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Reflections on the use of Bayesian belief networks for adaptive management

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Abstract

A broad range of tools are available for integrated water resource management (IWRM). In the EU research project NeWater, a hypothesis exists that IWRM cannot be realised unless current management regimes undergo a transition toward adaptive management (AM). This includes a structured process of learning, dealing with complexity, uncertainty etc. We assume that it is no longer enough for managers and tool researchers to understand the complexity and uncertainty of the outer natural system—the environment. It is just as important, to understand what goes on in the complex and uncertain participatory processes between the water managers, different stakeholders, authorities and researchers when a specific tool and process is used for environmental management.

The paper revisits a case study carried out 2001–2004 where the tool Bayesian networks (BNs) was tested for groundwater management with full stakeholder involvement. With the participation of two researchers (the authors) and two water managers previously involved in the case study, a qualitative interview was prepared and carried out in June 2006. The aim of this ex-post evaluation was to capture and explore the water managers' experience with Bayesian belief networks when used for integrated and adaptive water management and provide a narrative approach for tool enhancement.

Keywords: Groundwater management; Bayesian belief networks; Qualitative interview; Adaptive management; IWRM; Tool enhancement; Participatory integrated assessment; Social learning; Newater; Organizational complexity

1. Introduction

Human dependence on water leaves us vulnerable to climate change, flood and drought hazards, and poverty (Downing et al., 2005). Vulnerability is the differential exposure to stress experienced by different exposure units, and is also a dynamic process, changing over a variety of inter-linked time scales. Social vulnerability is rooted in the actions and multiple attributes of human actors. Social networks drive and bound vulnerability in the social, economic, political and environmental context. Therefore, social and economic vulnerability should be incorporated into decision support systems and tools to capture the dynamic element of vulnerable groups and their relationship to water resources, and to represent the decisions of actors in the construction of adaptive systems. Indicators and indexes are available e.g. poverty index, water stress index etc. (Rijsberman, 2006). Indicators which acknowledge different values, not only in monetary or market units, but thoroughly represent ethical, social and political values and the complexity of water management as it is seen from different mental frames and interest group positions should be used in adaptive water management.

The broad range of tools available for integrated water resource management (IWRM) includes e.g. GWP Toolbox, HarmoniCA/Catchmod tools, decision support systems, simple and comprehensive models, participatory tools etc. (Barlebo et al., 2006). In a new EU research project NeWater (www.newater.info), a tool is defined as: 'A tool supports operational actions to perform IWRM. A tool can be a guideline, a procedure or protocol, a method or technique, a device, an apparatus and a software program' (Barlebo et al., 2006). NeWater is based on the hypothesis that IWRM cannot be realised unless current management regimes undergo a transition towards more

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adaptive water management (Pahl-Wostl and Sendzimir, 2005).

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.

It is anticipated that AM will (Allan and Curtis, 2003):

- Allow management to proceed in the face of complexity and uncertainty.
- Make learning about water resource systems more efficient.
- Help build flexible management capacity.
- Be a large scale, holistic alternative to reductionism science; and
- Involve social and political values in water resource management.

Walters and Holling (1990) describe adaptive management as a structured process of *learning by doing* with the aim being to

(1) Work with stakeholders to develop a shared understanding of the system to be managed and the desirable outcomes, by developing a system model that can be used for policy screening;
(2) Use this model to identify policies that are likely to succeed or that probe key uncertainties;
(3) Implement policies;
(4) Monitor and evaluate outcomes; apply learning to develop a better understanding of the system.

Uncertainty is a central theme in integrated and adaptive water management, where different disciplines need to be brought together to find a solution that is adequate from multiple perspectives. This, not only requires coping with various sources and types of uncertainty, but also with the ambiguity produced by the various ways in which uncertainty is interpreted and handled. Tools for AM therefore also have focus on transition processes and analysing ambiguities and mental frames that may hinder agreement on a common goal or state.

Bayesian networks (BNs) used with full stakeholder involvement is an example of a tool enabling integration of vulnerability of humans related to their use of water (Henriksen et al., 2007a, b). BNs were tested in a recent EU research project MERIT (Bromley, 2005; www.merit-eu.net) 2001–2004, and this tool is currently considered in NeWater as a possible valuable tool for AM, for interactive and flexible system and action plan modelling that allows integration of environmental and socio-economic complexity and uncertainty in a practical way.

The term *tool* (*for AM*) is broadly framed, which implies that *tool enhancement* (for AM) can have different meanings. Tool enhancement can guide when and how to use a certain tool in the planning cycle in relation to IWRM or the water framework directive (WFD). It can consist of structuring the tool according to a transition framework to AM e.g. from the NeWater knowledge base. It can be by linking the tool to the different themes of importance for AM e.g. for learning, evaluation and for exploring complexity and uncertainty (Barlebo et al., 2006).

In this paper we propose an approach for tool enhancement based on a qualitative interview (Kvale, 1996) of a pair of water managers allowing reflections and interpretations of good and bad about the tool and the participatory process in which it was used when viewed (ex-post) from the perspective of the adaptive water manager. Thereby a narrative is produced which condenses and captures the experiences of the water managers when using a tool for dealing with uncertainty and complexity of the outer system and which attempt to describe the water managers thinking and reflections about the management regime and the organising of the participatory process.

2. BNs with stakeholder involvement and the NeWater context

2.1. Bayesian networks

A Bayesian belief network, also called a BN, is a type of decision support system based on probability theory which implements Bayes' rule of probability. This rule shows mathematically how existing beliefs can be modified with the input of new evidence.

