regina)	Java	Y	WUM	D	Y	N	N	Y	0	D	?	-
XBAIES 2.0	Cowell (City U.)	N	N	W	G	Y	Y	N	Y	0	CG	Jtree	-

Description of abbreviations

Src = source code included? (N=no) If so, what language?

API = application program interface included? (N means the program cannot be integrated into your code, i.e., it must be run as a standalone executable.)

Exec = Executable runs on W = Windows (95/98/NT), U = Unix, M = Mac, or - = any machine with a compiler.

Cts = are continuous (latent) nodes supported? G = (conditionally) Gaussians nodes supported analytically, Cs = continuous nodes supported by sampling, Cd = continuous nodes supported by discretization, Cx = continuous nodes supported by some unspecified method, D = only discrete nodes supported.

GUI = Graphical User Interface included?

Params = Learns parameters?

Struct = Learns structure? CI = means uses conditional independency tests

Utility = utility and decision nodes (i.e., influence diagrams) supported?

Free? 0 = free (although possibly only for academic use). $ = commercial software (although most have free versions which are restricted in various ways, e.g., the model size is limited, or models cannot be saved, or there is no API.)

Undir? What kind of graphs are supported? U = only undirected graphs, D = only directed graphs, UD = both undirected and directed, CG = chain graphs (mixed directed/undirected).

Inference = which inference algorithm is used? jtree = junction tree, varelim = variable (bucket) elimination, MH = Metropols Hastings, G = Gibbs sampling, IS = importance sampling, sampling = some other Monte Carlo method, polytree = Pearl's algorithm restricted to a graph with no cycles, none = no inference supported (hence the program is only designed for structure learning from completely observed data)

Comments = If in "quotes", I am quoting the authors at their request.

The above table is a shortlist from a database of over 40 software packages. The following gives further details of software options from the above table which are considered most applicable for the current research.

1. Analytica

Lumina Decision Systems, Inc.

http://www.lumina.com

Development: The emphasis in Analytica is on using influence diagrams as a statistical decision support tool. Analytica does not use Bayesian network terminology, which can lead to difficulties in identifying aspects of its functionality.

Technical: Analytica 2.0 GUI is available for Windows and Macintosh. The Analytica API (called the Analytica Decision Engine) is available for windows 95/98 or NT 4.0, and runs in any development environment with COM or Automation support.

CPTs: Analytica supports many continuous and discrete distributions, and provides a large number of mathematical and statistical functions.

Inference: Analytica provides basic MDMC sampling, plus median latin hypercube (the default method) and random latin hypercube, and allows the sample size to be set. The Analytica GUI provides many ways to view the results of inference, through both tables and graphs: statistics, probability bands, probability mass (the standard for most other packages), cumulative probability, and the actual samples generated by the inference.

Evidence: Specific evidence can only be entered for variables previously set up as "input nodes".

DBNs: Analytica provides dynamic simulation time periods by allowing the user to specify both a list of time steps and which variables change over time. Note: Analytica does not use DBN terminology or show the "rolled-out" network.

Evaluation: Analytica provides what it calls "importance analysis", which is an absolute rank-order correlation between the sample of output values and the sample for each uncertain input. This can be used to create so-called importance variables. Analytica also provides a range of sensitivity analysis functions, including "what-if" and scatter plots.

Other features: Analytica supports the building of large models by allowing the creation of a hierarchical combination of smaller models, connected via specified input and output nodes.

2. GeNIe

Decision Systems Laboratory, University of Pittsburgh

http://www.sis.pitt.edu/˜ genie/

Development: Developed by Druzdzel's decision systems group, GeNIe's support of decision networks, in addition to BNs, reflects their teaching and research interests in decision support and knowledge engineering. GeNIe 1.0 was released in 1998, and GeNIe 2.0 is due for release in mid-2003.

Technical: GeNIe (**G**raphical **N**etwork **I**nterface) is a development environment for building decision networks, running under Windows. SMILE (Structural Modelling, Reasoning, and Learning Engine) is its portable inference engine, consisting of a library of C++ classes currently compiled for Windows, Solaris and Linux. GeNIe is an outer shell to SMILE. Here we focus on describing GeNIe.

CPTs: Supports chance nodes with General, Noisy OR/MAX and Noisy AND distribution, as well as graphical elicitation of probabilities.

Inference: GeNIe's default BN inference algorithm is the junction tree clustering algorithm, however a poly-tree algorithm is also available, plus several approximate algorithms that can be used if the networks get too large for clustering (logic sampling, likelihood weighting, self importance and heuristic importance sampling, backward sampling). GeNIe 2.0 provides more recent state-of-the art sampling algorithms.

Evidence: Only handles specific evidence.
Decision networks: GeNIe offers two decision network evaluation algorithms: a fast algorithm that provides only the best decision and a slower algorithm that use an inference algorithm to evaluate the BN part of the network, then computes the expected utility for all possible policies. If the user does not specify the temporal order of the decision nodes, it will try to infer it using causal considerations, otherwise it will decide an order arbitrarily. To simplify the displayed model, GeNIe does not require the user to create temporal arcs, inferring them from the temporal order among the decision nodes. *Viewing results*: The value node will show the expected utilities of all combinations of decision alternatives. The decision node will show the expected utilities of its alternatives, possibly indexed by those decision nodes that precede it. GeNIe provides the expected value of information, i.e., the expected value of observing the state of a node before making a decision.
Evaluation: GeNIe supports simple sensitivity analysis in graphical models, through the addition of a variable that indexes various values for parameters in question. GeNIe computes the impact of these parameter values on the decision results (showing both the expected utilities and the policy). Using the same index variable, GeNIe can display the impact of uncertainty in that parameter on the posterior probability distribution of any node in the network.
Other features: GeNIe allows submodels and a tree view. It can handle other BN file formats (Hugin, Netica, Ergo). GeNIe provides integration with MS. Excel, including cut and paste of data into internal spreadsheet view of GeNIe, and supports for diagnostic case management. GeNIe also supports what they call “**relevance reasoning**”, allowing users to specify nodes that are of interest (so-called target nodes). Then when updating computations are performed, only the nodes of interest are guaranteed to be fully updated; this can result in substantial reductions in computation.

3. Hugin

Hugin Expert, Ltd
http://www.hugin.com
Development: The original Hugin shell was initially developed by a group at the Aalborg University, as part of an ESPRIT project which also produced MUNIN system [9]. Hugin’s development continued through another Lauritzen-Jensen project called ODIN. Hugin Expert was established to start commercializing the Hugin tool. The close connection between Hugin Expert and the Aalborg research group has continued, including co-location and personnel moving between the two. This has meant that Hugin Expert has consistently contributed to and taken advantage of the latest BN research. In 1998 Hewlett-Packard purchased 45% of Hugin Expert; one consequence of this seems to have been the tailored development of Hugin to support trouble-shooting.
Technical: The Hugin API is called the “Hugin Decision Engine”. It is available for the languages C++, Java and as an ActiveX-server, and runs on the operating systems: Sun Solaris (Sparc), HP-UX, Linux, and Windows. Versions are available for single and double-precision floating-point operations. The Hugin GUI (called “Hugin”) is available for Sun Solaris (sparc, x86) Windows, and Linux red-hat. Hugin also offers “Hugin Advisor” for developing trouble shooting applications, and “Hugin Clementine” for integrating Hugin’s learning with data mining in SPSS’s Clementine system.
Node Types: Good support for continuous variable modelling, and combining discrete and continuous nodes, following on from research in this area.
CPTs: CPTs can be specified with expressions as well as through manual entry. The CPTs don’t have to sum to one; entries that don’t sum to one are normalized.
Inference: The basic algorithm is the junction tree algorithm, with options to choose between variations. The junction tree may be viewed. There is the option to vary the

triangulation method, and another to turn on compression (of zeros in the junction tree) (see Problem 3, Chapter 3 in 'Bayesian AI'). An approximate version of the junction tree algorithm is offered, where all probabilities less than a specified threshold are made zero (see Problem 5, Chapter 3, in 'Bayesian AI'). In addition Hugin GUI computes P(E), the data conflict measure, described in _ 3.7.2, in 'Bayesian AI'.

Evidence: Specific, negative and virtual evidence are all supported.

Decision networks: Hugin requires the existence of a directed path including all decision variables. It gives the expected utility of each decision option in the decision table.

Other features: Supports object-oriented BNs.

4. JavaBayes

Fabio Gagliardi Cozman, Escola Politcnica, University of So Paulo

http://www.cs.cmu.edu/˜ javabayes/Home/

http://www.pmr.poli.usp.br/ltd/Software/javabayes/ (recent versions)

Development: JavaBayes was the first BN software produced in Java and is distributed under the GNU License.

Other features: JavaBayes provides a set of parsers for importing Bayesian networks in several proposed so-called "interchange" formats. JavaBayes also offers Bayesian **robustness analysis**, where sets of distributions are associated to variables: the size of these sets indicates the "uncertainty" in the modelling process. JavaBayes can use models with sets of distributions to calculate intervals of posterior distributions or intervals of expectations. The larger these intervals, the less robust are the inferences with respect to the model.

5. MSBNx

Microsoft

http://research.microsoft.com/adapt/MSBNx/

CPTs: MSBNx supports the construction of the usual tables, as well as local structure in the form of context-sensitive independence (CSI), (see _ 9.3.4 in 'Bayesian AI'), and classification trees (see _ 7.4.3).

Inference: A form of junction tree algorithm is used.

Evidence: Supports specific evidence only.

Evaluation: MSBNx can recommend what evidence to gather next. If given cost information, MSBNx does a cost-benefit analysis, otherwise it makes recommendations based on an entropy-based value of information measure (note: prior to 2001, this was a KL-divergence based measure).

6. Netica

Norsys Software Corp.

http://www.norsys.com

Development: Netica's development was started in 1992, by Norsys CEO Brent Boerlage, who had just finished a Masters degree at the University of British Columbia, where his thesis looked at quantifying and displaying "link strengths" in Bayesian networks. Netica became commercially available in 1995, and is now widely used.

Technical: The Netica API is available for languages C and Java, to run on Mac OSX, Sun Sparc, Linux and Windows. The GUI is available for Mac and Windows. There is also a COM interface for integrating the GUI with other GUI applications and Visual Basic programming.

Node Types: Netica can learn node names from variable names in a data file (called a case file). Netica discriminates continuous variables but allows control over the range selection.

CPTs: There is some support for manual entry of probabilities, with functions for checking that entries sum to 100 (Netica has a default option to use numbers out of 100, rather than probabilities between 0 and 1), automatically filling in the final probability, and normalizing. Equations can also be used to specify the CPT, using a large built-in library of functions and continuous and discrete probability distributions, and there is support for noisy-or, noisy-and, noisy max and noisy-sum nodes.
Inference: Netica's inference is based on the elimination junction tree method (see _ 3.10). The standard compilation uses a minimum-weight search for a good elimination order, while an optimized compilation option searches for the best elimination order using a combination of minimum-weight search and stochastic search. Both the junction tree and the elimination order may be viewed. Netica also reports both the probability of the most recent evidence, and the probability of all evidence currently entered, and provides the MPE and its probability (but not for networks containing decision nodes). Netica can generate random samples by junction tree or logic sampling.
Evidence: Netica supports specific (which they call "positive"), negative and likelihood evidence. Multiple likelihood evidence may be incorporated for the same nodes. Netica also handles sets of evidence (cases) by case files and direct database access.
Decision networks: Netica infers a temporal order for decision network, if it can. DN evaluation gives the expected utilities for a one-off decision, but only the decision table for sequential decision making.
DBNs: Netica supports DBN specification and roll-out.
Learning: Netica supports parameter learning only. It uses the Spiegelhalter & Lauritzen parameterization algorithm, allows missing values, and allows the specification of a weighting to the original probabilities, providing a form of adaptation. Netica can also do EM learning and gradient descent learning, to handle large amounts of missing data, or latent (unobserved) variables. It also supports fading, with the user able to specify a factor from 0 (no new learning) to 1 (removes all previous learning).
Evaluation: Netica supports sensitivity to findings. It also provides a number of measures for statistical validation including a count form of predictive accuracy, a confusion matrix, the error rate, scoring rule results, logarithmic loss and quadratic loss, and spherical pay off, calibration results, and a "times surprised" table (indicating when the network was confident of its beliefs but was wrong).

7. PrecisionTree
Another option for building the influence diagram and decision graph element of the 'Water saving component' is to use risk analysis software. PrecisionTree (Palisade software) is one such software package which uses Bayesian concepts and can be used to build decision networks similar to decision graphs, and also to carry out sensitivity analysis. It is complimented by other software @RISK.

Software selection

Selection of the most appropriate BN software for the current research needs to consider the following criteria:

1. Is manual input of probabilities supported?
2. Is the software output suitable for use in the Demand Forecasting model?
3. Can it communicate with the Demand Forecasting model – are other APIs available in other programming languages?
4. Does it support influence diagrams and decision graphs?
5. Ability to analyse the results from the questionnaire?
6. User Friendly?

7. Is training available?
8. How much does it cost?

Technical

Analytica, Hugin, Genie, MSBNx and PrecisionTree all meet the technical criteria above. The level of communication required between the Demand forecasting and Water saving components will require further consideration at the programming stage, therefore the Application Programming Interface (API) should, if possible, be the same.

Customer survey

Ideally the software chosen will be capable of analysing the results from the customer survey and comparing them with the prior influence diagram structure, weights and rates. However, there is no methodology explained for analysing the output of customer surveys in any of the software and it may be necessary to process the results and compare the results manually, or develop a methodology.

User Friendly, Training, costs.

Hugin, Genie and MSBNx utilise a similar user interface, with chance, decision and utility nodes and manual input of probability distributions which was found to be the most user friendly of the above software options. Training is most accessible for Hugin as the text book, 'Bayesian Networks and Decision Graphs' (Jensen, 2004) is available in the library and gives exercises which are aimed at beginner-users of Hugin. There is also a three-day training course in Hugin at the end of October in Denmark (£800).

