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Public participation modelling using Bayesian networks in management of groundwater contamination

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Abstract

Negotiation and active involvement with participation of water managers, experts, stakeholders and representatives of the general public requires decision support tools (Environmental Decision Support Systems; EDSS) that build on transparency and flexibility in order to reach sound action plans and management instruments. One possible EDSS for active involvement of stakeholders is application of Bayesian networks (Bns). The paper gives an example of a case study (The Danish case) where 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 Bns. By adopting this approach, it was possible to view the results from either point of view, accepting the reality of the situation, not becoming mired in an insoluble conflict, and in this way laying the foundation for future compromises. The paper explores Bns as a tool for acting on and dealing with management of groundwater protection. Bns allow stakeholders' divergent values, interests and beliefs to be surfaced and negotiated in participatory processes for areas where conventional physically based groundwater models are insufficient due to lack of data, physical understanding, flexibility or lack of integration capability. In this way, the agency will be able to address the institutional arrangement influencing groundwater protection in all its complexity.

Keywords: Public participatory modelling; Pesticides; Groundwater management; Bayesian networks; Active involvement; Negotiation; Planning; Stakeholders; MERIT; EDSS

1. Introduction

The objective of the present paper is to describe the way Bayesian networks (Bns) can be applied as a tool for public participatory modelling in the management of groundwater contamination.

The topic will be discussed and exemplified by making reference to a real world case study in Denmark, focusing on pesticide contamination and protection strategies for a well field outside Copenhagen in Denmark, where drinking water is abstracted from a deeper groundwater aquifer for the Danish capital area.

In the following we define public participatory modelling (PP modelling) as a modelling process that concerns reasoning and decision making about whole systems using computer-based modelling and analysis technology, and with active involvement of stakeholders. The guidelines for planning in relation to the WFD (EC, 2003) encourage active involvement of stakeholders but do not give details for use of EDSS.

Development of EDSS and PP modelling involves disciplines such as computer science, decision theory, statistics, psychology, information and knowledge engineering, and

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organisational science (Eom and Farris, 1996; Eom, 1999; Myrsiak et al., 2005).

Traditional groundwater models for flow and transport are constructed according to model protocols in dialogue between model experts and the water manager with reviews when passing different milestones (Refsgaard and Henriksen, 2004; Refsgaard et al., 2005; Scholten et al., 2004). Such types of models are excellent for water resource assessments and predictive simulations, but in most cases they do not link directly to the wider social, cultural and economic aspects of water management.

A basic requirement for PP models with high level stakeholder engagement in the decision process, is that manager, expert and stakeholders should try to use a shared language for the dialogue and communication in order to reach informed decisions. Even though the goal is not necessarily consensus, dialogue can only make progress with an enlivened process where stakeholders exchange viewpoints. They may not agree on the outcome, problems, results etc., but the process may reveal common ground (as well as uncommon). What we share is not necessarily as interesting as what we do not share (Campell, 2000). Differences in ideas, attitudes and experiences may result in new types of knowledge and new solutions to common problems. This raises the question, whether Bns can support and enable such dialogue and negotiation processes.

The paper is structured in the following way. After the present introduction, Section 2 describes the theoretical basis. Section 3 describes EU WFD terminology and how Bns as EDSS for PP modelling can be applied. Section 4 describes institutional framework. Finally, Section 5 describes a test case where Bayesian networks were constructed with active involvement of stakeholders for the purpose of groundwater management and protection.

2. Theoretical basis

2.1. EU Guidelines on public participation

As illustrated in Fig. 1, there could be PP modelling for every phase of the overall planning cycle, feeding input into comprehensive modelling and vice versa. The guidance document on public participation (EC, 2003) categorised into three levels, which are of importance to the Water Framework Directive (see Table 1):

- Information provision (about management timetables, issues and to the participants. It is considered the foundation for all further participation activities).
- Consultation (encouraging written and oral responses).
- Active involvement (involving people in "developing and implementing plans" that could form the final plan decided upon).

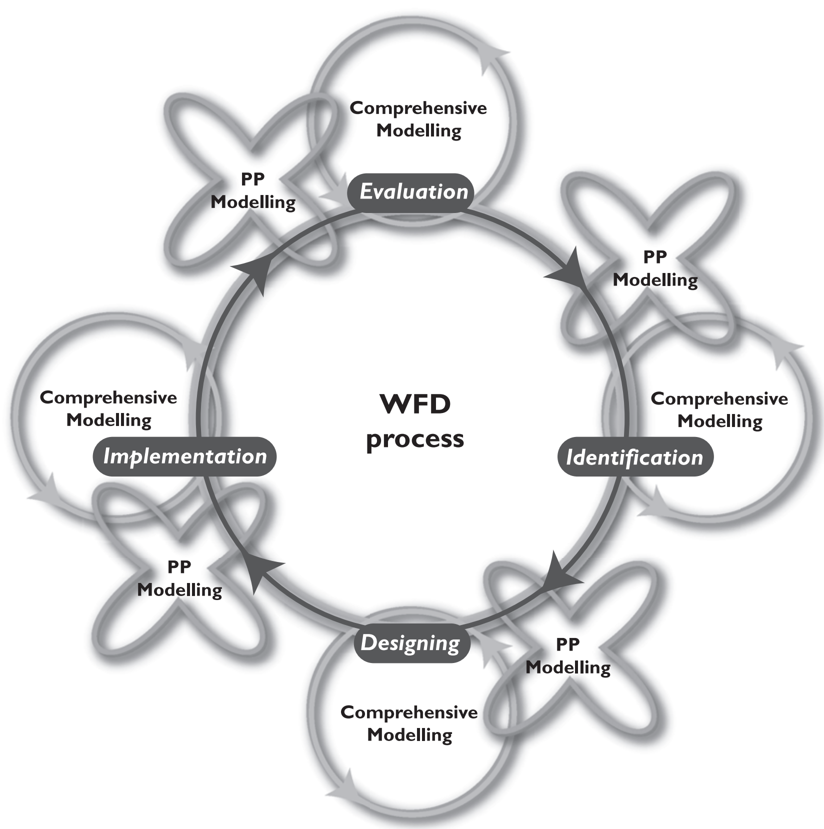

Fig. 1. Water Framework Directive planning process. Public participation (PP) will take place in WFD processes within the inner circle, whereas comprehensive modelling are expected to take place outside as a part of modelling loop. PP modelling should give input for comprehensive modelling and vice versa.

