Bayesian belief networks as a tool for participatory integrated assessment and adaptive groundwater management: the Upper Guadiana Basin, Spain

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Las Tablas de Daimiel, together with other wetlands in La Mancha, Spain, situated in the Upper Guadiana Basin (Fig. 1), has been catalogued as a Biosphere Reserve Area since 1981 as part of the UNESCO *Man and the Biosphere* programme. Between the mid-1970s and late 1980s, over 150 000 hectares of new irrigation areas were established, mainly as a result of private initiative. The average recharge rate of groundwater in the western La Mancha aquifer in the Upper Guadiana Basin is estimated to be between 200 and 500 million m^3 per year, in dry and wet years respectively. Recharge also depends on the depth of the water table (Martínez-Cortina & Cruces 2003). Abstraction reached 600 million m^3 per year by the end of the 1980s. Up to this time a total of 3000–5000 million m^3 of the Upper Guadiana Basin aquifer's water reserves was withdrawn (Bromley *et al.* 2000; Lopéz-Geta *et al.* 2006). The intensive use of groundwater has been a main factor for the improvement of the social and economic situation in this region, with a population of about half a million people, and where the agricultural sector is very important (Llamas *et al.* 2006). Water-table drawdown due to the intensive abstraction of groundwater for irrigation has caused severe negative impacts on wetlands, streams and rivers, and has resulted in a lowering of groundwater levels by up to 50 m. The main conflicts in the area are between farmers and conservationists, between central, regional and local government water agencies, and between small farmers and big farmers. The conflicts began about three decades ago (Llamas 1988) and have not yet been settled. In 2001 the Spanish Parliament asked the Government to present a hydrological plan for the Upper Guadiana Basin within one year. More than 20 draft proposals have been presented, the last one in 2006 with a budget of almost four billion Euros. This proposal has been met with strong opposition from most farmer lobbies.

The Guadiana Basin is one of seven transboundary case studies of the EU NeWater research project (*New Approaches for Adaptive Water Management under Uncertainty*). The principal water-management issues in the project are addressed by adaptive and integrated water-resource management. This includes uncertainty and risk mitigation, governance, cross-sectoral integration, scale analysis, information management, stakeholder participation, financial aspects, system resilience and vulnerability. One work block in the NeWater project has the task of translating research outputs into tools for practitioners and end-users. As part of this effort, Bayesian belief networks (Bns) were selected as one possible tool to be developed as an aid to stakeholder participation in integrated assessment of gaps, being a suitable tool for dialogue in order to identify gaps in water-resource management functions, gaps to meet the goals of the EU Water Framework Directive and to analyse management potentials and constraints.

Fig. 1. Location of the Guadiana Basin in Spain. The Upper Guadiana Basin includes Las Tablas Daimiel and upstream areas in the Castilla-La Mancha region. Major rivers indicated.

The purpose of this paper is to describe the testing of Bns as a tool for participatory integrated assessment and adaptive and integrated water-resource management in the Upper Guadiana Basin.

Participatory integrated assessment

Participatory integrated assessment can be considered a form of participatory policy analysis, which aims to support the policy process by designing and facilitating policy debate and argument. Assessment is integrated when it draws on a broader set of knowledge domains than are represented in the research product of a single discipline. Assessment is distinguished from disciplinary research by its purpose: to inform policy and decision-making, rather than to advance knowledge for its intrinsic value (Hisschemöller *et al.* 2001).

A wide range of methods and techniques can be drawn from social psychology, policy sciences, decision analysis and anthropology (Hisschemöller *et al.* 2001) for high-level participatory integrated assessment. Some of these, like brainstorming or decision seminars, although well established, are of limited value for integrated water-resource management because a proper understanding of the spatial and temporal variation and the complexity within river basins requires a modelling approach (Croke *et al.* 2007). According to Jakeman & Letcher (2003) the tools for participatory integrated assessment must:

1. be problem-focussed, using an iterative, adaptive approach that links research to policy;
2. possess an interactive, transparent framework that enhances communication;
3. be enriched by stakeholder involvement and dedicated to adoption;
4. connect complexities between the natural and human environment, recognising spatial dependencies, feedbacks and impediments; and
5. attempt to recognise essential lacking knowledge.

Jakeman & Letcher (2003) list several tools for participatory integrated assessment, e.g. system dynamics, Bns, metamodels, risk assessment approaches, coupled component models, agent-based models and expert systems. Here Bns are in focus as a tool for adaptive and integrated water management in the Upper Guadiana Basin test case.

Bayesian belief networks

A Bayesian belief network (Bn) is a type of decision support system based on probability theory which implements Bayes' rule of probability (Jensen 2002; Bromley 2005). This rule shows mathematically how existing beliefs can be modified with the input of new evidence. Bns organise the body of knowledge in a given area by mapping out relationships among key variables and encoding them with numbers that represent the extent to which one variable is likely to affect another.