The on-line tutorials of both PrecisionTree and @Risk are easy to follow and in combination would be a suitable alternative. However, whilst PrecisionTree would probably be suitable for the 'meter/no meter decision element of the water saving component, it is probably too simplified for the Influence diagram of receptivity theory. PrecisionTree is available at a 90% student discount.

Appendix D Knowledge elicitation questionnaire

Mapping Expert Knowledge:

Domestic water conservation planning in Sofia

Interviewee details

Name:

Title:

Time: (2.5 hours)

Date:

<u>Objectives</u>

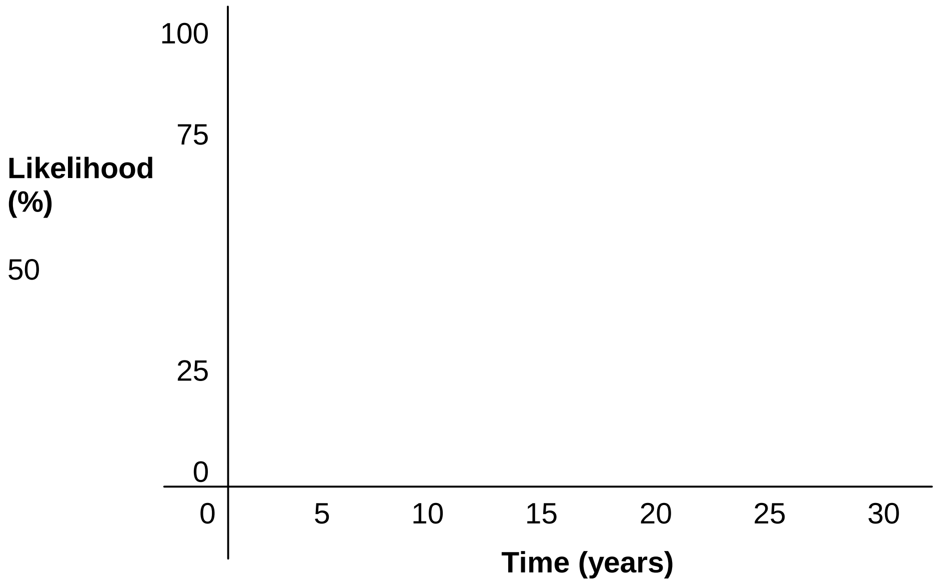
1. Elicitation of decision criteria for four water conservation problems:
    a. ***Effective targeting***
    b. ***Uptake mechanisms***
    c. ***In-building leakage detection and repair***
    d. ***Risk Management vs. Crisis Management***
2. Map the decision making process at the organisational level:
    a. Who makes the decisions?
    b. Who is responsible for implementation?
3. Explore institutional constraints and propose measures for moving forward.

<u>Methods</u>

During the 2.5 hour session a semi-structured questionnaire will be used to prompt a discussion relating to the above objectives. Causal maps and influence diagrams will be developed.

Q1. What is your organisations role in the domestic water conservation planning and decision-making process in Sofia?

Q2. Draw a line on the graph below representing your beliefs about the likelihood that severe drought resulting in supply interruptions and reduced economic productivity will occur in Sofia within the next thirty years.



Comment on conditionality and indicators: *e.g. reservoir levels, key months, days without rainfall etc*:

Q3. Which factors need to be considered in deciding when to implement water conservation?

Q4. Within the Sofia context which water conservation measures do you consider suitable for reducing domestic demand within a three month time horizon? *Use Table 1

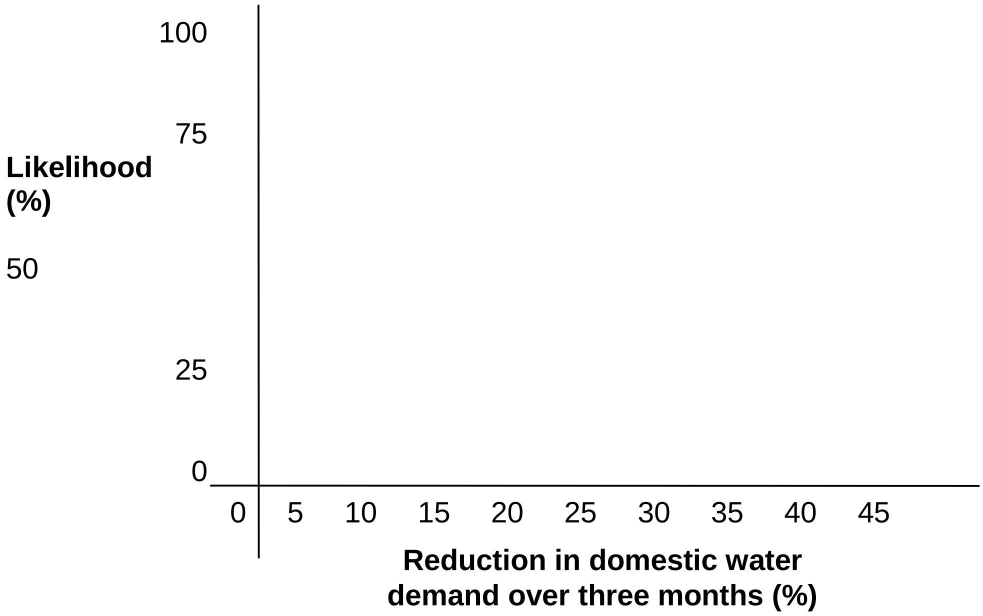
Q5. How do you rate these measures as to their water saving potential?

Very high **High** **Medium** **Low** **Very low**

Q6. How would you rate these measures as to ease of implementation?

Very difficult **Difficult** **Moderate** **Easy** **Very easy**

Q7. If a drought alert were to be forecast today, by how much do you think that domestic water demand could be reduced by using domestic water conservation measures, given a three months time horizon?



Comment:

Q8. Some water conservation options will be more difficult to implement than others. Can you describe the constraints that exist for each option?

Q9. Using the constraints mentioned in Q8, how could the measures be shaped to move forward from the constraints mentioned?

Up to now we have considered water conservation in the short-term. I'd now like to switch the emphasis to long-term (pre-emptive) water conservation.

Q10a. Do you think that domestic water consumption needs to be reduced in the long-term?

If 'YES' go to Q10b
If 'NO' go to Q11

Q10b. By how much do you think that domestic water demand needs to be reduced in Sofia so that short-term measures can be used successfully (i.e. three months) to adapt to drought?

______%

Q11. Within the Sofia context which pre-emptive measures are available for reducing domestic demand to the necessary level within a five-year time horizon?

Q12. How do you rate these measures as to their water saving potential?

Very high **High** **Medium** **Low** **Very low**

Q13. How would you rate these measures as to ease of implementation?

Very difficult **Difficult** **Moderate** **Easy** **Very easy**

Q14. Some water conservation options will be more difficult to implement than others. Can you describe the constraints that exist for each option?

Q15. Using the constraints mentioned in Q14, how could the measures be shaped to move forward from the constraints mentioned?

The following question concern the targeting of domestic water conservation tools at specific customers

Q16 Consider the idea of targeting specific water conservation tools at particular water consumers - what factors need to be considered when deciding where to target technical water conservation tools (e.g. low flow appliances)?

Are there any other tools that you consider suitable for targeting?

The following two questions concern the organisation arrangements and their impact on domestic water conservation implementation.

Q17. Within your organisation, how do the current practices and inter-organisational arrangements constrain implementation of domestic water conservation in Sofia?

Q18. Suggest ways in which these arrangements might be moved forward.

The following questions concern in-building leakage detection

Q19. What are the main causes of in-building leakage in Sofia?

Q20. What is the current decision process for carrying out in-building water audits for leakage detection?

Q21. Are indicators available for remote detection of in-building leakage?

TABLE 1 – BLANK – short term measures

ST Domestic water conservation options	Water saving potential	Ease of implementation

TABLE 2 (BLANK) long-term measures

LT Domestic water conservation options	Water saving potential	Ease of implementation

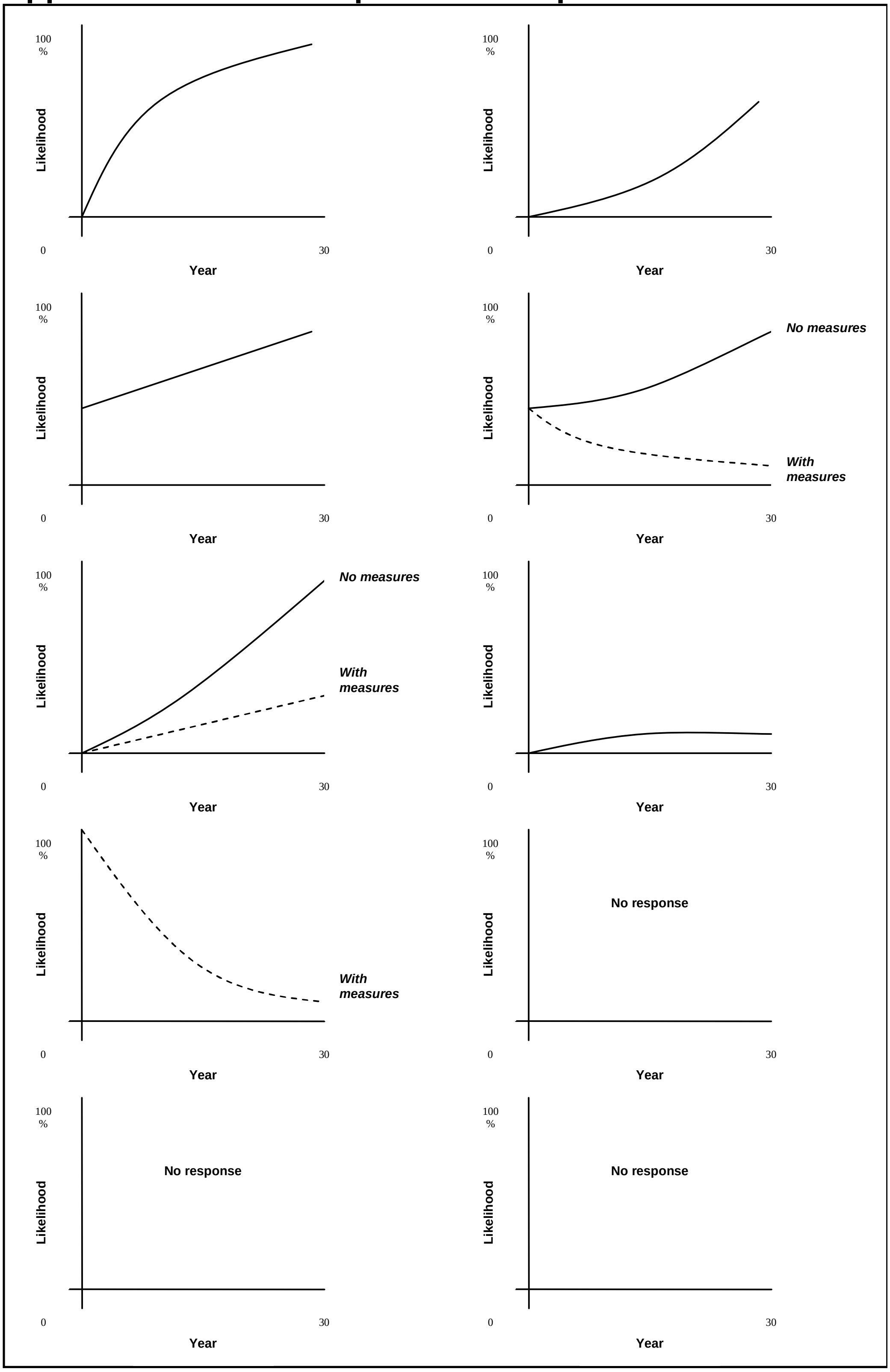
SHOWCARD 2

1. **Very difficult**
2. **Difficult**
3. **Medium**
4. **Easy**
5. **Very easy**

SHOWCARD 3

1.	**Very high**	**(over 15%)**
2.	**High**	**(10-15%)**
3.	**Medium**	**(5-10%)**
4.	**Low**	**(3-5%)**
5.	**Very low**	**(less that 3%)**

Appendix E Informed practitioners perceived risk of drought



Appendix F Maximal probabilities of water abstraction from the Iskar reservoir for five time periods