Table 1
Involved parties for different level of participation (EC, 2003)

	Public	Stakeholders	Competent authority
Information provision	Obligatory	Obligatory	Should exercise participation
Consultation	Obligatory	Obligatory	Should exercise participation
Active involvement	Not prescribed	Encouraged	Should exercise participation
Shared decision making	Not prescribed	Not prescribed	Solely responsible
Awareness raising	Encouraged	Encouraged	Encouraged

There is also a meta-level of participation termed "awareness raising and developing a learning approach", something that will support all the other levels of participation and management, which should be remembered. Participation in river basin management concerns three separate groups (Table 1): Public (general public); Stakeholders (interested parties) and Competent authority.

2.2. Bayesian networks as EDSS for active involvement and dialogue

A Bayesian network (Bn), also called a Bayesian belief network, is a type of decision support system based on probability theory. This rule, devised by Thomas Bayes, an eighteenth-century English clergyman, 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 (Pearl, 1988; Cowel et al., 1999; Jensen, 2002; Korb and Nicholson, 2004). 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. They are also capable of handling uncertain information in a practical and easy understandable way (Jensen, 2002; Soncini-Sessa et al., 2003; Henriksen et al., 2004, 2005; Castelletti and Soncini Sessa, 2006; Bromley et al., 2005).

Bns have gained a reputation of being powerful techniques for modelling complex problems involving uncertain knowledge and impacts of causes. Ideally, Bns are techniques to assist decision-making and are especially helpful when there is uncertainty in the data and the factors are highly interlinked. Constructing the qualitative part of a Bayesian network (nodes and links), although elaborate, is relatively straightforward, and experts are comfortable doing so.

This part of the net is relatively easily communicated to stakeholders (Henriksen et al., in press). On the other hand, when parties negotiate, the process is speeded up considerable, when they focus on the selection of states, variables, links and the quantitative part, with the probabilities over the variables, the numbers. Numbers and conditional probability tables are the most critical part of Bns, but at the same time the most important and powerful feature compared to more soft EDSS tools like "multi-criteria techniques" or "spreadsheets".

In the early stages of the Bn construction phase, it may be most efficient to have broader groups of stakeholders and the general public to provide input to Bn development. In the later, more quantitative stages, it is often better to consult stakeholders at individual meetings focusing on "domains of interest" (Henriksen et al., 2004). Experts or domain models may be necessary for quantitative inputs but credible Bns require engagement of stakeholder groups in order to validate Bns as a whole (Henriksen et al., in press), encouraging authorities to identify all the relevant information, for clarifying gaps in knowledge and to build support before subsequent implementation. It is impossible to be certain about the consequences of any environmental management decision. This fact must be recognised together with the effect of the uncertainty of the decision.

Many commercial software tools are available for implementing Bn based models, among which Hugin is one (www.hugin.com). Hugin was selected for the case study in Denmark as graphical user interface and decision engine providing the following main features:

1. The Graphical User Interface:
   - Construction, maintenance and usage of knowledge bases using Bayesian networks and Influence diagrams technology
   - Supports development of object-oriented Bayesian networks
   - Interface to automated learning of Bayesian networks from databases
   - Wizard for generation of probability tables
2. The Hugin Decision Engine:
   - Calculation of revised beliefs, optimal strategy, conflict analysis, and other features for exploiting graphical probabilistic models
   - Automated learning/construction of Bayesian networks

3. New concepts for relation between decision making and modelling process

3.1. Planning and modelling in WFD

WFD planning is an ongoing process that can be described as a cyclic process of four main steps: Identification, design, implementation and evaluation. For each of these steps different types of modelling may be carried out to support decision making (see Fig. 1).

Identification consists of establishment of status and overall goals, building commitment to reform process and gaps analysis. Design includes the preparation of strategy and action plan and building commitment to actions. Implementation comprises implementing of the programme of measures. Evaluation involves establishment of monitoring programmes and evaluation of the first period and planning of the next (EC, 2003).

Unorganised groups of individuals in the community who nevertheless have a stake in the management of the river basin are termed *general public*. *Stakeholders* are persons, groups or organisations affected by a management plan, e.g. professional bodies, government authorities, resident organisations, farmers groups, individual landowners or residents. Usually stakeholders invited to participate are representatives of such groups. *Competent authorities* are the authorities given final responsibility for deciding on and implementing the management plan.

4. Institutional framework

According to North (Kemper, 2003) a distinction has to be made between institutions, as the "underlying rules of the game" and actors—the individuals, agencies and organisations—here the public, stakeholders and competent authorities. Actors interact with, and influence, the institutional framework. Institutional arrangements and actors compose the institutional framework and how the different parts of an institutional framework interact.

An institutional arrangement of major importance in the context of groundwater management relates to contracts and property rights, since economic activity takes place in the form of contracting. The institutional arrangement can facilitate these actions—for instance, by providing clear rules on contract layout and by helping to enforce such rules (Kemper, 2003).

The institutional framework defines the management instruments to be used (e.g. groundwater use rights, pricing, information, water user participation, farming contracts etc.). This framework in turn has an impact on the management results (e.g. groundwater allocation, use and future groundwater quality). It should be noted that there is a feedback between institutional framework and management instruments and again between management instruments and management results (Kemper, 2003). Management results feed back into the system for reinforcement, adjustment and refinement.

The institutional framework does not only consist of *formal institutional arrangements* (like groundwater laws and decrees, etc.), but also strongly depends on *informal institutional arrangements* in the water sector (cultural and social norms, beliefs and values). Furthermore, *other institutional arrangements* indirectly may affect groundwater (e.g. energy, health and agricultural policy etc.).

In the following we will use the term "T-organisation" (temporary organisation) for the collective of an agency and the temporarily involved stakeholders in the groundwater protection activities.

Using the definition of an organisation by Argyris (1960):

> "An organisation is (a) A plurality of parts, (b) Maintaining themselves through their interrelatedness, and (c) Achieving specific objectives. While accomplishing (a) and (b), an organisation (d) Adapt to the external environment, thereby (e) Maintaining their interrelated state of the parts",

the T-organisation is characterised by a highly dynamic network of collective action, an arena for exchange of meaning and influence, social learning and awareness.

In the T-organisation (see Fig. 2) the agency has the leadership (authority to run process and make the final decisions), while stakeholders and citizens are invited as stakeholders to participate in the construction of the EDSS as members of working groups, negotiations and evaluation of the final Bns.

A T-organisation, or any working group within it, is exposed to both intra-group and inter-group characteristics (Alderfer, 1987). Stakeholders are members of different groups and categorise themselves and others according to identity, interests, values and attitudes towards the problem or project (Mikkelsen and Riis, 1996).