BNs organise the body of knowledge in any given area by mapping out cause-and-effect relationships among key variables and encoding them with numbers that represent the extent to which one variable is likely to affect another (Jensen, 2002). Factors, associations and probabilities can be adjusted and validated and BNs are powerful for integrating data and knowledge from different sources and domains, e.g. domain models and are also capable of handling uncertain information in a practical and understandable way (Jensen, 2002; Henriksen et al., 2004, 2007a, b; Bromley, 2005).

BNs have gained a reputation of being powerful techniques for modelling complex problems involving uncertain knowledge and impacts of causes. BNs are a technique which is especially helpful when there is a scarcity and uncertainty in the data used in making the decision and the factors are interlinked, all of which makes the problem highly complex. The part of the net defined by variables and links is relatively easily communicated to stakeholders (Henriksen et al., 2007b). However the quantitative part, with the conditional probability tables (CPTs), the numbers, is the step where negotiation between parties involved will emerge and become more difficult. Encoding and populating BNs with numbers and CPTs are the most critical part of the construction process but at the same time the most important and powerful feature of BNs, compared to more soft tools for participatory integrated assessment e.g. 'brainstorming', 'multi-criteria techniques', 'consensus conferences' etc. (Hisschemöller et al., 2001).

The validity of BNs can be improved when stakeholder groups are engaged in the construction process (Henriksen et al., 2007b). BNs encourage water managers and stakeholders to identify all the relevant information for clarifying gaps and/or multiple frames in knowledge and to build commitment to reform before subsequent implementation. It is impossible to be certain about the consequences of any environmental management decision and this fact must be recognised together with the effect of the uncertainty of the decision.

2.2. The NeWater and AM-IWRM context

The principal water management issues that NeWater addresses in the IWRM context include uncertainty and risk mitigation, governance, cross-sectoral integration, scale analysis, information management, stakeholder participation, financial aspects, system resilience and vulnerability. The project is oriented toward development of practical tools and their use for adaptive water management, testing their applicability in seven transboundary river basins in Europe, Central Asia and Africa. This shall contribute among others, to the implementation of the EU WFD and EU Water Initiative. The NeWater Consortium consists of 40 national institutions from 14 countries and 3 international institutions. NeWater is a four year project (2005–2008).

The starting point of the IWRM process is the identification of water resource management and development issues. Uncertainty arises with respect to priority setting and conflicting demands of different economic sectors, and different perspectives on resource impact issues. Conflicts of interests require involvement of different groups of stakeholders for ensuring the participatory process on such issues (multi-stakeholder dialogue). The ambiguity in defining operational targets needs to be clearly recognised in this process. The political will is a prerequisite and comes high on the list of priority actions therefore building commitment is important in all reform processes.

The preparation of a strategy and an action plan addresses the above gaps in the framework for water management and aims at reforming policies, legislation and financing (enabling environment), including institutional roles and capacities, and enhanced management instruments required to deal with the priority of water resource issues. There are links to national policies in this step.

This is followed by implementing measures which pose huge challenges. Reforms often mean considerable changes in established structures and roles which can raise resistance to change. Implementation is followed by monitoring and evaluation, where indicators of progress toward IWRM are examined.

Tools for bringing the AM concept into the above IWRM cycle may be applied for different types of processes and steps. Participatory integrated assessment mainly belong to the IWRM management step 'analyse gaps' (Jønch-Clausen, 2004), where the water manager on the basis of the established status and goals and the existing policy, legislation and institutional framework carry out an analysis to identify the further functions required to achieve the agreed goals. These processes include IWRM functions (resource management functions, water services and infrastructure and financing functions), gaps to meet water resources goals and management potentials and constraints. Most of the uncertainties are related to different assessments of what will be required, which to a large extent may be coloured by the differences of interest among the different actors and the source of uncertainty in this respect is multiple frames (Keur et al., in preparation).

As multiple frames is an inherent part of IWRM the question here is how to handle this uncertainty and complexity in a practical way meeting the demands of water managers, researchers and stakeholders. AM here offers a systematic process for continually improving management policies and practices by learning from the outcomes of implemented management strategies. Participatory integrated assessment is here a form of problem structuring for identification of gaps, ambiguity and multiple frames, confrontation, and integration of the most divergent views with respect to a given problem situation.

Additional methods and tools that AM require compared to IWRM, are tools for developing scenarios, designing monitoring programmes, evaluation processes, assuring transparent integrated research-policy and learning processes encompassing a wider range of processes. Uncertainty analysis is fundamental throughout planning and implementation processes in AM.

3. Case study testing BNs as part of the EU research project MERIT

3.1. Introduction

The aim of the case study 2001–2004 was to test BNs with full stakeholder involvement in one of four case studies that was included in MERIT. Other case studies were located in Italy, Spain and UK. The scope of the Danish case was to test BNs as a tool for identifying instruments against pesticide threats which Copenhagen Energy (CE) could implement as part of groundwater management and protection (Henriksen et al., 2007a, b). First we will give a short summary of the stakeholder involvement process applied in the Danish case for CEs wellfield at Havelse in North Zealand. Next we will summarise the BN-construction and the results of the BN-analysis.

3.2. Stakeholder involvement process

The stakeholder involvement process in the case study followed a seven step procedure: (1) define the context; (2) identify factors, actions and indicators; (3) build pilot networks; (4) collect data; (5) define states; (6) construct CPTs and (7) collect feedback from stakeholders (Fig. 1).