	1966-1978	1978-1990	1990-1993	1993-1995	1995-2000
Inflow	Monthly inflow to Iskar reser... 0.00 509 - 1851 0.00 1851 - 11245 0.00 11245 - 32716 100.00 32716 - 134702	Monthly inflow to Iskar reser... 0.00 509 - 1851 100.00 1851 - 11245 0.00 11245 - 32716 0.00 32716 - 134702	Monthly inflow to Iskar reser... 0.00 509 - 1851 100.00 1851 - 11245 0.00 11245 - 32716 0.00 32716 - 134702	Monthly inflow to Iskar reser... 0.00 509 - 1851 0.00 1851 - 11245 0.00 11245 - 32716 100.00 32716 - 134702	Monthly inflow to Iskar reser... 0.00 509 - 1851 100.00 1851 - 11245 0.00 11245 - 32716 0.00 32716 - 134702
Domestic demand	Monthly municipal water s... 66.00 0 - 10721 100.00 10721 - 18762 51.00 18762 - 25463 72.75 25463 - 67009	Monthly municipal water s... 11.52 0 - 10721 17.45 10721 - 18762 31.07 18762 - 25463 100.00 25463 - 67009	Monthly municipal water s... 62.98 0 - 10721 95.42 10721 - 18762 100.00 18762 - 25463 50.72 25463 - 67009	Monthly municipal water s... 39.87 0 - 10721 100.00 10721 - 18762 30.77 18762 - 25463 8.77E-7 25463 - 67009	Monthly municipal water s... 5.26 0 - 10721 26.18 10721 - 18762 25.20 18762 - 25463 43.37 25463 - 67009
Reservoir volume	Monthly volumes Iskar reservo... 0.00 53909 - 202067 0.00 202067 - 343784 0.00 343784 - 466175 100.00 466175 - 698075	Monthly volumes Iskar reservo... 0.00 53909 - 202067 0.00 202067 - 343784 100.00 343784 - 466175 0.00 466175 - 698075	Monthly volumes Iskar reservo... 0.00 53909 - 202067 100.00 202067 - 343784 0.00 343784 - 466175 0.00 466175 - 698075	Monthly volumes Iskar reservo... 100.00 53909 - 202067 0.00 202067 - 343784 0.00 343784 - 466175 0.00 466175 - 698075	Monthly volumes Iskar reservo... 0.00 53909 - 202067 0.00 202067 - 343784 0.00 343784 - 466175 100.00 466175 - 698075
Other sector demand	Monthly water supply to ... 100.00 0 - 962 16.67 962 - 3273 16.42 3273 - 9242 17.32 9242 - 19255	Monthly water supply to ... 100.00 0 - 962 19.05 962 - 3273 22.22 3273 - 9242 23.81 9242 - 19255	Monthly water supply to ... 100.00 0 - 962 32.20 962 - 3273 32.20 3273 - 9242 20.34 9242 - 19255	Monthly water supply to ... 100.00 0 - 962 24.59 962 - 3273 18.03 3273 - 9242 21.31 9242 - 19255	Monthly water supply to ... 59.36 0 - 962 13.90 962 - 3273 13.49 3273 - 9242 13.25 9242 - 19255
Release volumes	Release volumes (mill.Mm3... 10.71 7610 - 14200 42.86 14200 - 21448 55.36 21448 - 27378 100.00 27378 - 73504	Release volumes (mill.Mm3... 19.15 7610 - 14200 76.60 14200 - 21448 68.09 21448 - 27378 100.00 27378 - 73504	Release volumes (mill.Mm3... 45.45 7610 - 14200 100.00 14200 - 21448 88.64 21448 - 27378 56.82 27378 - 73504	Release volumes (mill.Mm3... 50.00 7610 - 14200 100.00 14200 - 21448 100.00 21448 - 27378 20.00 27378 - 73504	Release volumes (mill.Mm3... 5.13 7610 - 14200 20.51 14200 - 21448 26.50 21448 - 27378 47.86 27378 - 73504
Total Demand	Total monthly supply from ... 100.00 6871 - 15921 36.68 15921 - 21092 51.00 21092 - 26909 72.75 26909 - 71509	Total monthly supply from ... 17.45 6871 - 15921 14.77 15921 - 21092 31.07 21092 - 26909 100.00 26909 - 71509	Total monthly supply from ... 95.42 6871 - 15921 45.13 15921 - 21092 100.00 21092 - 26909 50.72 26909 - 71509	Total monthly supply from ... 60.41 6871 - 15921 100.00 15921 - 21092 0.00 21092 - 26909 0.00 26909 - 71509	Total monthly supply from ... 2.69E-3 6871 - 15921 32.49 15921 - 21092 20.95 21092 - 26909 46.56 26909 - 71509
Year	Year range 100.00 1966 - 1978 0.00 1978 - 1990 0.00 1990 - 1993 0.00 1993 - 1995 0.00 1995 - 2000	Year range 0.00 1966 - 1978 100.00 1978 - 1990 0.00 1990 - 1993 0.00 1993 - 1995 0.00 1995 - 2000	Year range 0.00 1966 - 1978 0.00 1978 - 1990 100.00 1990 - 1993 0.00 1993 - 1995 0.00 1995 - 2000	Year range 0.00 1966 - 1978 0.00 1978 - 1990 0.00 1990 - 1993 100.00 1993 - 1995 0.00 1995 - 2000	Year range 0.00 1966 - 1978 0.00 1978 - 1990 0.00 1990 - 1993 0.00 1993 - 1995 100.00 1995 - 2000

Max-propagation

The max-propagation method is used to find states belonging to the most probable configuration (a configuration is a list of states ($a_1, a_2, ..., a_n$)) of the list of all nodes in a network ($A_1, A_2, ..., A_n$)).

If a state of a node belongs to the most probable configuration it is given the value 100. All other states are given the relative value of the probability of the most probable configuration they are found in compared to the most probable configuration. That is, assume a node *N* has two states *a* and *b*, and *b* belongs to the most probable configuration of the entire network which has the probability 0.002. Then, *b* is given the value 100. Now, assume that the most probable configuration which a belongs to has probability 0.0012. Then, a is given the value 60.

If there are several states of maximal probability, then for some variables ($A_1, A_2, ..., A_m$), there are serveal states of maximal probability in their max-marginalised distributions. Unfortunately it does not hold that all combinations of these max-probable states form a configuration of maximal probability. If you request one of them, you can enter a max-probable state as evidence and perform a new max-propagation. If there are still several max-probable states in some of the remaining variables, you can repeat this operation until all the variables have only one max-probable configuration (Jensen, 2001, p207)

Appendix G Sensitivity Analysis for Iskar dam forecasting variables

Evidence on : Selected information variables : Average INFLOW (prev. 12 mnths) Average VOLUME (prev. 12 months) Current month INFLOW Current month TOTAL SUPPLY Current month VOLUME

Sensitivity of FORECAST VOLUME (18 months) to findings at Average INFLOW (prev. 12 mnths):

Belief ranges:	min	current	max
- 53909 - 331528	0.2	0.33	1
- 331528 - 45992	0	0.33	0.42
- 459920 - 69807	0	0.33	0.57

Mutual information : I(FORECAST VOLUME (18 month, Average INFLOW (prev. 12 mnths) | Selected Evidence) = 0.07

- -

Sensitivity of FORECAST VOLUME (18 months) to findings at Average VOLUME (prev. 12 months):

Belief ranges:	min	current	max
- 53909 - 331528	0.13	0.33	0.51
- 331528 - 45992	0.31	0.33	0.37
- 459920 - 69807	0.18	0.33	0.55

Mutual information : I(FORECAST VOLUME (18 month, Average VOLUME (prev. 12 months) | Selected Evidence) = 0.08

- -

Sensitivity of FORECAST VOLUME (18 months) to findings at Current month INFLOW:

Belief ranges:	min	current	max
- 53909 - 331528	0.24	0.33	0.46
- 331528 - 45992	0.31	0.33	0.37
- 459920 - 69807	0.22	0.33	0.45

Mutual information : I(FORECAST VOLUME (18 month, Current month INFLOW | Selected Evidence) = 0.03

- -

Sensitivity of FORECAST VOLUME (18 months) to findings at Current month TOTAL SUPPLY:

Belief ranges:	min	current	max
- 53909 - 331528	0.2	0.33	0.46
- 331528 - 45992	0.32	0.33	0.35
- 459920 - 69807	0.21	0.33	0.45

Mutual information : I(FORECAST VOLUME (18 month, Current month TOTAL SUPPLY | Selected Evidence) = 0.03

- -

Sensitivity of FORECAST VOLUME (18 months) to findings at Current month VOLUME:

Belief ranges:	min	current	max
- 53909 - 331528	0.13	0.33	0.45
- 331528 - 45992	0.25	0.33	0.42
- 459920 - 69807	0.16	0.33	0.61

Mutual information : I(FORECAST VOLUME (18 month, Current month VOLUME | Selected Evidence) = 0.1- -

Appendix H Review of Delphi methods for knowledge elicitation

The following is a review of methods, known collectively as “Delphi methods”, that informed the knowledge elicitation questionnaire design and the methods for eliciting conditional probabilities for the water savings Bn in Chapter 4.

1. Delphi methods review to inform consultation questionnaire

The US RAND Corporation first developed the Delphi method in the 1950s to pool expert judgement primarily with reference to strategic implementation of new technology. The use of the term Delphi in this context was originally a joke. As Turoff and Hiltz (1996) comment *'the image of a priestess, sitting on a stool over a crack in the earth, inhaling sulphur fumes, and making vague and jumbled statements that could be interpreted in many different ways, did not exactly inspire confidence in the method*.' Despite its name, the technique has been applied in many fields of research and its results have influenced both corporate planning and government policy-making (Mckinnon and Forster, 1999).

Linstone and Turoff (1975) have defined a Delphi survey as *'a method of structuring a group communication process, so that the process is effective in allowing a group of individuals, as a whole, to deal with complex problems'*. They see an important role for Delphi surveys where:

- A problem does not permit the application of precise analytical techniques but can *'benefit from subjective judgements on a collective basis'*
- The relevant specialists are in different fields and occupations and not in direct communication.
- The number of specialists is too large to *'effectively interact in a face-to-face exchange'* and too little time and/or funds are available to organise group meetings.

Several attempts have been made to classify Delphi surveys. Strauss and Zeigler (1975), for example, categorise them as *numeric, policy* or *historic* while Van Dijk (1990) differentiates *conventional*, *policy* and *decision* Delphis. Generally speaking, there are four approaches to forecasting: extrapolating past trends, analysing past relationships and analogies, constructing future scenarios and development trajectories and finally, building a consensus of expert opinion (Saaty and Boone, 1990). The Delphi method supports the last of these approaches by offering a formal means of capturing and consolidating expert opinion.

In interpreting the result of a Delphi survey, one should be aware of its many limitations. Sackman (1974) and Rowe *et al* (1991) discuss these in detail. The main shortcomings are as follows:

2. Delphi surveys can exaggerate the concept of expertise.
3. The composition of the panel is seldom random, reflects the personal biases of the researchers and is not necessarily representative of specialist knowledge in the field.
4. Anonymity relieves panel members of accountability and hence can lead to careless responses.
5. By seeking consensus, Delphi surveys promote a conservative view of the future, discourage original thinking and suppress radical views. They can have the effect of reinforcing existing paradigms.
6. They offer little insight in the reasoning underlying the panel members' responses and give no opportunity for their arguments to be tested in face-to-face discussion.

7. As Delphi questions are intrinsically very difficult to answer, they elicit, at best, a series of 'guestimates'. The quantification and averaging of these guestimates' can give a spurious sense of scientific accuracy.
8. The iterative nature of Delphi surveys makes them slow and time-consuming.

In its defence, Linstone (1978) portrays the Delphi technique as 'a last resort' where no other, more scientific method can be deployed to investigate a particular subject given its complexity and uncertainty. In most cases, no quantitative data are available on past trends or the present situation and no attempt has been made to establish mathematical or statistical relationships between changes in these variables and other causal factors. In the absence of such modelling, one must rely on the subjective judgements of specialists in the field, ensuring that the analysis, feedback and summary of their responses is undertaken as rigorously and objectively as possible. This is what the Delphi technique aims to achieve. Dalkey (1968) found that a suitable minimum panel size is seven; accuracy deteriorates rapidly with smaller sizes and improves more slowly with large numbers.

Although there are no official guidelines for executing a Delphi study, Jillson (1975[2]) suggests a number of guidelines which should be considered when specifying and executing a Delphi study. These are:

- Standards for determining the applicability of the technique to the problem identified;
- Criteria for selecting respondents;
- Suggested questionnaire approach to be utilized, including number of rounds for each type of question, response scales;
- Types of analyses most appropriate; and
- Recommendations for the interpretation of results.

An effort has been made in the preparation of the current research to review different Delphi applications and methodologies, with reference to the above guidelines. The Delphi method specified by the RAND Corporation has undergone further development by a number of researchers (see Ford, 1975; Sahal and Yee, 1975; Jillson, 1975[1]) to improve on the original design and also to adjust to different contexts. Improvements involved changes to the method of execution and results analysis. Brief descriptions of five approaches for executing a Delphi study are given below:

1. Delphi I. A Delphi point-estimate technique without group feedback. For each question, the subject makes a single numerical estimate and is fed back that estimate on the next round.
2. Delphi II. The basic Delphi, with feedback limited to the subject's previous response and the group median and quintiles.
3. Delphi III. Delphi with distribution estimates. Feedback including the high, middle, and low estimates the respondent gave on the previous round and the group medians for each of the three estimates.
4. Delphi IV. Delphi with credibility function. Let the results from the first round Delphi exercise be a set of independent probability distribution functions, see Figure 1, below (below). These may be regarded as Type I functions. Anonymity is maintained while returning an entire set of distributions to each 'panel' member, and instead of asking the assessors to re-evaluate their initial PDF and give another one, the assessor is asked to give a credibility function, which is a measure of the fuzziness or precision of his initial estimates. In Good's (1962 in Sahal and Yee, 1975) terminology, Credibility Density Function CRDF is a Type II function, in a two level hierarchy of probabilities. "A second-order (type II) probability distribution supposedly

represents his uncertainty (or confidence) about his first-order probability considered as a random variable." If the assessor is certain that his PDF is very near the true distribution, the CRDF would be a uniform distribution and hence would not cause any change in his initial PDF. Sahal and Lee (1975) suggest that if it is reasonable to assume that each assessor's judgement, CAPDF, belong to the same family of the distribution function, it may be advantageous to aggregate in a manner similar to successive application of Bayes' theorem. For further explanation of the method involved they recommend reference to the work of Raiffa and Schlaifer (1961)

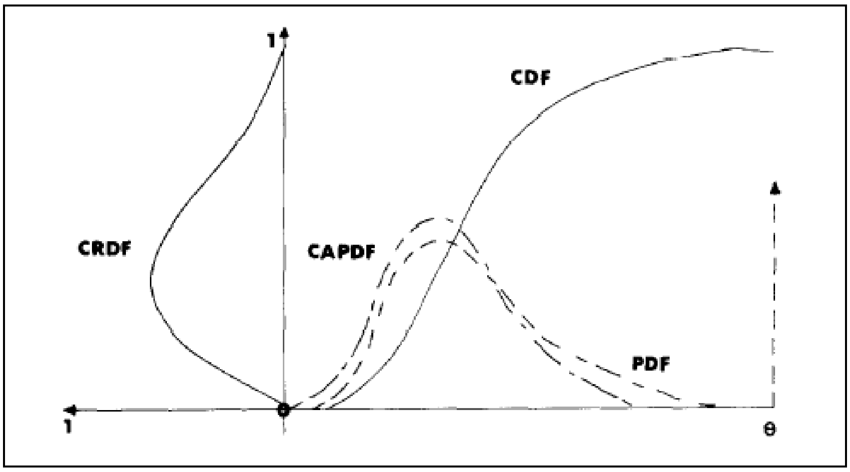


Figure 1. Cumulative Distribution Function, CDF; Probability Density Function, PDF; Credibility Density Function, CRDF; and Calibrated Probability Density Function, CAPDF (Sahal and Yee, 1975).