In order to deal properly with the primary task and to achieve the goals of the participatory process different requirements are necessary:

- (a) Structural subsystem which interacts with home stakeholder organisations (e.g. clear rules, planning, authority and decision making);
- (b) Technological subsystem selected according to PP modelling objectives (e.g. use of appropriate tools, acknowledgement of guidelines, procedures, work methods and knowledge bases); and
- (c) The philosophy of leadership and style balanced to consider both *formal* (e.g. involvement plan and task descriptions) and *informal* factors (roles and emotions), and appropriate according to authority relation and delegation of working group members.

Several ingredients are necessary for individuals (managers, experts and stakeholders) to come together and generate new meanings in dialogue. Primarily, each person must come as a responsible individual, aware of ideas and actions that he or she wants to contribute to the construction of new meaning. Secondly, an appreciation of difference among different people and points of view, which must be seen as a resource, not a threat. We cannot learn or progress from shared meaning; we only learn by encountering new ideas and acting them out in intersubjective acts. Thirdly, each person must honour an obligation to create meaning for the other's ideas or actions (Campell, 2000).

Creating new meaning in dialogues require clear rules of the game. It is necessary to prepare a *stakeholder involvement plan* describing how to involve stakeholders and general public which is balanced with respect to problem framing and the type of decision support systems used for the planning and/or implementation. Developing common understanding, defining goals, objectives and principles and the character of public participation and clarifying team roles and responsibilities are parts of stakeholder involvement plans. Furthermore, a list of all stakeholders to include with evaluation of groups' interest and responsibilities are valuable for the subsequent

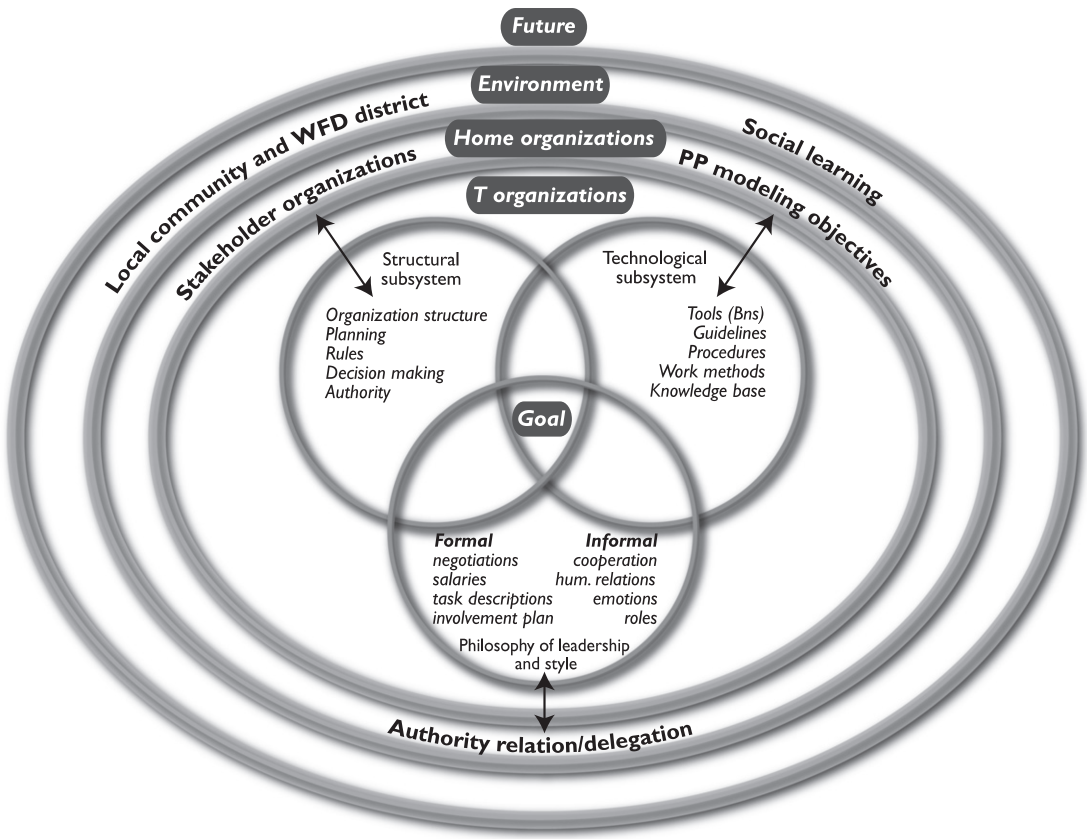

Fig. 2. Organisational cluster of a temporary organisation of water managers, domain experts, stakeholders and local citizens (T-organisation).

forming of working groups and planning of public meetings, selection of facilitator and clarifying plans for informing the general public. Finally, mission statements for all groups, time schedule for meetings and milestones, including allocation of resources for implementation of the stakeholder involvement plan, has to be decided and written down.

An enabling environment (the government's regulatory role and capacity building) is required if groundwater protection in relation to pesticide applications is to be efficient. In addition, a combination of top-down and bottom-up approaches has to be applied. The new management tool package should not only focus on market-based instruments such as pesticide taxes and/or water pricing but should also include PP tools and methods for involving the groundwater users in decision-making processes. Groundwater management is a field, which has to be developed in order to cope with present and future demands (WDF Guidelines and the new Groundwater Daughter Directive). Formerly, groundwater was simply an ''invisible resource''. Today it has become a highly visible resource in many areas due to problems of overabstraction and pollution affecting stakeholders' access to groundwater in different ways (Kemper, 2003).

Bayesian networks may be a good tool for dealing with the informal institutional arrangements in the water sector, e.g. the cultural and social norms, and the different perceptions among stakeholders, may they be of political, historical or religious origin. The question of how to actively involve stakeholders, e.g. farmers, residents and other interested parties, more effectively in the decisions necessary, to assure an improved protection of groundwater in local areas is important issues. The need is to illuminate the significance of various instruments (e.g. voluntary agricultural agreements, taxes on pesticides, pesticide-free buffer zones, etc.) and their influence on water cycle, groundwater quality, value of natural resources, macro-economics, and commercial and social aspects.

The question is whether establishment of a T-organisation with active involvement of stakeholders and application of Bns can provide a broader local acceptance of innovative decisions, as well as improve the dialogue between water companies, local stakeholders and the authorities. This is what we set out to investigate in the Danish case, Copenhagen Energy being the competent user responsible for groundwater management and experts and farmers' organisations as the main stakeholders involved.

5. Case study: Groundwater protection for Havelse well field with Bn construction with full stakeholder involvement

5.1. Introduction to case study

Basic hydrological data and land coverage maps were collected from several sources, and geochemical data from groundwater was extracted from databases at the Geological

Survey of Denmark and Greenland (GEUS). Data were also obtained from reports made available by Frederiksborg County and Copenhagen Energy (Henriksen et al., 2004).