Since stakeholder involvement requires some iteration, steps 3–7 was redone three times before the final configuration of variables, links and final CPTs for the BN for farming contracts were obtained.

The case study had a project leading committee with four members: two from Geological Survey of Denmark and Greenland, GEUS (project leader and secretary) and two from CE (project leader responsible for CE input and a process specialist in stakeholder engagement). This leadership group first met when the case study was initiated in June 2001. In the period from June 2001 to November 2002 the leadership group formed the foundation for the entire subsequent organisation by selecting a case study among different options, balancing vision with strategy, looking for the whole picture, and drawing a roadmap for the process.

The starting point was to identify additional domain experts and to list categories of stakeholders such as water users, potential groundwater pollution sources, and authorities in the area including: local waterworks; water consumers; farmers; industry; anglers; the local county; and three municipalities. The stakeholder involvement process and the extension of the organisation with new members representing stakeholders started off with a written invitation to a one-day workshop in October 2002, were all professional stakeholder organisations considered to have a potential or even marginal interest in groundwater protection in the specific area were invited. One result of this workshop was the formation of a professional stakeholder working group with 10 institutions in addition to the members of the leadership group and the facilitator (Henriksen et al., 2007a, b, 2004). Another important decision made by the leadership group, was to identify and contract with a facilitator for the subsequent stakeholder meetings. A facilitator from the local municipality Agenda-21-Centre was contracted. The facilitator's role was confined to promoting communication between the different parties (interest groups) and to facilitate the involvement of local stakeholders.

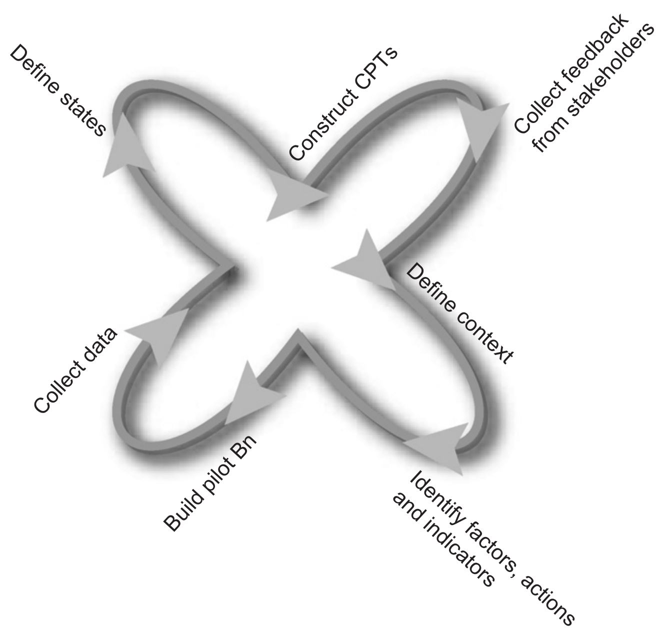

Fig. 1. Seven steps in construction of Bayesian networks (BNs) with full stakeholder engagement.

Since the case study was linked to a well field capture zone area outside Copenhagen involvement of landowners and farmers were vital for groundwater protection. In order to involve the local citizens in a separate citizens group a public meeting was arranged in November 2002 in the local community house. Invitations were distributed to more than 1100 local households, and the meeting was announced in the local newspaper. Approximately 100 persons showed up for this meeting and the outcome of this meeting was the formation of a local citizen group of nine people.

With the stakeholders organised in these two different groups the 'professional' stakeholder group and 'local citizens' stakeholder group, the process of constructing the BN with stakeholder involvement could begin. Two external subcontractors were contracted to deliver input for the BN construction, i.e. farm economics (Rasmussen, 2003) and value of biodiversity, land use, etc. (Schou, 2003). Besides these external experts the project also drew on groundwater modelling and monitoring expertise from within GEUS.

In order to have a focused dialogue about the seven steps in the BN construction (Fig. 1), three workshops in the professional group were held during 2003. The main topic of the first workshop was to obtain stakeholder opinions on roles and responsibilities, and on the consequences of different measures in active groundwater protection. The three workshops were followed by individual meetings with stakeholders in order to iterate one more time through steps 3–7. The last round resulted in additional variables and gave important input for the CPTs (Henriksen et al., 2007a).

The citizen group met five times in the first half of 2003, guided by the facilitator. The idea was to give the group the opportunity to develop its own identity without being influenced by professional stakeholders. GEUS and CE participated in two of the five meetings to answer specific questions and to introduce and discuss the development of the BNs. The citizens group was consulted, but not really involved in the construction process and the role of the group was more related to linking the BN test to the local community, thus informing other citizens about what was going on and providing feedback and local knowledge to us based on their discussions (Henriksen et al., 2007a). The citizen group published two newsletters in the first half-year of 2003 and a third newsletter was published in July 2004 after finishing the case study. Newspapers were distributed to 1000 households in the local area.

At the final joint meeting where both groups participated in March 2004 (step 7), the stakeholder groups were asked to comment on the involvement process on the basis of four questions: (1) Is there a need for further initiatives for the protection of groundwater? (2) How have you experienced the case study project progress (BNs, citizens' meetings, workshops, citizen groups, newsletters, individual meetings, etc.)? (3) How should stakeholders be involved in the future in, for example, active groundwater protection and the establishment of wetlands? (4) Other comments to the process?