5. Delphi V - This method was devised by Ford (1975) and the following is an extract from his paper – 'Shang enquiry as an alternative to Delphi: Some experimental findings'.

'Long before the ancient Greeks sought divine guidance through interpretations of the prophetic mutterings of their oracles, the ancient Chinese had been consulting oracular bones through which the wisdom of the gods was communicated.

> The broad shoulder-blades of cattle and the shells of tortoises . . . were employed. Before being used they were flattened, polished, and incised. When touched with a small glowing bronze rod, each of these incisions delivered an oracle. From the cracks thus produced, which were often distinguished by numbers in the inscriptions, the oracle was interpreted as 'yes' or 'no,' 'favourable' or 'unfavourable.' (Eichhorn, 1969 in Ford, 1975)

Such oracle inquiries were tantamount to appeals for expert judgment, for the Shang king was surrounded by a highly organized clergy who conducted divinations. As historians, the priests controlled knowledge of the past. As diviners, they were capable of controlling the answers to the inquiries.

It is of interest here that the Shang oracles yielded binary reponses -"yes" or "no," "favorable" or "unfavorable." How could the king ascertain the date of a pending enemy attack or the size of an enemy army? To elicit such numerical information, he would obviously have to ask a series of questions, each posing a number as a hypothesis. If the oracle could respond with "higher" or "lower" to locate the exact answer relative to those hypothesized, then the enquirer could select numbers in such a way as to “zero in” on the exact answer by narrowing the range in which it was located.’

As Ford (1975) points out there is no evidence that such an enquiring system was used by Shang rulers, but it suggests a methodology which he has called a “Shang enquirer.”

A criterion for the current research is transparent measure of accuracy and the experiments by Ford (1975) suggests a greater improvement in accuracy over iterations than conventional Delphi. This was possible because in tests carried out by Ford (1975) because factual data about the questions answered was available but unknown to the panel, and therefore he could track how different Delphi methods improved in accuracy over successive iterations by comparing the panel response to the true answer. From the results he was able to conclude that with correct estimating, the maximum error attributable to the method after three iterations would be 6.2% (CY = ,876); further iterations would produce results well within tolerable error limits. Table 1 (below) shows the improvement in accuracy at each iteration.

Table 1 Shang Enquiry Error and Accuracy results (Ford, 1975)

Iteration	Reference Points	Error	Accuracy
1	25.0% (or 75.0%)	25%	0.500
2	37.5% (or 62.5%)	12.50%	0.750
3	43.8% (or 56.2%)	6.20%	0.876
4	46.9% (or 53.1%)	3.10%	0.936
5	48.4% (or 51.6%)	1.60%	0.968

The use of second order probabilities to add inference as described in Delphi IV has been met with some criticism, namely from Savage (1954, in Sahal and Yee, 1975), who argues that ‘once second order probabilities are introduced, the introduction of an endless hierarchy seems inescapable. Such a hierarchy seems very difficult to interpret, and it seems at best to make the theory less realistic, nor more’.

However, as Sahal and Yee point out others do not agree. For instance, Jamison’s answer to Savage’s criticism of second order probabilities is ‘an endless hierarchy does not seem inescapable to me; we simply push the hierarchy back as far as is required to be ‘realistic’. In making a physical measurement we could attempt to specify the value of the measurement, the probable error in the probable error, and on out the endless hierarchy. But it is not done that way; probable errors usually seem to be about right order of realism. Similarly, I suspect that second-order probabilities will suffice for most circumstances.

The debate about second order probabilities is inconclusive. However, it is possible to say that in the case of using Delphi for forecasting as is intended in the current research, where uncertainty is, to some degree, unavoidable, the Further use of second order probabilities is sure to add complexity, but may not add to accuracy, making this method for the current research unsuitable.

Delphi is meant to reduce pressure towards conformity, and it is claimed that “there is no pressure to arrive at a consensus” (Dalkey, 1968) yet, as Ford (1975) points out, the controlled feedback of a typical exercise is designed to influence subsequent estimates in the direction of the whole group while ignoring possible emergent subgroups or cliques. There may not be overt pressure to reach a consensus, but feedback over iterations constitutes an obvious pressure to influence conforming response changes. An equal characteristic of the standard Delphi method is the situation where a stubborn individual is not receptive to information countering his position and will not change his response from round to round. In the worst case, Delphi does not force rethinking of a problem and thus tolerates the same answer over iterations without thought (Ford, 1975).

The Shang enquirer approach is structured to avoid the existing Delphi problems while incorporating its advantages. Ford (1975) evaluated the Shang approach through an experiment comparing it with a control method and two Delphi techniques. The study was more than a simple comparative analysis in that it demonstrated the effectiveness and accuracy of each approach in what was taken to be a realistic group judgment problem. The advantage of a Shang inquiry, with its binary responses, over requests for specific point estimates is that it does not encourage the respondent (be it oracle or expert) to become committed to a position; the respondent may never be asked to answer the same question twice. The absence of commitment to a position has two important implications. First, the respondent should be more likely to change his position if presented with good reasons for doing so, i.e., he will not be irrationally locked into a response. Second, a respondent with low commitment and low certainty in his responses may be expected to be more receptive to information supporting alternative answers than if he were highly committed (Mills and Ross, 1964 and Behling, 1971 in Ford, 1975).

The questions selected for use in Ford's study differed in several respects from the almanac-type characteristic of RAND experiments. First, unlike many almanac questions, the questions used were clearly bounded, i.e. each estimate fell on a well-defined numerical scale, independent of the specific substantive concerns. For example, six questions requested correlation values ranging from -1.00 to +1.00. The numerical scale was predetermined and given and was independent of the variables correlated. Second, the questions were clearly relevant to the background ("expertise") of the respondents. Third, the questions were not independent; answers to different questions were often closely related.

On the other hand, the questions used by Ford (1975), like almanac-type, satisfied criteria established by RAND for inclusion in judgment experiments. Dalkey (1968) has specified the following needs:

(1) Questions where the subjects did not know the answer but had sufficient background information so they could make an informed estimate.
(2) Questions where there was a verifiable answer to check the performance of individuals and groups.
(3) Questions with numerical answers to a reasonably wide range of performance could be scaled (sic).

The above points will be helpful in generating a questionnaire for use in the current study, and furthermore, it is foreseen that such a questionnaire will produce results which will require little data processing prior to application in the Bayesian Network influence diagram.

It is foreseen that a Delphi method with questions of the sort which might be used in conjunction with more exact research activities, such as model building, will be required. Thus, the use of almanac-type questions as used in the RANK methodology is rejected in favour of questions about findings from actual research.

Knowledge elicitation methods for developing CPT in Bns are also described by Cain (2001) and Bromley (2005).

Appendix I Conditional probabilities derived from knowledge elicitation

Table A Conditional probabilities derived from consultation questionnaire responses: water saving potential, given a three month implementation horizon, for seven WDM options

	WDM measure	Low			Middle			High			Experience
		savings range %	p	midpoint % (adjusted see *)	savings range %	p	midpoint % (adjusted see *)	savings range %	p	midpoint % (adjusted see *)	
1	Outdoor restrictions	5-10%	0.660	1.7	10-15%	0.330	2.9	-	-	-	3
2	Education /awareness	3-5%	0.200	4.0	5-10%	0.800	7.5	-	-	-	5
3	Introduce IBT	5-10%	0.600	1.7	0ver 15%	0.400	4.0	-	-	-	5
4	Reduce pressure at service pipe	5-10%	0.400	7.5	10-15%	0.600	12.5	-	-	-	5
5	Retrofit of appliances	3-5%	0.500	2.5	5-10%	0.250	4.7	10-15%	0.250	7.9	4
6	Water efficiency standard	less than 3%	1.000	0.5	-	-	-	-	-	-	1
7	Repair HWCP	5-10%	0.330	1.9	10-15%	0.330	2.8	Over 15%	0.330	3.9	3

*Weightings for options 1 + 3 = 0.23 (only 23% of people in household survey have gardens, i.e. discretionary demand, so only these will be affected by price)

Weightings for option 5 = 0.63 (37% of survey participants said they already had a toilet installed)

Weightings for option 7 = 0.25 (only multi-family blocks have hot-water circulation and only a fraction of these need repairing)

Table B Conditional probabilities derived from consultation questionnaire responses: Water saving potential, given a five year implementation horizon, for seven WDM options

	WDM measure	Low			Middle			High			Experience
		savings range %	p	midpoint % (adjusted see *)	savings range %	p	midpoint % (adjusted see *)	savings range %	p	midpoint % (adjusted see *)	
1	Outdoor	5-10%	0.660	1.7	10-15%	0.330	2.9	-	-	-	3
2	Education	5-10%	0.200	7.5	10-15%	0.600	12.5	Over 15%	0.200	18.5	5
3	Introduce IBT	5-10%	0.600	1.7	0ver 15%	0.400	4.0	-	-	-	2
4	Reduce pressure	10-15%	1.000	12.5	-	-	-	-	-	-	2
5	Retrofit of	3-5%	0.167	2.5	5-10%	0.167	4.7	10-15%	0.663	7.9	6
6	Water efficiency	10-15%	1.000	7.9			-				1
7	Repair HWCP	5-10%	0.330	1.9	10-15%	0.330	2.8	Over 15%	0.330	3.9	3

*Weightings for options 1 + 3 = 0.23 (only 23% of people in household survey have gardens, i.e. discretionary demand, so only these will be affected by price)

Weightings for option 5 = 0.63 (37% of survey participants said they already had a toilet installed)

Weightings for option 7 = 0.25 (only multi-family blocks have hot-water circulation and only a fraction of these need repairing)

Table C Conditional probabilities derived from consultation questionnaire responses: Ease of implementation, given a three month implementation horizon, for seven WDM options

		Low		Middle		High		Experience
	WDM measure	Ease of implementation	p	Ease of implementation	p	Ease of implementation	p	
1	Outdoor	Very easy	0.250	Easy	0.250	Difficult	0.5	4
2	Education	Very easy	0.400	Easy	0.200	Medium	0.400	5
3	Introduce IBT	Medium	0.500	Difficult	0.100	Very difficult	0.4	5
4	Reduce pressure	Easy	0.200	Medium	0.8			5
5	Retrofit of	Easy	0.250	Difficult	0.750			4
6	Water efficiency	Medium	1.000					1
7	Repair HWCP	Medium	0.333	Difficult	0.667			3

Table D Conditional probabilities derived from consultation questionnaire responses: Ease of implementation, given a five year implementation horizon, for seven WDM options

		Low		Middle		High		Experience
	WDM measure	Ease of implementation	p	Ease of implementation	p	Ease of implementation	p	
1	Outdoor	Medium	1.000					1
2	Education	Easy	0.500	Medium	0.250	Difficult	0.250	6
3	Introduce IBT	Easy	0.250	Medium	0.250	Difficult	0.5	2
4	Reduce pressure	Easy	1.000					1
5	Retrofit of	Medium	0.500	Difficult	0.500			6
6	Water efficiency	Medium	1.000					1
7	Repair HWCP	Difficult	2.000					1

To calculate the conditional probabilities for combined programs the combined probabilities, i.e. P1*P2,* P…n, for each possible combination of the seven options were calculated. The sum of the mid-points (% water saving) in Tables A and B for the combined program were then discretised i.e. 0-5%, 5-10%, 10-15% etc, and the probabilities within a specific range were summed.

Appendix J Variable operating costs for Sofiyska Voda (2005-2006)

Tables A & B below show details of the cost raw water abstraction (Water Tax) and raw water treatment paid by Sofiyska Voda in 2005 and 2006. The rows in blue are the cost components that are dependent on volumes used, and as such are the 'variable operational costs' that will be reduced by any WDM program.

Table A Water Taxes* paid by Sofiyska Voda (2005-2006)

CATEGORY	ACTUAL DATA	
	2005	2006
WATER TAX (exl. Samokov, Borovets)	**4 950 679 BGN**	**4 997 677 BGN**

*Data source – Sofiyska Voda, Unaccounted for Water Report (2007)

Table B Operational costs* paid by Sofiyska Voda (2005-2006)

CATEGORIES	2005 PWTP		2006 PWTP		2005 Chlorination		2006 Chlorination	
	BGN	%	BGN	%	BGN	%	BGN	%
Personnel Expenses	558 826	45.02%	576 266	46.66%	597 253	68.37%	522 940	64.40%
Fuel and Lubricants	194 383	15.66%	125 113	10.13%	7 478	0.86%	8 316	1.02%
Current repairs of plant and equipment	2 053	0.17%	759	0.06%	51 277	5.87%	55 412	6.82%
Power	**76 774**	**6.18%**	**75 676**	**6.13%**	**55 097**	**6.31%**	**51 267**	**6.31%**
Chemicals	**305 308**	**24.60%**	**359 356**	**29.10%**	**85 193**	**9.75%**	**90 823**	**11.18%**
All others	103 950	8.37%	97 769	7.92%	77 272	8.85%	83 301	10.26%
TOTAL EXPENSES	***1 241 294***		***1 234 939***		***873 571***		***812 059***	
EXPENSES RELATED TO UFW VOLUMES	**382 082**	**30.78%**	**435 032**	**35.23%**	**140 290**	**16.06%**	**142 090**	**17.50%**

*Data source – Sofiyska Voda, *Unaccounted for Water Report* (2007)

Appendix K   Supply curve example

Turner and White (2003) recommend that a process of ranking should be applied. Once analysed, a supply curve can be generated, where the WDM options are ordered in terms of their unit cost. Figure A (below) is an example of a supply curve from a recent study reported in Australia.