The Havelse waterworks well field catchment area covers an area of 26 km^2 with a well field zone of about 3.7 km^2 with 21 boreholes. The land use is mostly agricultural, with small villages. The Havelse waterworks catchment area covers the lower part of the Havelse Creek catchment area. The geology at the depth of one meter below the surface is in the southern part of the area covered with a clayey till; the northern part is meltwater sand. Stretched SE-NW across the area is a large sand and gravel esker. Along the streams are postglacial freshwater deposits, and deposits from the Stone Age period near downstream part of the Havelse river.

The primary groundwater reservoir in the area is limestone and chalk deposits from the Danian period. The limestone may be in hydraulic contact with overlaying meltwater sand. The surface of the limestone is located at about 20 m below sea level. The reservoir is generally well protected by the overlying clayey till, which is from 15–30 m thick in large regions of the catchment area. Running through the area along N–S direction is an area where the thickness of the clay is less than 5 m, and it may be totally lacking in some spots. This area may represent a 500-m-wide and buried valley filled with meltwater sand. The clay thickness is also reduced along the esker, to a layer five to ten metres thick in a 250-m-wide zone (Henriksen et al., 2004).

In the area there is a threat of pesticide contamination of the groundwater. South-east, in an area with thin clay layers above the primary reservoir, there have been a few findings of pesticides but in general the data coverage is limited. The primary reservoir is meltwater sand overlaying limestone and covered by 4–16 m of clayey deposits. The pesticide found is BAM—2,6 dichlorbenzamide—which is a metabolite of the herbicides dichlobenil or chlorthiamide. BAM is the greatest threat to groundwater quality at the moment in Denmark and the use of these herbicides is now prohibited.

Similar vulnerable or very vulnerable areas are also found inside the catchment area and in the present well field zone. The vulnerability is here an expression of the thickness of the clay layer above the primary reservoir and whether the aquifers are unconfined or confined. A recent pesticide survey in five drilled wells, four dug wells and Havelse Creek show pesticides in two dug wells and one drilled well, but also in Havelse Creek, with all findings above the MAC value of pesticides used today.

Groundwater is the ‘‘backbone’’ for drinking water supply, industrial supply and supply for aquatic environment in the greater Copenhagen area. In Denmark, 99% of the water supply is groundwater. Furthermore, most Danes agree that clean groundwater and drinking water has the highest priority of all environmental issues. Chemical treatment of groundwater is rarely accepted before it is supplied to the consumers.

From a preventive groundwater protection point of view, the goal should be no pesticides in the groundwater above the maximum limit value. Perhaps the vulnerability of the area with respect to the deeper aquifers is less than for other Danish aquifers, but we do not know in detail which parameters or factors we should base such an assessment on. In fact, we know very little about the vulnerability of the deep groundwater in the Havelse area at the depths from which groundwater is abstracted. We do know that pesticides have a very low degradation rate (nearly none) once they have reached the anaerobic parts of the aquifer, which in this area is located a few meters below the surface.

5.2. Bn construction process

In the Danish case study the water company responsible for decision making and actions towards well field protection is Copenhagen Energy representing the Municipality of Copenhagen.

The construction process of Bayesian networks with stakeholder involvement followed a seven step procedure (see Fig. 3). There is no single best way to involve stakeholders, but that does not mean that there is not a need for guidelines for how to construct Bayesian networks with stakeholder involvement. In a recent EU research project (Bromley et al., 2005) one main deliverable was to establish such a proposal for guidelines for Bns, and the sequence suggested in Fig. 3 follows roughly this proposal.

In Step 1: *Define context* (see Fig. 3), physical and socio-economical boundaries, area of interest, alternative actions and indicators are defined. In Step 2: *Identify factors, actions and indicators*, a list of stakeholder and general public concerns is drawn up, and actions to be taken and important indicators are defined. A synopsis of data sources, reports and existing models is described. In Step 3: *Build pilot Bn*, the important variables are identified and directed edges are selected and connected. In Step 4: *Collect data*, the data from different sources are collected. Data are analysed and a simple Bn prepared to illustrate what to do in next step. In Step 5: *Define states*, input from stakeholders and general public is important.

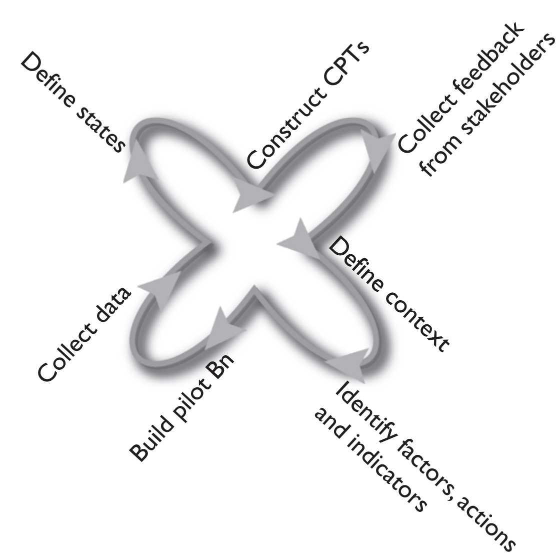

Fig. 3. PP modelling cycle. Seven steps in construction of Bayesian networks (Bns), Henriksen et al. (2004).

States are implemented in Bns for all variables. Step 6: *Construct CPTs*—construction of conditional probability tables (CPTs)—includes a review of the networks at stakeholder meetings. Structural learning is encouraged as a method of consulting stakeholders in an interactive mode. Input from models and experts for CPTs is also part of this step. Bns should also be carefully checked for internal consistency at this stage. Finally, in Step 7: *Collect feedback from stakeholders*, stakeholders and general public opinions on the final network (perceptions, motivation etc.) are collected, and a conclusion based on the final Bn is drawn.

Like the overall planning cycle PP modelling (Steps 1–7) is a cycle that may be circulated several times in a specific case study. In our case study at least three full rounds were done.

The aim of the case study was to test the benefits of Bns as an EDSS with full stakeholder involvement. The scope was to identify instruments against pesticide threats, which could be implemented as part of groundwater protection based on voluntary agreements with farmers. In the present section we want to analyse to which extent Bns can be used as a decision support tool for water resource management, in what ways Bns are helpful for focusing on the primary task in temporary organisations (T-organisations)? We also want to evaluate what was experienced about efficient involvement of stakeholder groups in the decision-making process and the construction of Bns. What was learned from the process of involving stakeholders and citizens in T-organisations?