The result of the BN construction process showed 'a paradox'. On one hand, because of the flexibility of the decision support tool, BNs created space for an open and non-deterministic dialogue with stakeholders. However, getting stakeholders, citizens and even experts to understand and accept the idea behind BNs used for decision making proved to be demanding. BNs are difficult to understand for non-experts and thus requires time and training. Data manipulation is possible and BNs requires a panel of expert inputs and there is a danger if not used properly that BN causes ignoring of real data and knowledge. So to summarize, the test from MERIT showed that BNs were a good tool for focused dialogue—which is a very important part of integrated and adaptive water resource management. Furthermore BNs allowed exploring multiple frames and complexity issues.

3.3. The constructed BN and the way it influenced CEs strategy for groundwater management and protection

The constructed BN for farming contracts is shown in Fig. 2 (Henriksen et al., 2004, 2007a). The BN is focused on the possibilities and problems connected with five or ten year farming contracts that totally prevent the use of pesticides in return for compensational payment. The BN showed how introduction of agricultural areas with no pesticide application influences farming economy, groundwater quality, biodiversity and the aquatic environment. All these issues are included as variables, links and CPTs in the constructed BN (Fig. 2).

Here we provide a short summary of the results of the BN-analysis in order to describe the background for the qualitative interview exploring enhancement of BNs for AM. See Henriksen et al. (2004, 2007a, b) for a more thorough analysis of results of the Havelse test of Bayesian belief networks used for integrated management.

The context of the case study area is formed by different water issues and problems that are prevalent in the Havelse area (outside Copenhagen). These include plans for afforestation, establishment of a new wetland, and for moving the entire wellfield to another location. There is also the problem of occasional flooding. Three BNs were constructed for: flooding, afforestation and farming contracts. However, the focus of the present paper is restricted to the BN dealing with farming contracts.

Interference with the final BN documented that compensation payment must be in the highest state of the variable '*compensation*', the rather costly compensations of DKK 4400 per ha/yr (600 Euro/ha), if a minimum of 95% probability for the state 'true' of the safe supply is to be achieved, which could be a relevant goal since clean groundwater is very important and also of limited quantity in the capital area. For a compensation of DKK 500 per ha/yr, only very few farmers (4%) would join voluntary farming agreements prescribing no pesticide application. For DKK 1000 per ha/yr, a slightly larger fraction would join (11%). At DKK 2500 per ha, nearly 50% would join, but their willingness to sign voluntary farming contracts (no pesticides) is much less than the evaluation by the expert indicated (Rasmussen, 2003).

For water quality the final BN showed that the probability of polluting deep groundwater drops to below 5% with a compensation level of DKK 2500 per ha/yr, given that only farming contracts are implemented (no removal of point sources). If both farming contracts and point sources are removed the total effect (5% level) can be achieved for DKK 1000 per ha/yr.

Shallow groundwater has very high probabilities of pesticide content above (maximum allowed content (MAC) in drinking water); 42% in current situation and 33% (with farming contracts at DKK 1500 per ha/yr). There were similar results for surface water. This is confirmed by the discovery of pesticides in shallow groundwater and in the Havelse River.

The variable 'perception of vulnerability' was included in order to communicate disagreement and a special uncertainty regarding the controlling factor 'vulnerability of the subsurface with respect to pesticide leaching' (Henriksen et al., 2004). This variable implies that some stakeholders and/or experts have the perception that pesticides in shallow groundwater will not spread to the deeper groundwater aquifers. Other experts and stakeholders argued that the opposite is more likely to be the case, that it is a matter of time. There is an agreement about the poor quality of the shallow groundwater and the river, but ambiguity prevailed when it came to the overall outcome of the BNs.

Sometimes the expert and non-expert stakeholder cannot agree. This happened in the present case study where the farmers and hydrologists disputed the degree to which pesticide application affected the quality of deep groundwater. Instead of selecting one opinion or another, the decision was made to include both in the network through the addition of an extra variable with two states to represent the two different opinions. By adopting this course it was possible to view the results from either point