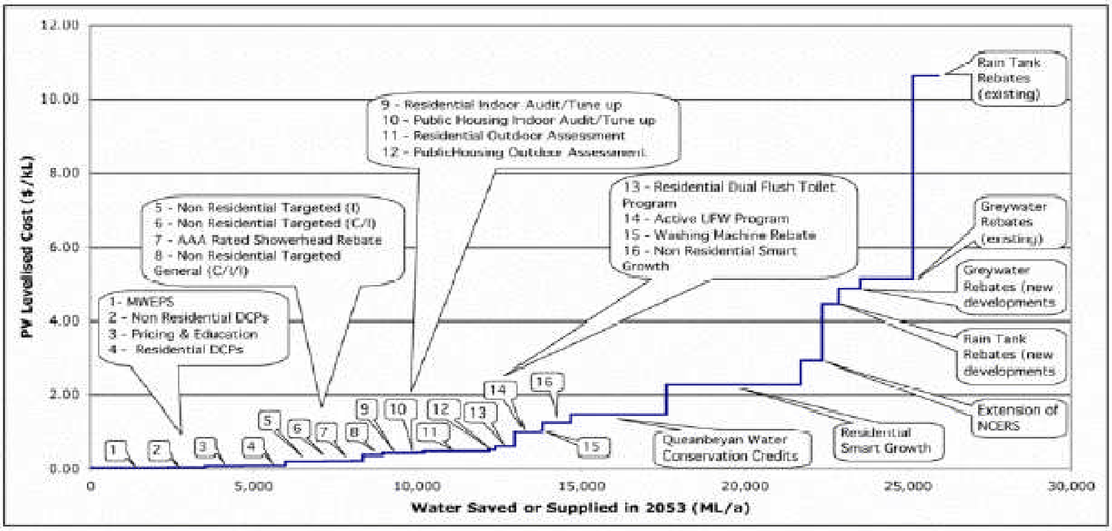


Figure A Typical supply curve for WDM options (Turner and White, 2003)

The supply curve, presented in Turner and White (2003), shows the cumulative water saved and supplied against the present value levelised cost of each option. Options are ordered in terms of least cost, ranging from low-cost water conservation options (MWEPS – minimum water efficiency performance standards) to high cost rainwater tank rebates. This exemplifies the pattern of lower cost water conservation options and higher cost source substitution and source augmentation options.

Supply curves provide utilities with an effective process to order their investment in DM options, directing implementation. The options shown in Figure A combine both technological and behavioural components, and the option analysis revolves around predicting take-up rates and water savings, so evaluation of the actual results is essential. Evaluation will provide higher certainty in the modelling outcomes.

Appendix L Utilities used in the conceptual model

Securityof Sofia'swater supply(SECURITY_OF_SUPP)

FORECAST_RI	High	Low
Utility	100.0	-100.0

Lifetime Avoided Cost of WDM program(LAC)

LIFETIME_OF	>15 years									< 15 yea	
WATER_SAVII	High			Low			None			High	
PAYBACK_PRI	High	Low	NA	High	Low	NA	High	Low	NA	High	Lo
Utility	-100.0	-70.0	0.0	-140.0	-100.0	0.0	0.0	0.0	0.0	-50.0	

LIFETIME_OF	< 15 years								NA		
WATER_SAVII	High		Low			None			High		
PAYBACK_PRI	Low	NA	High	Low	NA	High	Low	NA	High	Low	N
Utility	0.0	0.0	-95.0	-75.0	0.0	0.0	0.0	0.0	0.0	0.0	

LIFETIME_OF	NA						
WATER_SAVII	High	Low			None		
PAYBACK_PRI	NA	High	Low	NA	High	Low	NA
Utility	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The utility functions shown above were used in the conceptual model reported in Chapter 5. They demonstrate possible subjective (monetary or other) values for combination of model states represented by the chance nodes connect to the utility nodes (i.e. for Security of Sofia’s supplies see: FORECAST_RESERVOIR_VOLUME; for Lifetime avoided costs see: LIFETIME_OF_OPTION, WATER_SAVING, and PAYBACK_PERIOD.)

Appendix M Frequency histograms of variables included in the household survey

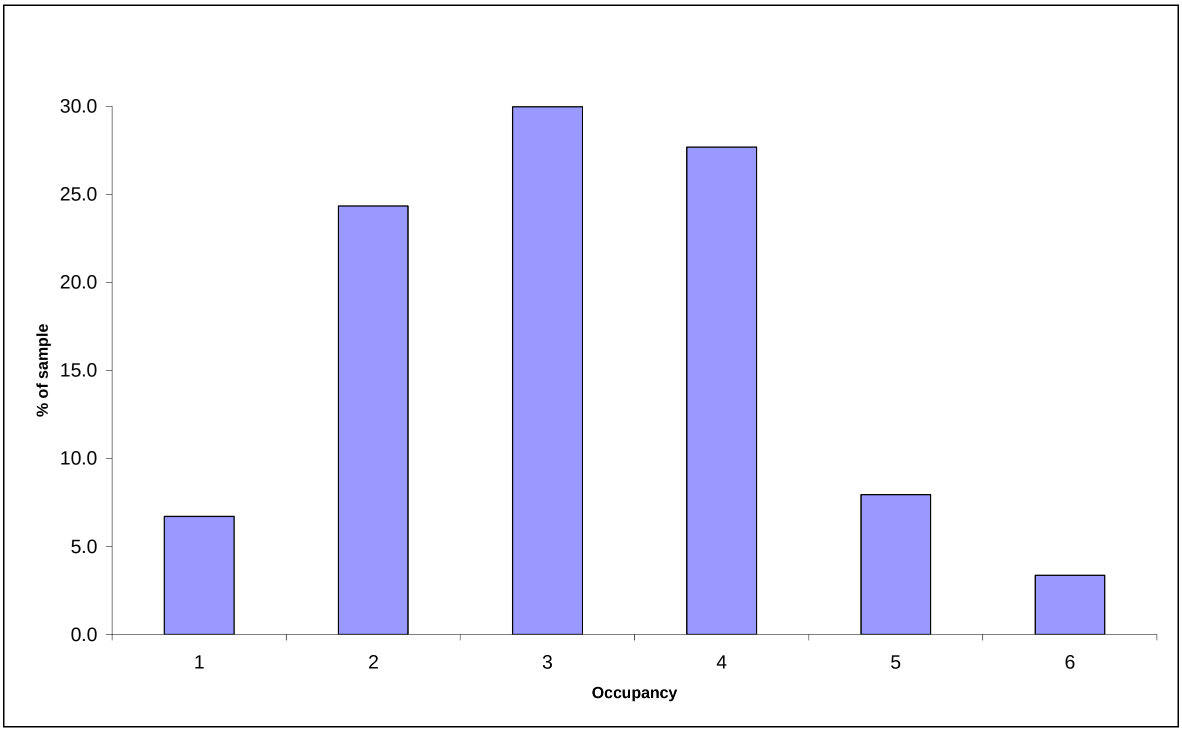


Figure A Occupancy distribution of household survey sample

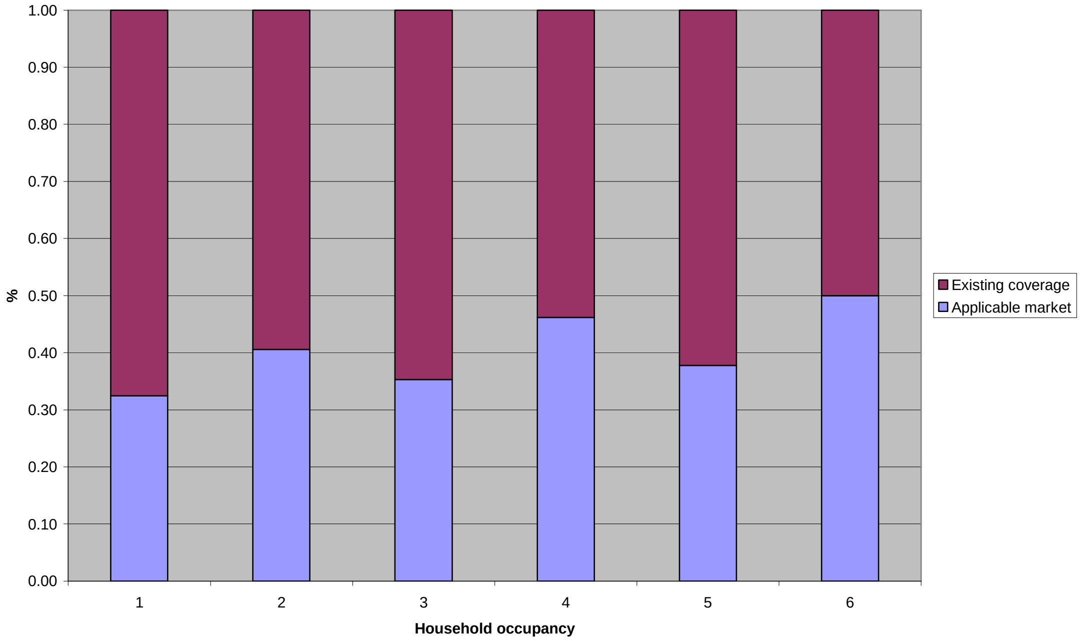


Figure B Existing coverage and applicable market for faucets

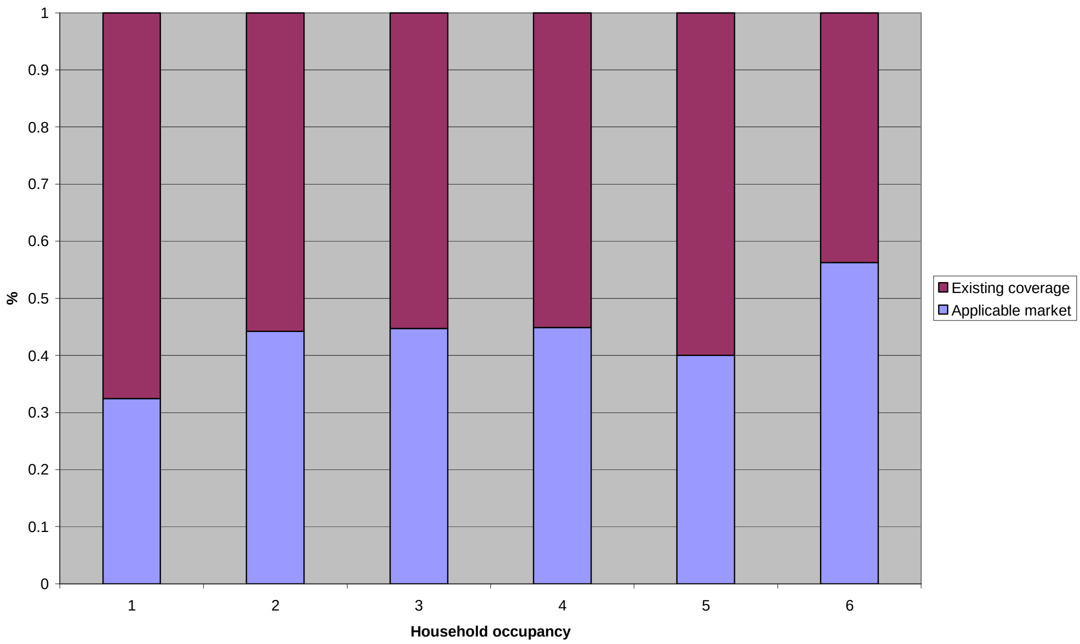


Figure C Existing coverage and applicable market for showers

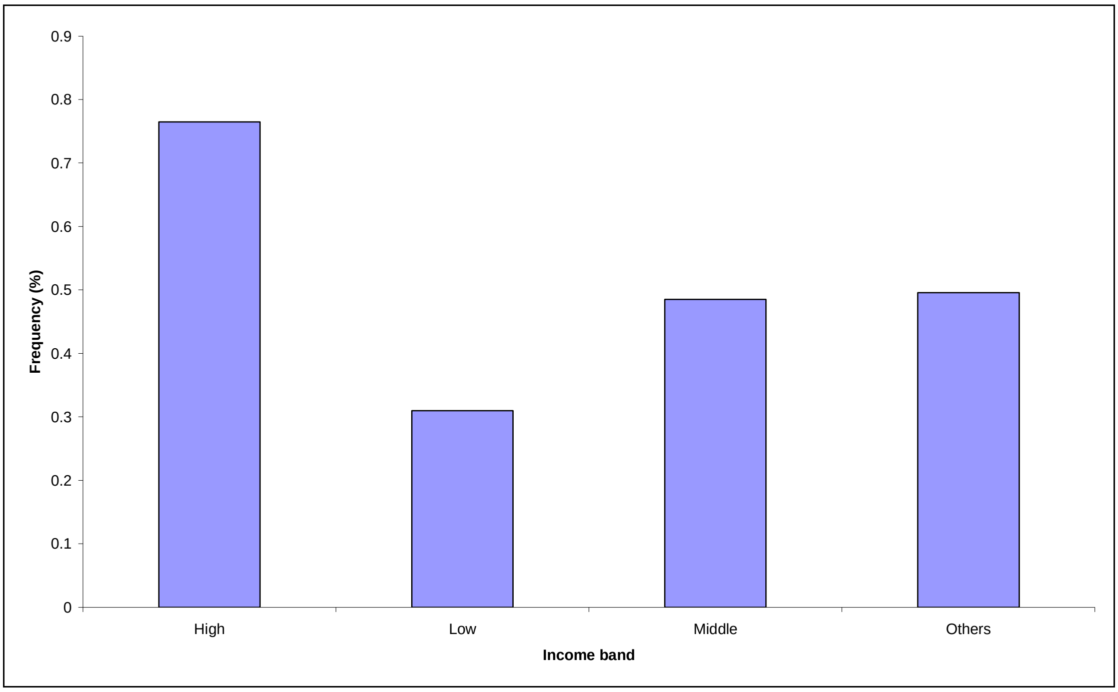


Figure D Coverage of water saving WCs for different incomes groups

Appendix N ‘Acceptance rate’ conditional probabilities

Intend to replace WC		*no*						
Uptake instrument		*Fully-funded*				*Free-installation*		
Household occupancy		*<3*		*>3*		*<3*		*>*
Installed low-flush WC		*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*
Acceptance rate	**yes**	0	0	0	1	0	0	0
	no	1	1	1	0	1	1	1