Bns have gained a reputation for being a powerful technique to model complex problems involving uncertain knowledge and uncertain impacts of causes. Ideally, Bns are a technique to assist decision-making that is especially helpful when there is scarcity and uncertainty in the data used in making the decision and the factors are highly interlinked, all of which makes the problem very complex. The graphical nature of Bns facilitates formal discussion of the structure of the proposed model. Furthermore, the ability of Bns to describe the uncertain relationships between variables is ideal to describe the relationship between events, which may not be well understood.

Bns help water managers, stakeholders and scientists (1) to visualise and recognise, in the face of complexity and uncertainty, the relationships between different actions and consequences; (2) to make learning about water-resource systems more efficient; and (3) to encourage the involvement of social and political values in water-resource management (e.g. Henriksen *et al.* 2007a, b). Furthermore, it has been judged that Bns are an excellent tool for integrating different domains, e.g. socio-economy, hydrology and groundwater quality data of different knowledge types (monitoring data, models and expert opinions; Henriksen *et al.* 2007a). Here the guidelines from the MERIT project (Bromley 2005) can help support a successful and efficient involvement of stakeholders in the participatory integrated assessment process, a process which is demanding to run due to multiple frames and opposing interests.

Design for testing the enhanced Bayesian belief network tool

A test of an enhanced Bn tool is being undertaken in the Upper Guadiana Basin as part of the NeWater project. The test involves the construction of a Bn to represent the management of groundwater levels in the region, taking into account the social, economic, hydrological and ecological consequences of alternative irrigation and groundwater management scenarios (Table 1).

In November 2006, an initial workshop was held at the Geological Survey of Spain (IGME) in Madrid with participants from the case study group. During this workshop a preliminary Bn for the Upper Guadiana Basin was developed by Bn experts from IGME, the University Complutense de Madrid, the Geological Survey of Denmark and Greenland, and the Centre of Ecology and Hydrology, Wallingford, UK,

Table 1. Management scenarios and impacts

Scenario	Agricultural output (mill. € per year)	Change in water level (m per year)	Recovery of wetlands (years)
A1	1000	−0.40	Never
A2	900	−0.08	Never
B1	510	+1.84	20–25
B2	490	+2.00	15–20

Scenarios A1 and A2 are based on business as usual (no recovery of wetlands). Scenarios B1 and B2 assume serious restrictions on the economic agricultural output, with technology as usual (resulting in recovery of wetlands).