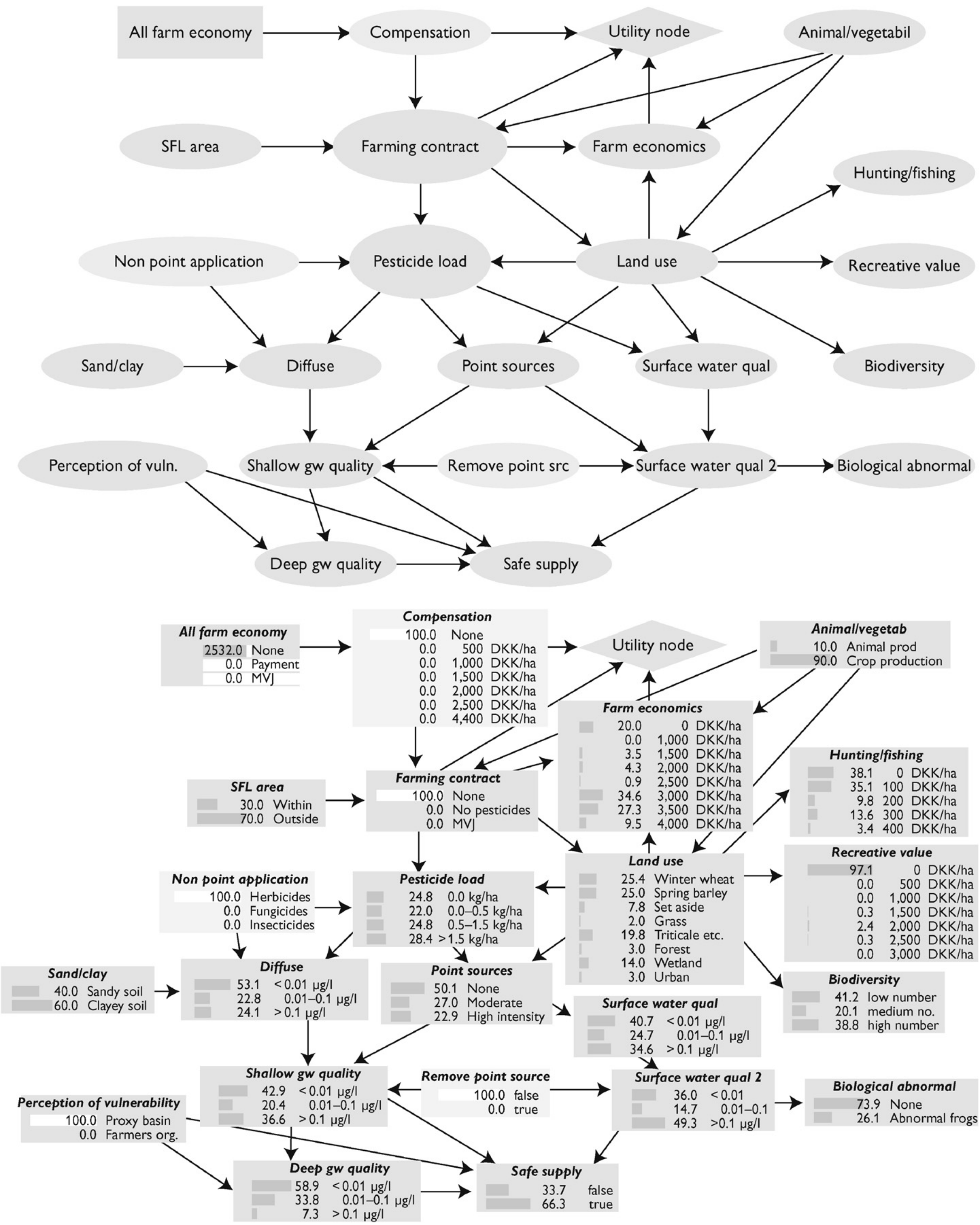

Fig. 2. Bayesian networks for farming contracts and pesticide pollution of groundwater constructed by active involvement of stakeholders and citizens'.

of view, accepting the reality of the situation, not becoming mired in an insoluble conflict, and laying the foundation for future compromise.

The MERIT guidelines (Bromley, 2005) provide a further introduction to the application of BNs in the four case studies in Spain (irrigation managing), Italy (reservoir managing), UK (water consumption managing) and Denmark (groundwater protection managing), see also Bromley et al. (2005).

4. Presentation of qualitative interview results with two managers

4.1. Methodology

The overall method is the following:

- There were a number of community events (a public meeting, workshop meetings, citizens group meetings and individual meetings) where Bayesian belief networks were used.
- An ex-post evaluation of the case study is carried out by a qualitative interview with two water managers at the same time. The two NeWater researchers were the interviewers (the authors).

In order to examine the requirements for tools for AM, we have chosen to provide an empirical investigation where the method is a qualitative interview (Kvale, 1996). An interview gives us the opportunity to describe and understand the reactions of water managers in a more comprehensive and patterned way.

When preparing the interview we developed our hypothesis and produced an interview guide for a $1\frac{1}{2}$ h qualitative semi-structured interview. After listening to the interview and selecting sequences addressing our research questions, we transcribed these to written text which we later condensed and analysed using three different theoretical frameworks to complete a kind of a narrative describing Bayesian belief networks as a tool for AM for the wider readership of environmental managers.

The interview guide was structured in three themes or research questions we wanted to capture and explore:

(1) In what/which way can BNs facilitate AM and allow water management to proceed in the face of complexity and uncertainty?
(2) How do BNs support development of a shared understanding of the system to be managed and provide a structured process of learning?
(3) How can BNs support the transition from the currently prevailing regimes of river basin water management into more adaptive regimes that are better able to deal with changing conditions?

In the section below we present the results of the qualitative interview in a condensed form using the authors' voice to summarise the dialogue. In Section 5 the results of the ex-post evaluation are analysed in depth applying three different theoretical frameworks. The two water managers the geologist Gyrite Brandt and the anthropologist Dorthe von Bülow, both from CE, will be presented as 'G' and 'D' in the following.

4.2. In which ways can BNs facilitate AM and allow water management to proceed in the face of complexity and uncertainty?

The interview starts with a discussion about how complexity and uncertainty can be viewed and specified. The water managers usually approach complexity with selection of scenarios. Uncertainty emerges in different steps e.g. establishing goals, gap analysis, selection of scenarios; but complexity and uncertainty are also related to the changing actors in the field of water management. In the Danish context the situation is influenced by the water managers' concerns about the future. A new governance reform will be introduced from January 2007 and at the moment the future politics for licensing are very uncertain, which is critical for a water supply company. Water Manager G tells us that the water company's licenses runs out in 2010. With the recent changes in governance the licenses have to go through an environmental assessment process.

G explains an example of such an environmental assessment process for establishment of an artificial recharge plant which started back in 2000 and has not yet been finished. She views the growing requirements for new licences as partly resulting from the WFD. G explains that the data needed to fulfil the WFD is not available for wetlands, streams and interaction between groundwater and surface water. This situation makes it very complex to discuss moving well fields to alternative placements.