Copenhagen Energy (CE), is the largest water supply company in Denmark. It supplies roughly one million inhabitants in the greater Copenhagen area with drinking water each day. CE operates Havelse well field together with 55 other large well fields located in northern and eastern Zealand (Fig. 4). The aim of the case study was to identify a groundwater protection strategy for CE against pesticide application to agricultural areas, which could be applied for all 55 well fields. Could voluntary compensational payment agreements with farmers (Brouwer, 2003) be an instrument for CE for dealing with the threats from pesticides? Because afforestation is not possible in the Havelse area to any great extent, CE decided to analyse farming contracts, for areas where more permanent change in land use from agriculture to forest are impossible, but what are the costs?

5.3. The final Bn and the outcome of the exercise

The final results of the Bn construction process are shown in Fig. 5.

The results of the Bns analysis are described in more details in Henriksen et al. (2004, in press). We do not need to go into detail here about the general results and how the Bns were constructed. Different options such as afforestation, establishment of a new wetland, a move of the entire well field to another location and occasional flooding were considered. The focus in the present paper is narrowed down to the construction of Bns for farming contracts.

The general idea with the Bn for farming contracts was to analyse the effects of compensation payments to farmers for not using pesticides on agricultural fields. The higher the compensation level, the more farmers will join such a voluntary contract. However, farmers signing a contract will also try to optimise land use by growing crops more suitable for farming without pesticides, and this means that contracts will also affect crop rotation.

Farming contract restrictions and crop rotation affect the farmers' bottom line, so to speak, and this, together with the compensation payment, has an impact on farm economics as a whole. The relationship between size of compensation and farmers' acceptance rate in this part of the Bn was provided by an expert (Rasmussen, 2003). The other part of the Bn shows variables concerning environmental impacts of pesticide application. These variables were based on information from monitoring data and from research projects. The variable "safe supply" of drinking water is an overall indicator for the likelihood of safe groundwater abstraction from the groundwater aquifer of good quality suitable for drinking water supply.

The final Bn documents that compensation payment must be in the highest state of the variable "compensation", the rather costly compensations of DKK 4400 per ha/year, if at minimum a 95% probability for the state "true" of the safe supply should be achieved. This could be a relevant goal since clean groundwater is very important and also of limited amount in the capital area.

For a compensation of DKK 500 per ha/year, only very few farmers (4%) would join voluntary farming agreements prescribing no pesticide application. For DKK 1000 per ha/year, a slightly larger fraction of 11% would join. At DKK 2500 per ha, nearly 50% would join, but their willingness to sign voluntary farming contracts is much less than evaluated by the expert (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/year, given that only farming contracts are implemented (no removal of point sources). If both measures are taken the total effect (5% level) can be achieved for a compensation payment of DKK 1000 per ha/year (cost of removing point sources not included).

Shallow groundwater has very high probabilities of pesticide content above the Maximum Allowable Content (MAC) (42% in current situation) and 33% (with farming contracts at DKK 1500 per ha/year). Similar results were the outcome for surface water. This is documented by findings 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 argue, 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 the T-organisation is split up when it comes to the overall outcome of the Bns.

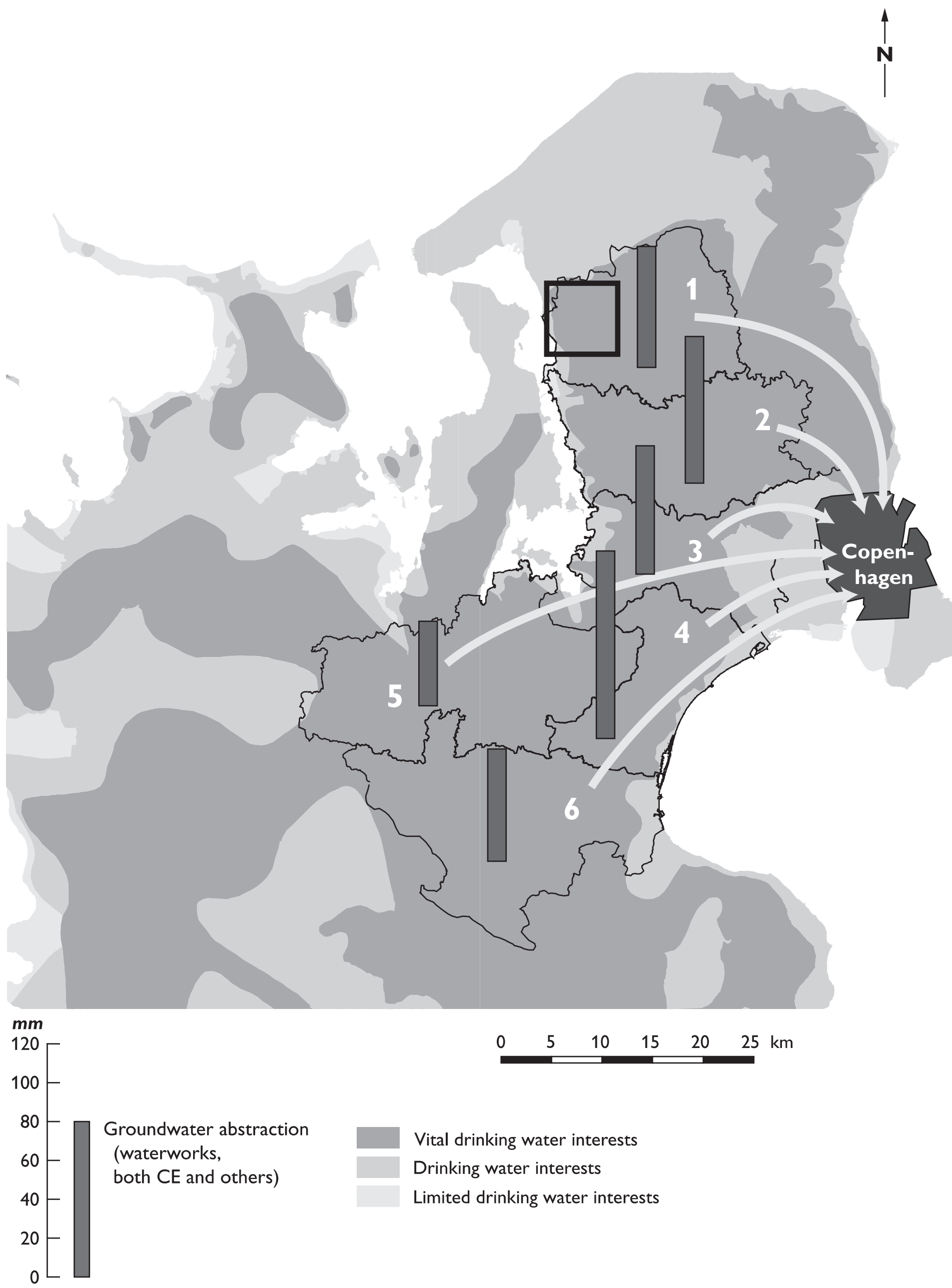

Fig. 4. Case-study area. Well fields in Copenhagen area. Study area is Havelse well field (shown with the black square), which is a groundwater source for Slangerup waterworks (Copenhagen Energy well field).