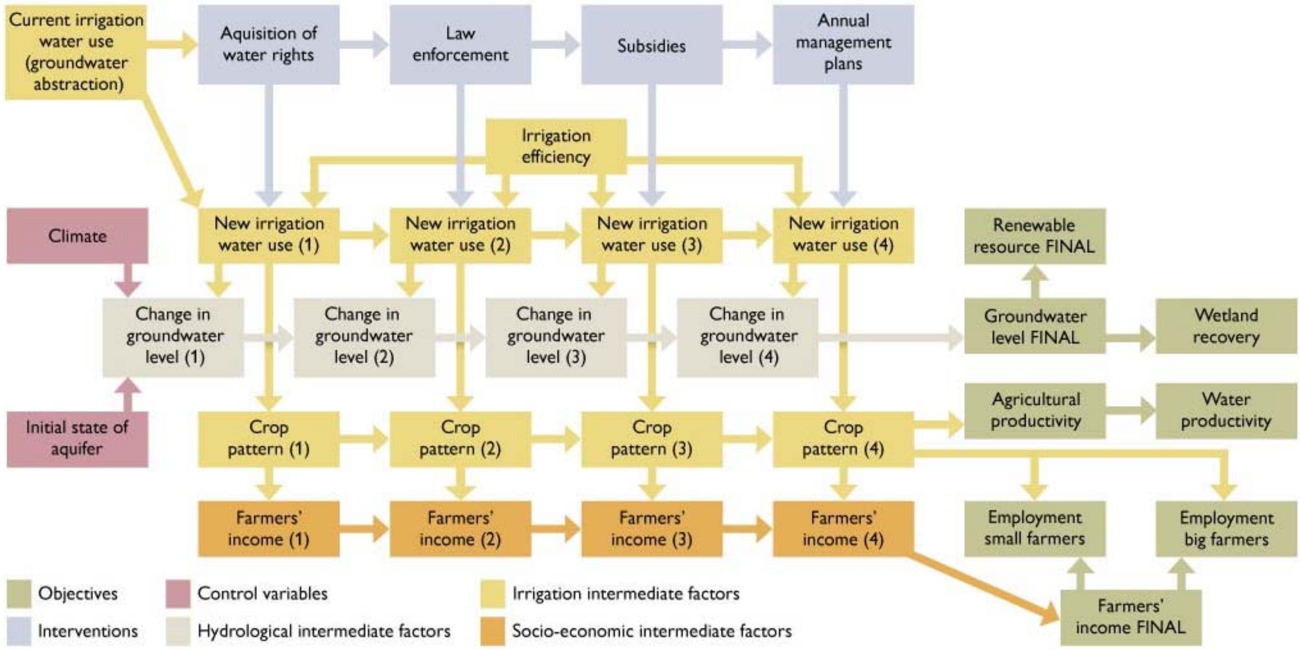

Fig. 2. Preliminary Bayesian network for the Upper Guadiana Basin. The objectives of the Bayesian network are to analyse the way in which different management actions will influence irrigation water use, change in groundwater level, crop pattern, farmers' income, wetland recovery, productivity and employment.

together with a representative of the water managers of the basin responsible for water planning in relation to implementation of the EU Water Framework Directive.

A joint workshop with all stakeholders to finalise the network has been planned for the first half of 2007. The process and method for constructing the Bn in the Upper Guadiana Basin test will follow the MERIT guidelines (Bromley 2005). In the following we present the preliminary Bn and the hypotheses relating to the use of the tool in participatory integrated assessment and adaptive management in the Guadiana Basin.

Results of testing Bayesian belief networks for adaptive water management

The initial step in network design was to establish the space and time boundaries of the system being modelled. It was agreed to restrict the model to the Upper Guadiana Basin, and a one-year time period for groundwater level and socio-economic consequences was decided. The pilot Bn for the Upper Guadiana Basin case which emerged from this process is shown in Fig. 2. The network deals with the way in which different management actions influence irrigation water use, groundwater level, crop pattern, farmers' income, wetland recovery, productivity and employment in the region (Fig. 2). Included among the potential actions that might be taken are: (1) acquisition of water rights; (2) law enforcement; (3) common agricultural programmes (CAP) subsidies; and (4) annual management plans. Climate and the initial state of the aquifer are included as control factors. The indicators (objectives) in the network include: (1) groundwater levels; (2) impact on wetland recovery; (3) agricultural productivity; (4) farmers' income; and (5) levels of employment in the region. When running the Bn, combinations of actions can be selected and calculated.

It is hypothesised that Bns fully support four of the five requirements proposed by Jakeman & Letcher (2003) for participatory integrated assessment (Table 2). One requirement, the representation of spatial dependencies, is only partly supported (e.g. input to the decision-making about which specific wetlands that will be recovered by a certain increase in groundwater level has to be evaluated using a groundwater model). However, as stated by Pascual (2005): "the beauty of Bns lies in their explanatory power: observations about any node generates knowledge about all other nodes, providing one with a tool to draw transparent, rational inferences in a probabilistic world". This illustrates that the tool can be used for diagnosis and social learning.

Bns allow targeted modelling, participatory integrated assessment and strong support for sense and decision-making in cases with multiple frames (e.g. when stakeholders perceive their environment differently, and frame and construct their world in different ways) that create ambiguous situations and conflicting interests hindering sustainable solutions for man-

Table 2. Hypotheses relating to the use of Bayesian belief networks as a tool for participatory integrated assessment and gap analysis within Integrated Water Resource Management (IWRM)

Requirement to tool for adaptive management and participatory integrated assessment*	Enhancement result	Comments: To be further tested for the Guadiana Basin
Being problem-focussed, using an iterative, adaptive approach that links research to policy	Yes	Bns allow flexible handling of complex systems, with clear overview of actions and indicators, and interferences. Flexible coupling of domains. Bns allow both hard and soft data.
Possessing an interactive, transparent framework that enhances communication	Yes	A good tool for a focussed dialogue. The tool enhances communication due to its flexibility and visual representation.
Being enriched by stakeholder involvement and dedicated to adoption	(Yes)	Easy to use with stakeholders for development of a shared conceptual understanding of the system. However, the conditional probability tables may be difficult to understand. Training is very important.
Connecting complexities between the natural and human environment, recognising spatial dependencies, feedback and impediments	Not fully	Spatial dependencies and feedback between variables cannot be handled fully. For such purposes coupled domain models are needed, but Bns can work on top of these models as a tool for coupling with other domains.
Attempting to recognise missing essential knowledge	Yes	Bns allow the exploration of complexity, uncertainty and multiple frames. A good tool for gap analysis within IWRM and subsequent negotiation and mutual understanding.

* Criteria according to Jakeman & Fletcher (2003).

agement of the environment. The tool and the probability tables (numbers) are not easily understood if not properly explained. Thus, training and introduction to the tool and the statistical background behind Bns is important (Table 2).

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