Intend to replace WC		*no*						
Uptake instrument		*Fully-funded*				*Free-installation*		
Household occupancy		*<3*		*>3*		*<3*		*>*
Installed low-flush WC		*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*
Acceptance rate	**yes**	0	0	0	1	0	0	0
	no	1	1	1	0	1	1	1

Intend to replace WC		*no*						
Uptake instrument		*Fully-funded*				*Free-installation*		
Household occupancy		*<3*		*>3*		*<3*		*>*
Installed low-flush WC		*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*
Acceptance rate	**yes**	0	0	0	1	0	0	0
	no	1	1	1	0	1	1	1

Appendix O Developing the demand forecasting model dataset

Indoor demand variables

System pressure

The WDM Procedure 6 report found that higher water pressure increases water losses in old buildings due to damaged plumbing fittings, e.g. toilet float valves. Using information in 0, the report concludes that different water pressure in buildings can explain 10-12% of the variation in per capita consumption. The variation in consumption however (104-236 l/c/d) is approximately 130%. The Further variation in per capita consumption can be explained by the customers' habits and culture (Dimitrov, 1979; Alitchkov and Kostava, 1996). Metering error combined with high pressure results in higher water consumption, and inaccurate bills. As 0 also shows, metering error could account for ±30% error in some household bills.

Effects of metering error and pressure on household water demand

Neighbourhood	**Average water consumption (l/c/d)**			**Pressure (bar)**	**Garden**	**Private borehole**
	Logger data l/c/d	*Household meter data l/c/d*	*Meter error*			
Gorni Lozen	214	154	-28%	7,2 – 8,1	NO	YES
Kurilo	111	126	+14%	4,0 – 7,0	YES	NO
Iskarsko Defile	114	103	-10%	4,0 –7,5	NO	NO
Ovcha Kupel, 25	86	91	+6%	3,7 –5,2	NO	YES
Gorni Lozen	64	108	+69%	2,5 – 7,5	NO	YES
Gorubljane	69	56	-19%	3,6 – 5,5	NO	YES

Following research carried out in Sofia, the following equation can be used to predict leakage due to high pressure:

equation:

qz = ap 1.86 (eq. 1)

where qz are the water losses, l/min;

a – parameter which varies from 0.15 to 0.6;

p – pressure in the service connection, MPa.

Using pressure of 8 MPa and the mid-point for the parameter (37.5) we estimate an increase in demand of 350 l/c/d in household with high pressure and faulty appliances. This volume was added to 50% of households in the household survey sample who stated that they considered pressure to be ‘too high’ and had not changed their WC within the last 10 years.

WC flush volumes

Flush volume distributions for WCs, shown in 0, below, were used for households without Water Saving WCs to adjust the litres/day volumes for different occupancies. A flush volume of 4.5 litres was used for interviewees who responded positively when asked whether their WC was a low-flush model, and their meter demand was adjusted accordingly. No data was available for WC flush volumes in Sofia and the volumes and frequencies shown are taken from a study in southern England (WRc, 2005) involving 447 household. The number of flushes per capita per day used was 4.8, which is the same as a number of studies in Australia and the UK (Ofwat, 2002).

Flush volume frequencies used for households without water saving WCs

FLUSH VOLUME (LITRES PER FLUSH)	FREQUENCY (%)	FLUSHES PER CAPITA PER DAY
9.5	38	4.8
10.5	28	4.8
11.5	13	4.8
12.5	7	4.8
13.5	5	4.8
14.5	3	4.8
15.5	3	4.8
16.5	2	4.8

Outdoor water demand

A comprehensive study of household water demand was carried out among rural households outside of Sofia as part of the WDM Procedure 6 report. To determine household water consumption, water meter readings for 46 houses over 128 days in neighborhoods in the suburbs of Sofia were analyzed. The histogram in 0 shows average metered water consumption per month for the houses all of which use water for outdoor use (i.e. garden and livestock watering). The histogram shows metered demand in houses without a borehole, alongside metered household demand in houses with a borehole.

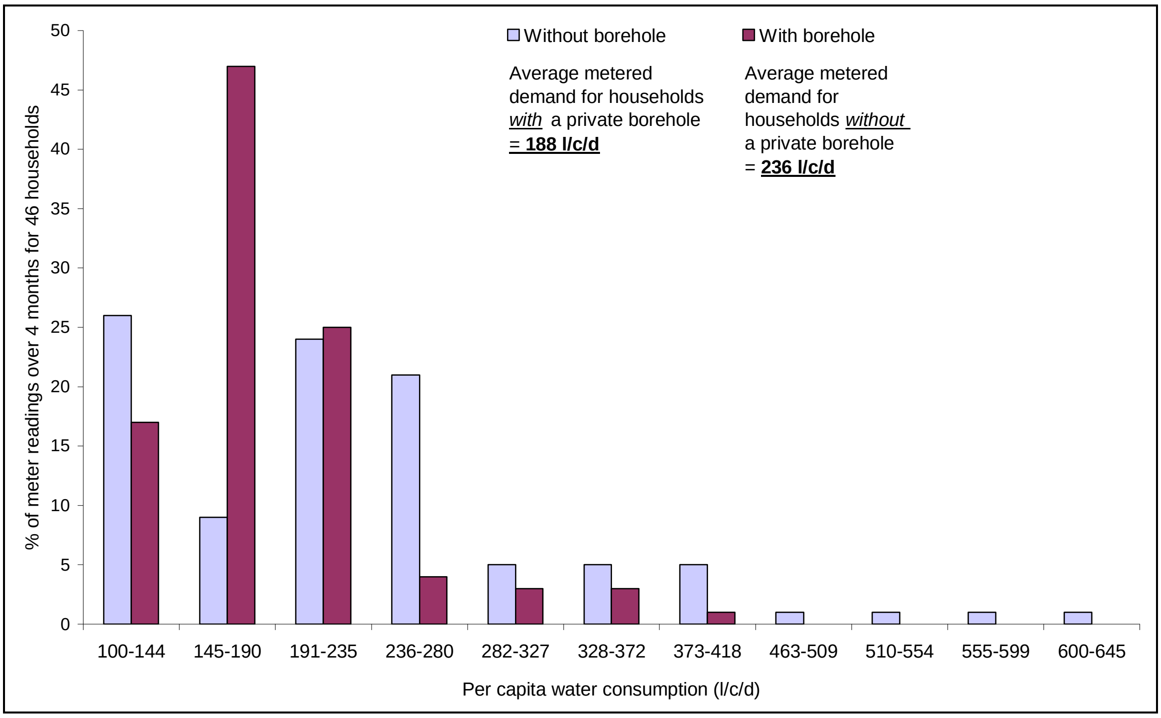


Figure A Frequency histogram showing water demand in houses with and without a private borehole – Data source, Sofiyska Voda 2004.

In households with a private borehole the average water consumption is 188 l/c/d whereas in households without a borehole 234 l/c/d. The higher rate of water consumption in the houses without a private borehole is due to watering with potable water. This finding was confirmed by comparing the water consumption of two houses that do not have private boreholes. For May, June, July, and August 2003 according to the water meter readings, water consumption averaged 328 l/c/d and 541 l/c/d. For the period 16 –23 Dec 2003 it was measured by data loggers and it was 158 l/c/d and 105 l/c/d.

On the basis of the metering and the consequent analyses of the results the following conclusions were made:

1. There are no water losses in the houses in the villages and residential quarters near Sofia.
2. The houses with gardens and without private boreholes have significant potable water consumption due to watering.

Appendix P Assumptions of water saving potential for demand variables

Table A Assumptions used for calculating utilities

Water saving assumptions for utility functions
1. Savings on showers and faucets from ***Pressure reduction*** per hh occupancy are: A) System pressure = too high, water savings = 20 litres per day B) System pressure = average, water savings = 10 litres per day (Water Saving toilet, yes/no, not relevant)
2. Savings on toilet demand (due to reduced leakage) from ***Pressure reduction*** : A) System pressure = too high, water savings = 15 litres per day B) System pressure = average, water savings = 5 litres per day (Water Saving toilet, yes, no savings; Occupancy not relevant)
3. Savings on toilet demand from ***WC retrofit*** : A) Water Saving toilet, yes, no savings; B) Water savings toilet, no, Water savings for leakage reduction, System pressure = too high, Water saving = 20, average, Water saving = 10 (plus additional for occupancy see below)
4. Savings on toilets from ***WC retrofit*** : A) Water Saving toilet, yes, no savings; B) Water savings toilet, no, Water savings per occupancy = (9.5-4)*5 = 28: ***Components of water saving for WC retrofit*** Average flush volume = 9.5 litres Flush volume of new WS WC = 4 Number of flushes per day = 5

WDM option	1. Pressure reduction																							
Water saving WC installed	no												yes											
System pressure	too high						average						too high						average					
Household occupancy	5	3	2	4	1	6	5	3	2	4	1	6	5	3	2	4	1	6	5	3	2	4	1	6
Utility (Water saving (l/hh/d))	115	75	55	95	35	135	55	35	25	45	15	65	100	60	40	80	20	120	50	30	20	40	10	60

WDM option	2. Water appliance retrofit																							
Water saving WC installed	no												yes											
System pressure	too high						average						too high						average					
Household occupancy	5	3	2	4	1	6	5	3	2	4	1	6	5	3	2	4	1	6	5	3	2	4	1	6
Utility (Water saving (l/hh/d))	160	104	76	132	48	188	150	94	66	122	38	178	0	0	0	0	0	0	0	0	0	0	0	0

WDM option	1 & 2 combined																							
Water saving WC installed	no												yes											
System pressure	too high						average						too high						average					
Household occupancy	5	3	2	4	1	6	5	3	2	4	1	6	5	3	2	4	1	6	5	3	2	4	1	6
Utility (Water saving (l/hh/d))	260	164	116	212	68	308	200	124	86	162	48	238	100	60	40	80	20	120	50	30	20	40	10	60

Figure B Utility table for the water savings for a single household

Appendix Q Definition of full costs

the full supply cost, being the financial costs related to the production of the water, which consists of the operational and maintenance costs (transport, distribution, collection, treatment of supplied water/waste water), the costs of invested capital (that result from the need to raise loans for investment in infrastructure) and capital depreciation (see Gleyses *et al*, 2003);

the full economic cost, which in addition includes the opportunity cost and the economic externalities. The opportunity cost relates to the fact that water should be allocated to its highest value uses in order to maximise social welfare and thus represent the cost of depriving the next best user of consuming the water. The economic externalities (to which we add social externalities) are the costs incurred by other parties because of certain uses and that are not taken into account;

the full cost, which in addition includes the environmental externalities (costs from damage of the environment and aquatic ecosystems) that certain water users impose on other users, including future users, or on the society as a whole (Socratus, 2005 ; Junguo, 2003).

Appendix R Sofia household survey

Water Use and Conservation **in Sofia** Household Survey

To be completed before the interview	To be completed after the interview
Address of the interviewee:	Name of interviewee:
Metered: Y / N	Telephone number of interviewee:
No. of storeys:	Income band:
Multi-family (MF) block [ ] Single (S) house [ ]	Name of interviewer
Gender of interviewee Male Female [ ] [ ]	Signature of interviewer:
Is the interviewee the person who pays the bills in the household: Y / N	Interview number (Albena):

Interviewer introduction: **Hello/ Good morning, my name is ___________________ and I am conducting research on behalf of the University of Architecture, Civil Engineering and Geodesy in collaboration with the European Commission. I am here to ask if you would mind answering some questions about household water conservation. You do not have to participate if you do not wish. If you agree to let me ask some questions, the information gathered will be used in research, but your personal details will not be used by any third party or government agencies. All information you give is completely confidential. Our aim is to better understand how households cope with water scarcity, so as to develop policies that may be put in place in European countries to improve the security of the water supply to households during drought periods. Participation in this survey is completely voluntary and you are under no obligation whatsoever to participate. The interview will take no longer than 30 minutes and we will be very pleased if you will agree to participate. If you do agree, you may skip any question that you do not wish to answer."**

Tick box to confirm agreement to participate

YES, I AGREE

A: Water use in your home

First I would like to ask you about water use in your own home.

A1. Do you have a water meter installed in your property?

YES *Go to question A2*	**NO** *Go to question A5*
1	1

A2. Do you check the water volume consumed on your household water bill?

YES	**NO**
2	2

A3.Do you have experience living in a house without a water meter?

YES *Go to question A4*	**NO** *Go to question A5*
3	3

A4. Have you changed your water use behaviour around the house since having a water meter fitted?

YES	**NO**
4	4

If the answer to question A4 is YES, please explain how you have changed your behaviour.

M5

A5. Approximately how much water do you use per month?
This question is about awareness so respondent should not refer to their water bill

___M6_____m^3 per month ____M6____I don't know

A6. On your water bill how high is the amount you pay for 'common use'?