5.4. Stakeholder involvement process

The case study had a project leading committee with four members: two from GEUS (project leader and secretary) and two from CE (project responsible for CE input and a process specialist in stakeholder engagement). The group first met when the case study was initiated in June 2001. In the following this group will be named the ''leadership group''. The group represented different perspectives about leadership, both from experiences with the field of project leadership but also experiences with stakeholder involvement in partnership building between CE and local communities.

There was considerable scientific knowledge about groundwater problems and comprehensive groundwater modelling. By the start of the project we did not know anything about Bns or how to apply Bns in a proper way, and which capacity such models had. Before the primary task of testing Bns and involving stakeholders in the construction, the leadership group therefore spent some time with ''hands-on experiences'' with the software Hugin Researcher©.

The leadership group was a core group of the T-organisation, which only consisted of these four members in the period from June 2001 to November 2002. However, during this period the leadership group formed the core of the subsequent

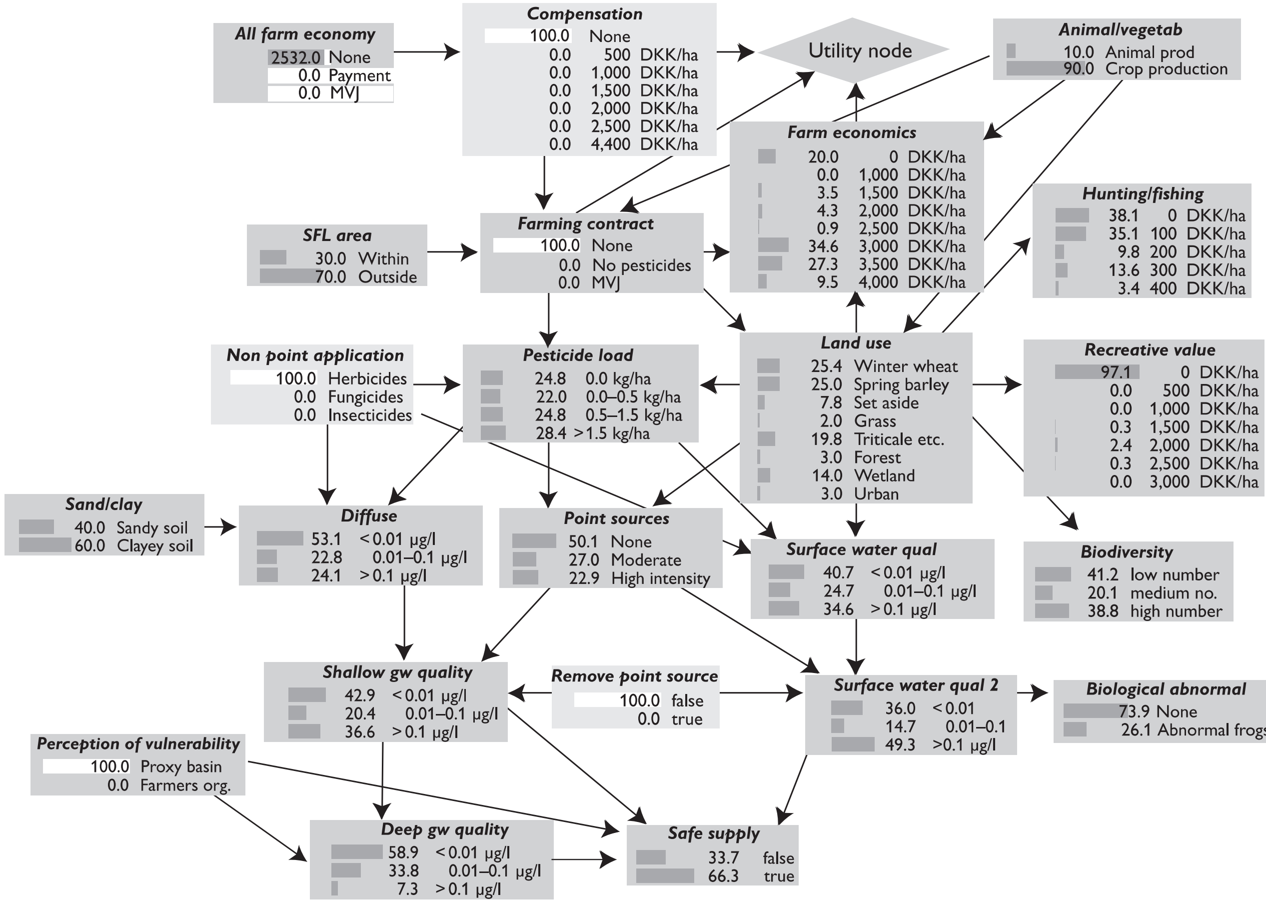

Fig. 5. Bayesian networks for farming contracts and pesticide pollution of groundwater constructed by active involvement of stakeholders and citizens' group (Henriksen et al., 2004).

T-organisation by selecting a case study among different optional, balancing vision with strategy, looking for the whole picture, and drawing a road map for the process.

The starting point was to identify stakeholders, additional domain experts and to list categories of water users, potential groundwater pollution sources, and authorities in the area: local waterworks, water consumers, farmers, industry, anglers, county and municipalities. Draft evaluations of formal institutional arrangements (groundwater laws, decrees etc.) and other institutional arrangements indirectly affecting groundwater (e.g. health and agricultural policies) were discussed in the leadership group.

A broad range of various management instruments was evaluated (current groundwater user partnerships, innovative instruments for groundwater protection) and current management results (groundwater allocation and use, quality of shallow and deep groundwater etc.) were initially identified. However, at this point the informal institutional arrangements (e.g. cultural and social norms and historical perceptions) in the water sector in the case study was rather unknown, and a local water user partnership had not been established dealing with groundwater protection in the area. The leadership group in this initial phase developed a first Bn for the purpose of informing stakeholders and the general public about different management instruments and allow prediction of most likely management results (e.g. groundwater quantity and quality and exploitable resources). The preliminary network was made up of three main branches:

- Management actions against urban pesticide sources (removal of urban point sources, use of pesticides on public areas and use of pesticides in private gardens).
- Management actions against rural pesticide sources (instruments directed towards rural point sources, farm forestry, low use farming and set aside areas).
- Management actions related to groundwater use allocation (well field renovation).