G would like to have integrated assessment tools that can combine groundwater modelling, monitoring data and planning restrictions for e.g. wetlands, habitats and other administrative data. The water company has identified a long list with 54 projects that are planned to be carried out within the next 12 yr, but now they are going to prioritize those. G believes that this is where the BNs could come in for analysis of the costs and benefits within a 20 yr period. Water manager D views BNs as an alternative approach to the ordinary welfare economic analysis. Water managers and the economists are thinking along completely different lines. The economists are thinking along welfare economic theory, which is an overall society evaluation of the outcomes and the effect. By contrast, water managers are more interested in the benefits for the Copenhagen citizens and for the company itself. In that situation D thinks the BNs could help to delineate the complexities and also handle some of the uncertainties that they are confronting in terms of the value of clean groundwater.

The water managers need focused tools for participatory integrated assessments. The problem is how to assess water cost efficiency and value for money combined with other non-monetary values and how to learn to specify this in partnerships with stakeholders and economists. There is a need for social learning. D makes it clear that BNs can be an alternative tool when it comes to fixing values. In welfare economy terminology value is measured according to a market—whether it is a factual or a hypothetical market. Groundwater protection is dealing with a hypothetical market. Economists assume that there is a market for water comparable to any other commodity and that groundwater only has any other monetary value. D believes that this perspective is too narrow. Instead stakeholders should be involved in the process of assessing the value of certain activities and in prioritizing between issues and effects. Thus BNs allow for the co-existing of different types of values contrary to the welfare economy, where only monetary value counts. BNs allow ethical, social and political values to be included in a participatory integrated assessment.

The lessons learned from the Havelse wellfield experiment are that the magnitude of compensational payment for growing crops without applying pesticides is significantly above previous estimates by farm economy specialists, and beyond the level of payment within reach for CE. The whole issue of voluntary farming contracts is not simply a matter of economy for the farmers, but much more a matter of cultural lifestyle and social relationships.

For the water managers it turned out that farming contracts was not a feasible and practical tool. The tool is out of their toolbox for groundwater protection. BNs tested a tool. And the water managers believe that BNs could be used to test other tools and management actions as well.

One of the strengths of the BNs is that the tool gives the water managers a visual picture. It presents the complexity, so that the water managers in their minds can sort out and can see the relationships between different actions and consequences. When the water manager talks or discusses matters they have a visual picture of the BN in the back of their mind, as D expresses it, which helps to see the other alternatives simultaneously. However, the managers would like to have a better interface and standardized BNs for how to handle different issues. In the MERIT project the BN modelling with the software Hugin (www.hugin.com) was done by one of the authors, however the vision of the water managers is to become yet more involved in the modelling process.

The interview highlights the need for training when using BNs for participatory modelling that allow water managers and stakeholders to engage and participate actively in the construction and design process. This leads us to question two, concerning how BNs support shared understanding and learning processes.

4.3. How do BNs support development of a shared understanding of the system to be managed and provide a structured process of learning?

G tells us that 'lag time'—the time it takes for a pesticide to travel from the land surface where it is used to a deep groundwater aquifer or to arrive at an abstraction well in a wellfield—does not fit into the ordinary 'public common sense' or 'economic man way of thinking'. Economists sometimes calculate over a certain period of time e.g. 20 yr, but without considering lag time. G makes it clear that the calculation period should be much longer say 50–100 yr.

The different groups (wetland people, wellfield managers, economists etc.) do not have a mutual understanding or a shared mental model of the meaning of time in relation to groundwater protection. This leads to ambiguity between groups and multiple frames, something which the water manager has to deal with and solve. The interview send a clear message to the researchers in NeWater, which we can formulate as a hypothesis: 'Ambiguity and multiple frames emerge every time domains are integrated. Handling of ambiguity and multiple frames becomes an issue and a source of uncertainty which requires new or enhanced tools for the water manager's toolbox in order shape and strengthen the IWRM leadership'.

There were problems having all stakeholders at the same round table. G tells that she would have preferred to have a single group of stakeholders e.g. farmers or NGOs in separate groups which would have made conversations more fluid with not so much fighting or positioning. It makes it easier to discuss with single groups around the table because people are otherwise very closed in multi-stakeholder group sessions. D unfolds this further. There is always an agenda. When you bring together different stakeholders from different interest backgrounds the situation gets complicated. D thinks that we were a bit naive as to how open people can be in a public forum or public space. We assumed that people would be free to speak their opinion, since it was a pilot project, where the task was to test a tool. But the case showed something else. Stakeholders stuck very strictly to the policy and they let only certain representatives of the stakeholder group talk on their behalf. The rest was tacit. D found it an example of good learning.

In the citizens group other processes were working 'below the surface'. D had observed that some members had strong interests and others were more invariant. However, in the process the whole group switched to back up those with the strong interests, the farmers. The group became a spokes-group for farmers. Due to solidarity or pressure, they suddenly changed from being ordinary citizen in this area to talking in favour of the farmer's interest.

The water managers felt that the stakeholders in both groups were very suspicious about what the BN construction was all about. A way to reduce that suspicion and to avoid inflated expectations that are created in stakeholder groups about water managers and researcher intentions with a BN construction is to spend more resources and time when introducing the tool (BNs) including hands on training. Resources for that would be gained later on by speeding up the difficult parts of the construction process.