Very high	High	Average	Low	Very low
7	7	7	7	7

Don't know how much is the common use	7

A7. I'm now going to ask some questions about the water appliances in your own home. Do you have any of the following appliances in your house and if so:

1. **How many are there?**
2. **How often are they used?**
3. **Are they water efficient?**

APPLIANCE	NUMBER IN HOUSE (1, 2, 3 …)	USE BY ALL PEOPLE LIVING IN YOUR HOME		IS IT A WATER EFFICIENT MODEL? (YES / NO)
Shower	8	16	***minutes per day***	24
Toilet	9	17	***flushes per day***	25
Bathroom tap	10	18	***minutes per day***	26
Bath	11	19	***baths per week***	27
Washing machine	12	20	***loads per week***	28
Dish washer	13	21	***loads per week***	29
Kitchen tap	14	22	***minutes per day***	30
Other	15	23		31

A8. Have you replaced any of the following water appliances in your home in the last 10 years?

APPLIANCE	REPLACED YES / NO	WHEN (Years ago)	WHY (e.g. not functioning properly, wanted more modern design … etc)

Toilet	32	38	44
Shower	33	39	45
Bathroom tap	34	40	46
Kitchen tap	35	41	47
Dishwasher	36	42	48
Washing machine	37	43	49

A9. Which of the following HH appliances *__are you likely__* / *__would you like__* to replace in the next five years?

APPLIANCE	**REPLACE IN NEXT 5 YEARS**		
	Would like to? (YES / NO)	***If "yes", what is the reason***	***Within how many years do you think you will replace?***
Toilet	50	**56**	**62**
Shower	51	**57**	**63**
Bathroom tap	52	**58**	**64**
Kitchen tap	53	**59**	**65**
Dishwasher	54	**60**	**66**
Washing machine	55	**61**	**67**

Now, I would like to ask some questions about your outdoor water use

A10. Approximately how big is your garden?

_____68___square metres

Go to question A14 if you don't have a garden

A11. How many times per week do you water your garden in the summer?

___69_____times per week

A12. How long do you spend watering your garden each time?

___70_____minutes each time

A13. How do you water your garden? (e.g. hosepipe, watering can, flood irrigation …)

71

A14. How many times per month do you wash your own car (s) using water from your own house?

___72_____times per month

A15. Please tell me any other outdoor water demands you may have? (e.g. to wash driveway, balcony, for swimming-pool use)

73

A16. Which water source do you use for outdoor demands?

Normal tap water	**Private borehole**	**Other -** please describe
74	74	74 (TEXT)

B: Water price

Now I am going to ask you some questions about your water bill.

B1. How much is your water bill each month?
This question is about awareness so respondents should not refer to their water bill

_____75 (TEXT)_____**LEV per month**

Don't know

75

B2. How much do you pay for each cubic meter of water used in your home?
This question is about awareness so respondent should not refer to their water bill

_____76 (TEXT)___**LEV per cubic meter**

Don't know

76

Go to question B5

B3. In your opinion, is the current water rate:

Too high	Neither too high or too low	Too low
77	77	77

B4. Compared with other utility payments such as electricity fee, is the current water tariff:

Too high	Neither too high or too low	Too low
78	78	78

B5. Do you think introducing a policy whereby people who use more water pay a higher per cubic meter price is a good idea?

YES Go to question B6	Don't know Go to question C1	No Go to question B7
79	79	79

B6. Please explain why you think introducing a policy whereby people who use more water pay a higher per cubic meter price is a good idea

80

B7. Please explain why you think introducing a policy whereby people who use more water pay a higher per cubic meter price is not a good idea

81

C: Water saving

C1. Apart from financial reasons, do you consider reducing your water consumption to be a worthwhile activity?

YES	NO
82	82

If YES, please describe why you consider saving water to be a worthwhile activity below:

83

C2. How motivated is your household to conserve water?

Highly motivated Go to question C3	**Motivated** Go to question C3	**Neither motivated nor unmotivated** Go to question C5	**Not motivated** Go to question C4	**Not motivated at all** Go to question C4
84	84	84	84	84

C3. Please explain what motivates you to want to conserve water? (Begin with the most important 1st)

1	85
2	85
3	85
4	85
5	85

C4. What are the reasons for not wanting to conserve water? (Begin with the most important 1st)

1	86
2	86
3	86
4	86
5	86

Now I'd like to ask you some questions about ways to save water through changes to the technology used both in your house, and in your community.

C5. From your perspective, how difficult would it be to purchase and install water efficient appliances (e.g. low-flush toilets or low flow shower-heads) in your home today?

Very difficult	Difficult	Neither difficult nor easy	Easy	Very easy
87	87	87	87	87

C6. Please consider the water saving measures in the table below.

Can you describe the factors that might make it difficult for you to implement these measures?

MEASURE	WHY WOULD IT BE DIFFICULT / PROHIBITIVE TO IMPLEMENT THESE MEASURES?	ALREADY HAVE INSTALLED
Low-flush toilet	88	93
Low-flow shower with timing valve	89	94
Replace or install hot water circulation pump	90	95
Pressure reducing valve	91	96
Change vertical pipe in building	92	97

Now I'd like to ask some questions about your willingness or ability to make a financial investment in reducing your household water consumption.

C7. Over <u>a one year period</u>, how much would you be willing to pay per month to reduce your water consumption under the following conditions:

- **No change in your water bill**

Nothing	No more that 5 LEV per month	No more than 10 LEV per month	No more than 15 LEV per month	Over 15 LEV per month
98	98	98	98	98

- **With a saving on your water bill of:**

10%	20%	30%
__99	_100	_101_

C8. Over <u>a five year period</u>, how much would you be willing to pay per month to reduce your water consumption under the following conditions:

- **No change in your water bill**

Nothing	No more that 5 LEV per month	No more than 10 LEV per month	No more than 15 LEV per month	Over 15 LEV per month
102	102	102	102	102

- **With a water saving on your water bill of:**

10%	20%	30%
103	104	105

C9 Are you aware of a hot water circulation pump in your residence?

YES	NO
106	106

C10. If you were told that a one off investment by each person within this housing block of 15 LEV to replace (or fit) your communal hot water pump could reduce your water consumption by 10%, would you make this investment?

YES	NO
107	107

C11. When you turn the tap or shower on, do you consider the pressure to be:

Too high	Average	Too low
108	108	108

C12. If you were told that a one off investment of 50 LEV could reduce your water consumption by 10-15% by reducing the pressure would you make this investment?

YES	NO
109	109

D: Demographic characteristics

D1. How many people live in your household in the following age groups?

1-5 years	6-20	20-40	40-60	60+
110	111	112	113	114

115 (=total 110-114)

D2. What is the type of the housing ownership?

Rented (State)	Rented municipal	Rented private	Private owned
116	116	116	116

D3. What is your household's annual income?

Less than 6000 LEV	Between 6000-25000 LEV	Over 25,000 LEV	No response
117	117	117	117

E: Drought in Sofia

Now I would like to ask some general questions about the management of drought in the region of Sofia.

E1. Have you ever suffered from drought in any way?

YES	NO
118	118

E2. Can you explain why there are droughts and why they cause damage (problems)?

119

E3. What should be done to reduce the impact of drought on households?

120

E4. Who do you think should be responsible for paying for water conservation? ***Please rank the following (i.e. 1 = has the greatest responsibility to pay for water conservation; 6 = least responsibility)***

WHO?	RANKING
National politicians : the parliament and the government	12
The local politicians (district and municipal) : municipal councils and municipalities' authorities	122
The local Water company	123
The European Union	124
The people themselves	125
Someone else ______________________________	12

E5. Who do you think is able to contribute to solving the drought problem? ***Please rank the following (i.e. 1 = most able to contribute to solving the problem; 6 = least able***

WHO?	RANKING
National politicians : the parliament and the government	127
The local politicians (district and municipal) : municipal councils and municipalities' authorities	12
The technicians and engineers	129
The NGOs	130
The European Union	131
The people themselves	132
Someone else ______________________________	13

This work is ongoing. Would you be happy for us to contact you in the future to ask about your participation in future research?

YES *Ask for telephone number for future contact*	NO
134	134

Telephone number ___________________________

Give householder a follow-up card

Thank you for your time and co-operation.

Appendix S Decision tree for water conservation manager problem

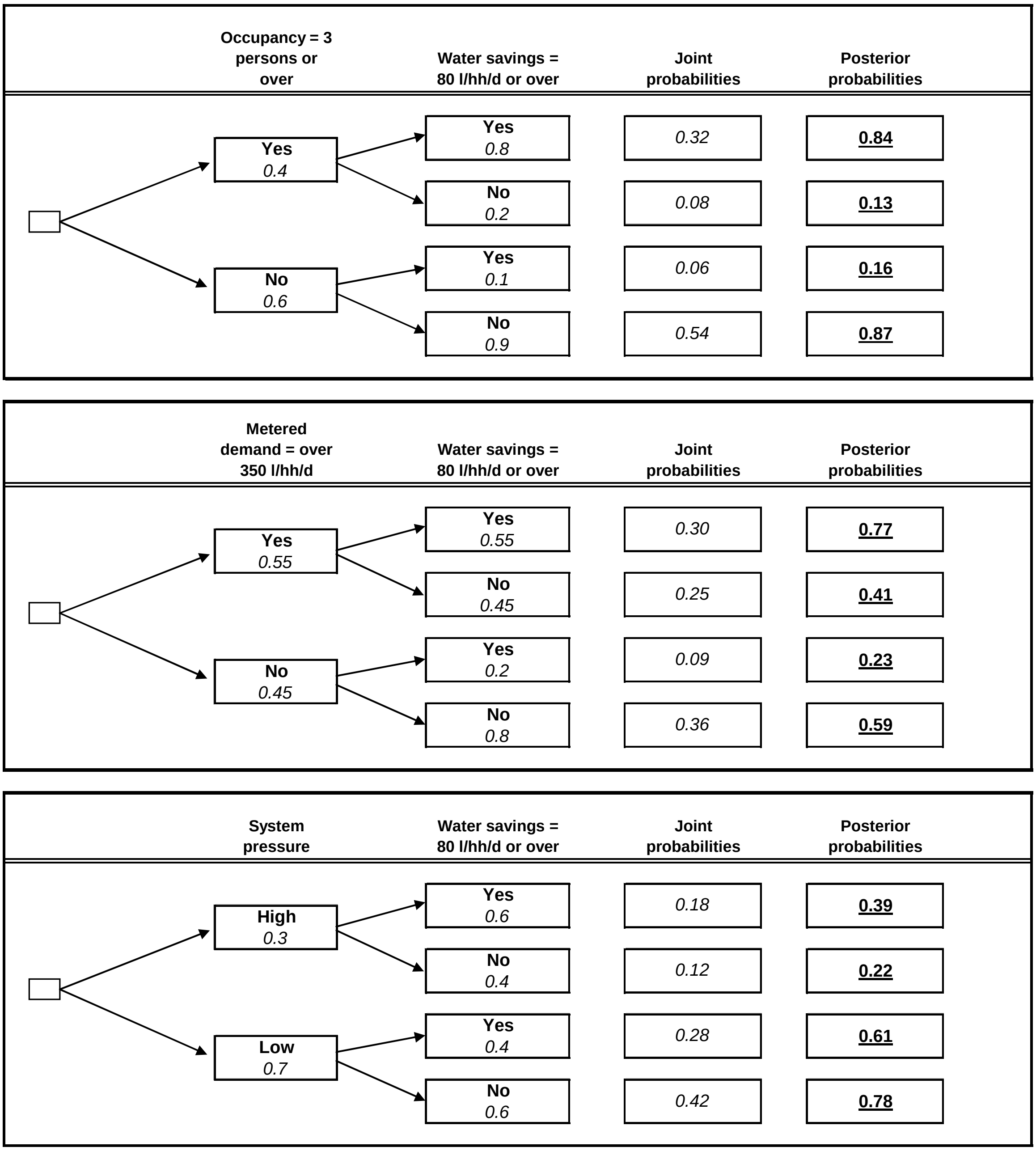


Figure XX Probabilistic layer of decision tree showing posterior probability calculation for low flush WCs

From the joint probabilities in Figure XX we can calculate the probability of achieving the target water savings with no evidence, i.e. from a randomly selected household:

p(water savings over 80 l/hh/d, no) = 0.59
p(water savings over 80 l/hh/d, yes) = 0.41

Appendix T End-user evaluation questionnaire

Water Demand Management in Sofia

Evaluation Workshop Questionnaires

Statement of consent

1. I agree/do not agree to use the BLG sector as a case study for this research. (Please circle your choice)
2. I agree/do not agree to participate in this study by completing questionnaires at different stages in the process. (Please circle your choice)

I understand that:

3. I am free to withdraw from the study at any time and am free to decline to answer particular questions.
4. While the information gained in this study will be published, I will not be identified, and individual information will remain confidential.

Your name: ______________________________

Name of your organisation: ______________________________

Type of organisation ______________________

Your position in that organisation: __________________________

Number of years experience in the water sector ____________________

Participant's Signature: ________________________

Date: __________________

The following pages contain two questionnaires. Page 2 is to be completed at the beginning of the workshop. Pages 3-7 are to be completed at the end of the workshop

Please complete the questionnaires by circling a number on each seven point scale.

If you circled '0', please indicate in the box below the question whether this is because you are unable to form an opinion.

Thank you!

Pre- workshop questionnaire

Please complete this section of the questionnaire at the beginning of the workshop

1. On average, how much of your working week do you spend working on water demand management issues

0%	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**

Decision conflict is the negative affective state experienced by a decision maker as a result of making explicit trade-off judgements among alternatives.

2. How would you rate the level of decision conflict that you experience when deciding which water demand management options are most suitable for Sofia?