The purpose of this initial Bn was to allow an open dialogue at the subsequent kick-off meetings with stakeholders providing a broad perspective and debate about various water problems in the area.

Another important decision taken by the leadership group was to identify and contract with a facilitator for the subsequent stakeholder meetings, which were planned for November 2002. A facilitator from the local joint municipality Agenda-21-Centre was contracted to run the meetings of the citizens' group (representatives of the general public).

Two external subcontractors were contracted to deliver input for the Bn construction, e.g. farm economics (Rasmussen, 2003), value of biodiversity, land use, etc. (Schou, 2003). In addition, the project drew on groundwater expertise from Geological Survey of Denmark and Greenland/GEUS with respect to groundwater monitoring data and modelling results from comprehensive modelling.

The PP process was initiated by inviting all stakeholders and professional stakeholder organisations with a potential interest in groundwater protection in the specific area to a one-day workshop in October 2002. 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. At the kick-off meeting with the professional stakeholder the initial Bn was shown but not discussed in details.

Since the case study was linked to a specific local area, the Havelse well field capture zone area, and because involvement of landowners and farmers is vital for groundwater protection, the leadership group decided to involve the local citizens in a citizens' group, a parallel working group to the group of professionals. A public meeting was arranged in November 2002 in the local community house. Invitations were distributed to around 1100 local households, and the meeting was announced in the local newspaper. Around 100 persons, and the local TV, showed up for this meeting. At the end of the meeting a local citizens' group of 9 persons was formed. The stakeholders were asked to present issues and problems they found important in relation to groundwater protection.

The initial Bn was not presented at this meeting. Instead, a small multi-choice test had been created that tested the knowledge of the locals. A sheet containing 15 questions and answers was to be filled in and returned before the correct answers were shown using an overhead projector and various charts. After a short collaboration in breakout groups, the various groups displayed their different suggestions for groundwater protection and land use at Havelse well field catchment area.

The representatives of stakeholders were organised in two different groups, the ''professional'' stakeholder group, and ''local citizens'' stakeholder group. The idea behind the two groups was the perception that the professional stakeholders were already deeply involved in groundwater management and protection, whereas local citizens might have another starting point for their involvement in groundwater management and protection.

Three workshops in the professional group were held during 2003. At the first workshop the main topic was to get stakeholder opinions on roles and responsibilities (in order to map the formal institutional arrangements) and on consequences of different management instruments in active groundwater protection. This had the dual purpose of creating a common understanding (not consensus) within the group of the different responsibilities and viewpoints among the stakeholders (a first input to informal institutional arrangements). The following two workshops were dedicated to Bn development and included inputs from external experts, especially from the expert in agricultural economics (including an initial picture of other institutional arrangements e.g. agricultural policy indirectly affecting groundwater).

The institutional framework defines the management instruments to be used and management instruments impact management results. Based on management results there is a feed back into the system for reinforcement, adjustment and refinement of institutional framework. Bns are an excellent tool for this dialogue process, because it is possible gradually to develop a network consisting of the most important variables (and states) and to establish links and conditional probability tables, which quantify relationships between management instruments and management results. And because the Bns are developed with active involvement of stakeholders, it is also possible to incorporate the possible effects of informal institutional arrangements (e.g. farmers that build up a social norm that voluntary farming contracts against pesticides should not be contracted).

The three workshops were followed by individual meetings with Frederiksborg County Council, Sjællandske Familielandbrug (Zealand Farmers' Union) to collect more data for the Bns, and to discuss the Bns in greater detail.

The citizens' group met five times in the first half of 2003. The idea was to give the group the opportunity to develop its own identity without being influenced by professional stakeholders. A facilitator was attached to the citizens' group to help organise meetings and to produce a newsletter with information about progress in the project to the local community. Two newsletters were published in the first half-year of 2003 and a third newsletter July 2004 introducing the members of the citizens' group to the general public and bringing papers related to groundwater protection, water supply and water quality. The newsletters were distributed to 1000 households in the local area. GEUS and CE were invited to participate in two of the five meetings to answer specific questions from the citizens and to introduce and discuss the development of the Bns.

At the final joint meeting in March 2004, 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 project progress (Bns, citizens' meeting, workshops, citizen groups, newsletter, individual meetings, etc.)? (3) How should stakeholders be involved in future in, for example, active groundwater protection and the establishment of wetlands? and (4) Other comments to the process?

5.5. *Positioning of stakeholders towards deep groundwater quality*

Both the professional stakeholder group and the citizens' group clearly expressed their opinions and concerns about water resource management and groundwater situation. This initial stage of stakeholder involvement was quite successful, among other things because it resembles the Danish administrative system built on information dissemination and public hearings, and the fact that groundwater abstraction, flooding problems and a planned restoration of a wetland area had been hot topics in the area during the past couple of years. The Havelse well field was established in 1955–1956 and is on CE's investment plan from 2002 to 2006. Abstraction has stopped in 2001 due to water quality problems as well as inundation problems. The well fields siphon system will be altered to a system based on individual centrifugal pumps in each new borehole. The well field will most likely be moved to a new location due to the County's plans to establish new wetlands in the area. Re-establishment of wetlands involve removal of drains and inundation of large areas in the downstream part of the river Havelse in order to reduce the total discharge of nitrates from the catchment to the Fiord of Roskilde.

The initial involvement of stakeholders during October and November 2002 were followed by half-day workshops with presentations and discussions in the first half-year of 2003. In the process it became clear that it is important to use facilitators to run workshops because they are considered neutral actors and are able to mediate between the parties involved while the project leadership group members are considered as stakeholders as well, especially when dealing with politically sensitive issues. The issue of what affects the quality of deep groundwater is such a sensitive issue, because it is very closely interlinked with drinking water quality (99% of the drinking water supply is based on groundwater in Denmark). Similarly, it is the experience from the project that active involvement of stakeholders in the construction of Bns and decision-making processes necessitates the existence of clearly defined rules for participation.

Workshops and meetings with representatives from several interest groups tended to become a political and tactical arena rather than a forum of open discussion and were therefore not very useful for more detailed discussions. This raised the question to which extent the professional group was dominated by individual motives, interest group relations or coalition groups' relationships that developed during meetings.

If we compare our results with an ordinary SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis for public participation, then we did not experience particular strengths such as "Brings our technical knowledge from the public and others" or "Allows the public to understand the system better". We did, however, identify issues not thought of beforehand, the barriers towards voluntary farming contracts, which we had not expected. We had solely based our work on expert assessments (e.g. the report from the Royal Veterinary and Agricultural College).