If it had been possible for the stakeholders to put in new values in the CPTs and experiment more with the tool, it could have made the entire exercise more dynamic and interactive and more transparent. The point is that any participatory process is built on trust, and it takes time, patience and transparency to build trust and to create ownership to BNs as a shared tool. Ideally all stakeholders should be partners in this process, as G explains it. So that it becomes the shared tool it has to be for participatory integrated assessment.

It is the water manager who is responsible for establishing a 'learning system' that considers both complexity and uncertainty in the outer system—the environment, as well as in the inner system—the organising IWRM and AM. Now we come to how this difficult problem can be balanced with the third question, how BNs can support the transition to adaptive water management regimes.

4.4. How can BNs support the transition from the currently prevailing regimes of river basin water management into more adaptive regimes that are better able to deal with changing conditions?

It takes some effort to explain what we mean by this question to the water managers. To give an example of how we understand AM, we use the double loop learning metaphor suggested by Argyris (1985) which is about uncovering what happens, reflecting and understanding. We explain that double loop learning is when one is trying to examine the underlying assumptions one is not normally even aware one is making.

The water managers then suggest that BNs could be used to say something about how efficient resources are used in the environmental management. To better evaluate different consequences of the managers actions, e.g. if the time used for modelling, monitoring etc. was used in an optimal way for a given context and problem. A better evaluation of how many hours the managers had used for dealing with a certain option or instrument. The managers tells us that MERIT and the BN saved them from talking to 50 farmers about voluntary farming contracts, which probably would have been an endless and costly action with very limited results. So the BN can be used for evaluating something you did before, to evaluate the managers' toolbox and assumptions in depth.

The water manager explains that there has to be plenty of time and room for reflection, which is not always the case in their daily work situation as water managers. But in the MERIT case study when using the BNs, room and time for reflection was enabled as part of the construction process. This MERIT exercise was much closer to the adaptive water management regime, than when dealing with more traditional daily working situations and tasks, as water managers in the water company.

G recalls a specific feature of BNs which she find useful for social learning processes. G tells the story about a day where a BN expert demonstrated how data could be interpreted using structural learning and training of CPTs with data. Structural learning is where you allow the software to determine the location and direction of links between nodes, based on the observed data, and subsequently, if a sufficiently large data set is available, automatically learn and generate CPTs. This was an eye-opener for G because such an exercise actually can change the mind of the participant, when carried out in an interactive and participatory mode. G suggests focusing more on structural learning because it allows a kind of spontaneity and an interactive dialogue between the parties. G recalls a data set from an English case which was water use, temperature and humidity, the structural learning was used in an interactive process to come up with a relationship which showed that when it was humid, then people took an extra shower: 'It was a totally mathematical tool but it can change your way of thinking', as G explains it. G suggests that BNs could be used on monitoring data from the AM cycle to evaluate by use of structural learning. We do have very traditional brains, as G explains it.

BNs are a tool for reasoning about complex and uncertain systems, by extending the information-processing capabilities of human beings. BNs are especially useful for monitoring and evaluation of actions, and for examining of assumption and shared and not shared mental models in depth. If possible BNs should be used as an interactive and participatory tool.

5. Discussion

5.1. Analysis with a social constructionism and systemic perspective

Social constructionism pursues mutual understanding—but not necessarily consensus (Campel, 2000). According to Campell several ingredients are necessary for people to come together and create meaning. Each shall come as a responsible individual, aware of ideas and actions that he or she wants to contribute with. Differences shall be seen as a resource, not a threat. We cannot learn or progress from shared meaning; only by acting new ideas out in intersubjective acts. Campell underlines that each person has to honour an obligation of creating meaning for the other's ideas or actions. The traditional view that meaning originates within the individual mind, and is deciphered within the minds of other agents, is for social constructionism deeply problematic (Gergen, 1994).

In response to this we begin our analysis at the level of the human relationship as it generates both language and understanding. Social understanding is generated from participation within the common system. Viewed from Gergens position we believe that the qualitative interview is a good method by which meaning stands open.

The goal of participatory integrated assessment using a tool like BN 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, and to encourage creative thinking, new ideas, and insights (Parson, 1996; Hisschemöller et al., 2001) and double loop learning.

Water management has become more challenging and difficult. New complex aspects such as governance, economics, implementation of the WFD have to be understood by water managers and this requires a more integrated management than before and IWRM leadership especially in the current transition phase to WFD. This brings us to an analysis of the way BNs influence organising participatory processes and second order complexity (Tsoukas and Hatch, 2001).

5.2. Analysing the interview from an organising analysis perspective

The process of organising is in an organisational analysis perspective understood historically, as collaborative action processes, as team work, through many contexts (sociological pragmatism), and through 'microsituations'. This theory is of relevance for understanding partnerships and stakeholder involvement processes. BN construction indeed took place through microsituations, it happened at a number of stakeholder meetings in Havelse; a small groundwater catchment of 35 km^2 in North Zealand with a few thousand inhabitants living in the area, and it influenced the way CE decided not to let farming contracts be part of their toolbox (Becker, 2003). Space was created for an open and non-deterministic dialogue with stakeholders, an unpredictable process but at the same time possible to trace, due to the flexibility of BNs. This allowed factors (nodes), associations (directed links) and probabilities of the graphical model to be adjusted, reconstructed and validated during the process of integrating different domains and issues e.g. hydrology, ecology, economy and social. This action was based on meaning, which was socially defined.