High Low

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

3. How much effort is required when deciding which water demand management program is most suitable for Sofia?

Much effort Little effort

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

Decision confidence refers to how accurate you perceive the output of the decision processes to be.

4. How would you describe your confidence in the current decision processes when making water demand management decisions?

Not confident Very confident

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

Please discuss in groups the causes of decision conflict, decision effort, and decision confidence in the Sofia context.

Post- workshop evaluation questionnaire

Please complete this section of the questionnaire at the end of the workshop

5. My organisation would benefit from applying Bayesian network modelling in its business activities

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

6. Using Bayesian networks would facilitate communication between the various organisations involved in water demand management implementation.

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

7. The Bayesian network models used during the workshop allowed me to address decision problems that I encounter in my day-to-day work

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

8. I would be confident applying Bayesian network models to guide the design of water conservation programs

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

9. The process of model development using evidence as applied during the workshop would allow me to present my arguments more convincingly to a third party

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

10. The Lifetime Avoided Costs model represented the significant performance indicators required for demand management decision-making

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

11. The Bayesian network modelling approach helped me to identify the evidence required to constrain the uncertainty of performance indicator values

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

12. The Bayesian network modelling approach helped me to identify the senstivity of performance indicators to influencing factors

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

13. The models allowed WDM decisions to be made in the context of wider water resource management issues

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

14. Bayesian networks allow very different types of data, economic, social, physical etc, to be linked together in a way that allows integrated analysis

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

15. The Bayesian modelling software gave me access to analytical tools that were relevant to identifying causal relationships

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

16. It was easy to understand how the results were obtained when using the software

Disagree Agree

-3 -2 -1 0 +1 +2 +3

Unable to form an opinion ☐

17. The information was presented on the screen in a way that was easy to understand

Disagree						Agree
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

18. Using the Bayesian network models has improved my understanding of the problem domain

Disagree						Agree
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

19. Using Bayesian network models promoted dialogue and enquiry

Disagree						Agree
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

20. The Bayesian network software was easy to use

Disagree						Agree
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

Decision conflict is the negative affective state experienced by a decision maker as a result of making explicit trade-off judgements among alternatives.

21. How would you rate the level of decision conflict that you experienced when applying the Bayesian network models on your own?

High						Low
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

22. Compared to your initial expectation, how much effort did it require to use the models on your own?

Much effort						Little effort
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

Decision confidence refers to how accurate you perceive the output of the models to be.

23. How confident were you in your final decisions when using the models?

Not confident						Very confident
-3	-2	-1	0	+1	+2	+3

Unable to form an opinion ☐

Appendix U Evaluation workshop agenda and modelling tasks

End-user evaluation workshop agenda

- ➲ Complete Part 1 of the evaluation questionnaire
- ➲ Presentation and demonstration of how to construct Bns
- ➲ Informed practitioners constructed a simple Bayesian network of causes and drivers of water conservation measure effectiveness
- ➲ Testing Submodel 1 – Iskar Water Balance
  - *Tasks and questions for Sub-model 1*
- ➲ Testing Submodel 2 – Household demand in Sofia
  - *Tasks and questions for Sub-model 2*
- ➲ Testing Submodel 3 – Indicators of economic efficiency of WDM program
  - *Tasks and questions for Sub-model 3*
- ➲ Roundtable discussion

Complete Part 2 of the evaluation questionnaire

Submodel 1 provided users with an opportunity to apply belief propagation, i.e. node instantiation, to update conditional probabilities in related nodes, and to explore what-if scenarios and forecasting using the balance model.

Submodel_1 tasks – Iskar_Water_balance

- What were the total demand and sectoral demands distribution prior to and during the 1990-1995 water crisis?
- What were the frequencies of inflows in the period 1990-1995?
- What were the release volumes?
- Was the cause of the drought: human error, water availability, or a mixture of both?
- Although it is not possible to directly explore, by referring to the graph (below) showing the total demand leading up to the drought and current (2005-2005) demand, what impact do you think a similar scenario of drought might have under current water demands?

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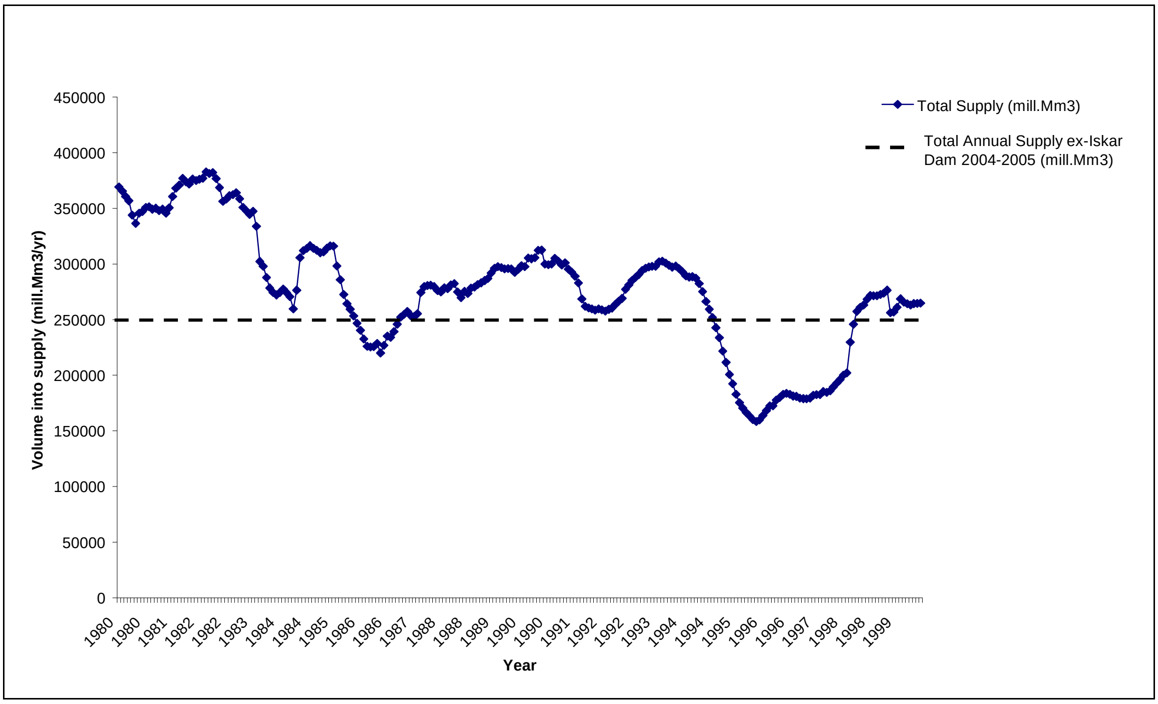

Figure 1 Total Annual Supply ex-Iskar Dam 1980-1999 (mill.Mm3)

Submodel_2 tasks: Households water demand forecasting

Using the following demand variables collected from Sofia households, instantiate the relevant nodes in Submodel_2.

- How well did the model perform in forecasting household metered demand?
- What are the possible causes of discrepancies between actual demand and model

forecasts?

Building type	Household income	Household occupancy	Garden size	Garden?	External water source	Pressure	WS toilet	metered demand (m3/yr)	metered demand (l/c/d)	Model predicted demand					
										High	*P*	Middle	*P*	Low	*P*
multi-family	low income	2	no garden	no	no garden	too high	no	39	53.42						
multi-family	middle income	2	no garden	no	no garden	too high	yes	132	180.82						
multi-family	middle income	2	no garden	no	no garden	average	no	139	190.41						
multi-family	middle income	2	no garden	no	no garden	average	no	36	49.32						
multi-family	middle income	4	no garden	no	no garden	average	no	134	91.78						
multi-family	NA	4	no garden	no	no garden	average	no	220	150.68						
multi-family	middle income	2	no garden	no	no garden	average	yes	91	124.66						
multi-family	NA	5	no garden	no	no garden	average	no	40	21.92						
multi-family	low income	4	no garden	no	no garden	average	no	180	123.29						
multi-family	middle income	1	>100	yes	rmal tap wa	too high	yes	60	164.38						
multi-family	middle income	2	no garden	no	no garden	too high	no	137	187.67						
multi-family	low income	2	no garden	no	no garden	average	yes	95	130.14						
multi-family	middle income	4	no garden	no	no garden	too high	yes	28	19.18						
multi-family	middle income	2	no garden	no	no garden	too high	yes	157	215.07						
multi-family	middle income	2	no garden	no	no garden	average	yes	83	113.70						
multi-family	middle income	4	no garden	no	no garden	average	no	67	45.89						
multi-family	middle income	2	no garden	no	no garden	average	yes	128	175.34						
multi-family	NA	3	no garden	no	no garden	average	yes	76	69.41						
multi-family	low income	2	no garden	no	no garden	average	yes	103	141.10						
multi-family	middle income	3	no garden	no	no garden	average	no	105	95.89						
multi-family	middle income	3	no garden	no	no garden	average	no	36	32.88						
multi-family	middle income	3	no garden	no	no garden	average	no	109	99.54						
multi-family	middle income	4	no garden	no	no garden	average	no	210	143.84						
multi-family	middle income	4	no garden	no	no garden	average	no	83	56.85						
multi-family	middle income	4	no garden	no	no garden	too high	no	28	19.18						
multi-family	NA	3	no garden	no	no garden	too high	no	143	130.59						
multi-family	middle income	3	no garden	no	no garden	too high	no	94	85.84						
multi-family	high income	4	0-50	yes	vate boreh	average	yes	98	67.12						
single-family	NA	2	0-50	yes	vate boreh	average	yes	250	342.47						
multi-family	middle income	4	no garden	no	no garden	average	no	274	187.67						
single-family	middle income	6	>100	yes	vate boreh	average	yes	172	78.54						
single-family	middle income	6	>100	yes	rmal tap wa	average	no	28	12.79						
multi-family	high income	2	0-50	yes	rmal tap wa	average	no	583	798.63						
single-family	NA	4	>100	yes	vate boreh	average	no	7	4.79						
single-family	NA	4	>100	yes	rmal tap wa	average	yes	16	10.96						

Submodel_3: Indicators of economic efficiency of WDM program

Instantiate the water demand nodes representing different domestic demand components and explore the impact on different economic indicators.

- Did the Lifetime Avoided Costs model represent the significant performance indicators required for demand management decision-making?

Appendix V End-user evaluation workshop results

Statements	1	2	3	4	5	6	7	8	9
Organisation and position	Professor of water demand management	Hydrologist at the Bulgarian Academy of Sciences	Assoc. prof in water infrastructure and building design	Vice Minister of Ministry of Environment and Water	Chief of water department in Ministry of Regional Development and Public Works	Water infrastructure engineer	Construction engineer	Chief of maintenance department in water company	Chief of assets department in water company
Experience and involvement in WDM									
1a. Number of years experience in the water sector	34	20	21	27	30	21	4	3	21
1b. On average, how much of your working week do you spend working on water demand management issues	70%	10%	50%	70%	40%	20%	10%	10%	30%
Decision stress, effort, and decision confidence in the existing decision process									
2. How would you rate the level of decision conflict that you experience when deciding which water demand management options are most suitable for Sofia?	2	3	1	1	-1	1	-	3	1
3. How much effort is required when deciding which water demand management program is most suitable for Sofia?	-1	-2	-1	-2	-2	2	-2	-2	-2
4. How would you describe your confidence in the current decision processes when making water demand management decisions?	-1	1	-1	2	2	-1	-1	-1	1
Organisational receptivity									
5. My organisation would benefit from applying Bayesian network modelling in its business activities	2	1	2	2	3	2	1	2	2
6. Using Bayesian networks would facilitate communication between the various organisations involved in water demand management implementation	1	1	3	1	2	1	2	2	2
7. The Bayesian network models used during the workshop allowed me to address decision problems that I encounter in my day-to-day work	2	2	1	2	1	1	-	2	1
Reliance on decisions									
8. I would be confident applying Bayesian network models to guide the design of water conservation programs	1	1	2	1	3	2	-	2	1
9. The process of model development using evidence as applied during the workshop would allow me to present my arguments more convincingly to a third party	2	3	1	2	3	2	2	1	2
10. The Lifetime Avoided Costs model represented the significant performance indicators required for demand management decision-making	2	-	1	2	3	2	1	-	1
Technical suitability									
11. The Bayesian network modelling approach helped me to identify the evidence required to constrain the uncertainty of performance indicator values	1	2	-	2	2	1	1	1	-
12. The Bayesian network modelling approach helped me to identify the sensitivity of performance indicators to influencing factors	2	2	-	2	1	1	1	2	-
14. Bayesian networks allow very different types of data, economic, social, physical etc, to be linked together in a way that allows integrated analysis	3	2	2	3	2	2	1	3	2
15. The Bayesian modelling software gave me access to analytical tools that were relevant to identifying causal relationships	1	2	2	2	2	2	1	2	2
Strategic planning									
13. The models allowed WDM decisions to be made in the context of wider water resource management issues	2	2	2	3	3	1	1	-	2
Transparency									
16. It was easy to understand how the results were obtained when using the software	1	3	3	2	3	1	3	2	2
17. The information was presented on the screen in a way that was easy to understand	3	3	3	1	3	2	3	3	2
Learning									
18. Using the Bayesian network models has improved my understanding of the problem domain	1	2	1	2	2	2	3	-	1
19. Using Bayesian network models promoted dialogue and enquiry	2	2	2	3	2	1	2	2	2
Ease of use									
20. The Bayesian network software was easy to use	1	3	3	2	3	1	2	3	3
Decision stress, effort, and decision confidence using Bbns									
21. How would you rate the level of decision conflict that you experienced when applying the Bayesian network models on your own?	1	-	1	-1	1	1	-	2	2
22. Compared to your initial expectation, how much effort did it require to use the models on your own?	-1	2	1	1	2	1	1	3	2
23. How confident were you in your final decisions when using the models?	1	2	2	2	2	1	-	-2	1