An important statement about stakeholder engagement based on our Danish case study experience is as follows: The use of Bns goes beyond information and consultation and requires the full involvement of stakeholders during the implementation phase of a given action plan.

Bns are excellent for structural learning, strategic considerations, integration and breakdown of barriers between different domains. However, they can be difficult to understand for non-experts, they are not useful for implementation of specific protection zones.

In the comments from the citizens' group, the group believes that Bns are necessary tools in making complicated decisions. They also say that it is essential that specialists prepare the Bns, but that it is also an absolute necessity that the citizens take part as well.

The citizens' group felt that it was a shame that the outcome of the activities concerning stakeholder involvement were not larger. The group's first impression was that the specialists did not want to involve themselves with the citizens.

At the final joint workshop in March 2004 only two groups presented their comments: the citizens' group and the farmers' organisations. Both groups positioned themselves against the leadership group. The farmers' organisation contested the need for further groundwater protection on the large scale. The organisation did, however, agree on establishment of larger well field zones and active groundwater protection in vulnerable zones. In other words a more "pinpointed" groundwater protection towards specific areas.

The citizens' group had decided to continue with a group of six or seven people under the title "clean water". This group had been reduced to the members who had expressed interest in groundwater protection. The group felt they were very much in opposition to the official representatives (CE and GEUS), the county and other authorities to form "common front" actively opposed by the interests of the citizens' group. Old stories were given new life, the group felt that everything had been arranged in advance between the official representatives and the other authorities participating in the project, and that the citizen's group would never stand a chance anyway, no matter what.

The citizens' group never made it to a real performing phase. As a member of the group said it: "Yes, it has been nice, but also highly frustrating because the meetings lacked structure and trailed off into a lot of local and personal problems". It was apparent, seeing the attempts of the meeting attendees to form a group, that all attempts to lead the group to a greater degree were futile. There was a strong group process that had its own inner logic, and in contrast to the professional group, where members were representatives of organisations, the members of the citizens' group needed to achieve a kind of consensus (at least that was what they thought). First at the very last meeting in the citizens' group, the group seemed to acknowledge the leader they had selected (an organic farmer). For some reason it was difficult for the citizens' group to take follow their selected leader.

Finally, two very important messages for the subsequent WFD design phase came out of the joint meeting in March 2004. The farmers' organisation (the strong leader of interest group against farming contracts) agreed that voluntary farming contracts is not the way forward, instead delineation of vulnerable groundwater areas should be the way forward and the waterworks should buy those vulnerable areas for groundwater protection. They also told us that use of Bns was not sufficient for the subsequent design phase and that more detailed modelling should be performed, based on comprehensive modelling. In spite of a lot of frustration, there was a clear outcome of the engagement of stakeholders.

Based on the voiced and written feedback from stakeholders, the Bns were adjusted with an additional variable, the "perception of vulnerability", in order to incorporate the splitting into the final networks, by an additional "uncertainty variable".

6. Conclusions

To be effective, groundwater protection strategies must win broad-based support from stakeholders to be effectively implemented. But they must also not fall into the trap of endless consultation at the expense of action. So mechanisms for negotiation and managing conflict are an important ingredient.

Bayesian networks comprise a tool that enables and supports decision makers to make rational and informed choices between alternative actions, which are based on agreed policies, environmental impacts and social and economic consequences. Bns are excellent tools for quantification of the whole picture, e.g. economics, hydrology, hydraulics, environmental and sociological impacts of various instruments and offers a transparent, inclusive, coherent and equitable methodology for dealing with groundwater management that incorporates both formal and informal institutional arrangements (including social norms) of different stakeholder groups.

Bayesian networks allow stakeholders divergent values, interests and beliefs to be surfaced and negotiated in participatory processes for areas where conventional physically based groundwater models are insufficient due to lack of data, knowledge, or mutual trust between parties. Social and ecological issues can be incorporated and coupled with hydrology. Bns are excellent for strategic considerations and dialogue. Expert knowledge and data can be combined. Algorithms for structural learning based on data are available for analysis of complex systems, or in cases where data sets are incomplete. Finally, uncertainty can be dealt with in a very practical and transparent way.

The Danish case study has documented that active involvement of stakeholders in construction and validation of Bns are not only possible, but are imperative for a proper construction of variables, selection of states, identification of links and evaluation of numbers for the conditional probability tables. The real strength and opportunity of Bns are to use this tool in a participatory process in an interactive dialogue and negotiation process.

Hereby, public participation and Bns construction did make use of local and citizens' knowledge not known by the agency and the experts. It did encourage diverse perspectives and helped identify important issues not originally thought of. It did enable a better and broader evaluation of the water issues. It did not only integrate the various natural and social science issues (hydrology, economy, ecology and informal institutional arrangements), but also provided the opportunity for an open debate.

Public participation can be weakened by a lack of resources (time, money, staff), a lack of rules of participation, a lack of in-depth involvement of authorities, a lack of hands-on use of Bns for the stakeholders, and a lack of professional supervision of the process. All these threats were at some time present in the Danish case. In contrast to the professional stakeholders, the citizens' group did not participate as much as they wanted to in the Bn construction but, in the end, they participated in the evaluation of the outcome and provided valuable input to data collection, unfolded uncertainty issues not incorporated, etc. Even though there was a lack of rules for the participation, much was learned from that case study experience. A better training of stakeholders in the use of the tool would have been an advantage, because it requires a new way of thinking about the system to use Bns and probabilistic reasoning. It could also have been helpful with a bit more professional supervision of the stakeholder involvement process, establishment of working groups, facilitation of meetings, etc. These concerns call for the importance of carefully preparing a stakeholder involvement plan that addresses all these issues: rules of the game, mission statements for working groups, time schedule for important milestones, allocation of sufficient resources, etc.

There are some pitfalls that should be avoided when using Bns. Bns are difficult to understand for non-experts without any training. Bns can be malconstructed and should be reviewed by an experienced Bn expert for consistency. Bns require expert input and should not be constructed for domains without such experts on board. Validation with participation of experts, stakeholders and citizens are imperative in order to increase the credibility of Bns. Skills in communication, organisation of participatory processes and practical psychological insight into group relations and human behaviour are vital.

Experts and non-expert stakeholders do not necessarily agree, as happened in the Danish case study where the farmers and hydrologists disputed the degree to which pesticide application affected the quality of deep groundwater. However, instead of selecting one opinion or another, the decision was made to include both in the networks 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 of view, accepting the reality of the situation, not becoming mired in an insoluble conflict, and laying the foundations for future compromises.

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