We have to keep the '*action frame of reference*' (Silverman, 1971; Fuglsang and Olsen, 2005) in mind which assumes that researchers, as well as those they study, are human actors. If we do not understand that people act in pursuit of human purposes, we will not understand human society in its complexity and its wholeness (Wiley, 1988), taking into consideration the intrasubjective level (the self, the personal level), the intersubjective level (interaction, interacting subject), the collective subjective level (social structure, collective subject), the organisational level (culture, without subject) and the institutional level (culture, without subject).

Participatory processes and active involvement using BNs helped authorities to understand their decisions better. However we also saw suspicion and experienced rather turbulent group processes. BNs should be used fully interactively, allowing everybody to suggest updates of variables, links and CPTs. Furthermore, sufficient resources for training workshops and facilitating the process have to be assured when BNs are used with full stakeholder involvement.

The value of Bayesian belief networks for organising was to encourage the authorities and partnerships of stakeholders to identify all the relevant information and analyse it in depth, clarifying gaps in knowledge and areas of dispute, and analysing deeper reasons for such disputes (values, belief etc.). The interview thus gave a strong signal about the relevance of NeWater and the attempts in this research project to enhance tools for AM by relating them to certain themes and IWRM processes and the need to focus on double loop learning including reflection about the complex and uncertain human and environmental systems. This leads to the next analysis of BN used as a tool for transition to AM where the human barrier to learning underlined by the psychodynamic system theory has its place.

5.3. Analysis with a psychodynamic system theory perspective

The most recent psychoanalytical theories increasingly emphasise the importance of relationships in forming the psyche of an individual (Gabriel, 1999; Stacey, 2003). There are two aspects of the psychodynamic system theory that are particularly important in an AM context dealing with transition and reframing. First, there is the idea that learning and change are inevitably associated with anxiety, at both the conscious and unconscious level. The management of learning is thus the management of anxiety and of resistance arising from the anxiety (Obholzer, 1999). The second contribution is with the theory of 'relatedness'—the conscious and unconscious emotional levels of connection that exist between and shape selves and others, people and systems (Armstrong, 2004; French and Vince, 1999). People in organizations are inevitably 'creatures of each other' (Hinshelwood, 1988).

For creativity and new approaches to be tolerated, one needs an environment and tools in which people feel safe enough to experiment and play but not so safe that they become complacent. An environment where change is the only constant is unlikely to be conducive to creativity and learning (Krantz, 2001); it is more likely that those working in that environment are preoccupied with surviving the change. Indeed too much change is likely to lead to basic assumption fight/flight mentality, where there is a little change of reality testing (Bion, 1961).

When using BNs as a kind of an experimental laboratory we established mutual trust and creativity within the group of water managers and researchers. It was our daily working room as researchers and adaptive managers in the MERIT project. But we forgot to analyse, what this room meant for the acting of the participating stakeholders. For them it was probably not a room experienced as a creative laboratory because it could have serious consequences for their future acting and doing in the real world. When stakeholders expressed suspicion about our intentions it might have been a response to insufficient preparation of the process from our side resulting in frustrations between stakeholders, fight/flight mentality and intersubjective anxiety about which direction the BN construction process was moving. The MERIT guidelines with seven steps (Bromley, 2005), can here be viewed as a tool for assuring more safe coordinates between the parties when constructing BNs in a participatory way. It is no longer enough to understand the complexities and uncertainties in the outer system, the environment; it is also important to understand what goes on between the different participating stakeholders, authorities and researchers in order to manage to learn and learn to manage.

6. Conclusion

Based on an ex-post interview, a narrative has been produced with interpretations and reflections about the use of Bayesian belief networks in a Danish case study and how it was able to simplify and deal with the complex qualitative and quantitative issues of a groundwater system exposed to contamination risks due to pesticide use, and to explore the participatory process in depth.

The water managers experienced that Bayesian networks (BNs) allowed for the integration of different domains and knowledge bases, e.g. expert knowledge, modelling results and monitoring data from hydrology, economy, ecology and social domains, and that it was a good tool for focused dialogue, e.g. it was a useful tool for participatory integrated assessment and for identification of gaps.

BNs tested a tool, and the water managers believe that BNs could be used to test other tools or to monitor the adaptive management (AM) cycle and evaluate actions and assumptions in depth. The water managers would like to have a better interface and standard BNs for how to handle different issues in different catchments and capture zones to their well fields. Coupling with GIS would further enhance BNs for AM. Among the strengths of the BN as a tool for participatory integrated assessment, are, that it provides the water managers and the stakeholders with a visual picture due to the graphical model. But it has to be a shared tool for all stakeholders, and an iterative use, e.g. by structural learning could support that this happens in practical water management. This implies that training of water managers and stakeholders is pre-conditional when the tool is used of AM.

Reflecting on the present situation and the water managers' expectations to the future the narrative unfolds that the water managers experience new complexities and challenges related to a new governance reform which was introduced in January 2007 in Denmark. The new reform and uncertainties threatens the water company's reinvestment plans and implementation of ongoing groundwater protection projects. This experience help the water managers to reflect on the BN test where they have the impression that stakeholders, with their real interests to defend, probably were not able to act with full curiosity, forgiveness, trust and togetherness in the creative room we created in the Danish case study as researchers and managers. Using BNs as a tool thus require realistic assessment of how much time water managers and stakeholders must devote to bringing change about. In general the message for NeWater is that it requires a high level of IWRM leadership and a great interpersonal sophistication to manage the stakeholder involvement processes. Use of facilitator, stakeholder involvement plan and guidelines for stakeholder involvement (MERIT guidelines) is strongly recommended. There is a need of further testing and evaluation of the learning from the ex-post evaluation by testing the MERIT guidelines for WFD.

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