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Integrated Meta-Modelling for Decision Support in Integrated Catchment Management

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Abstract: Developing supporting models for multidisciplinary, uncertain and complex Integrated Catchment Management (ICM) is a highly challenging task. Knowledge from multiple disciplines must be integrated, and the process is compounded by significant uncertainty. The key gap that provides the research context is the need for a holistic modelling framework to support ICM, able to capture system complexities and interrelationships, and identify long-term solutions to catchment management problems. In this paper, we present the feasibility study of a new framework for developing an integrated meta-model for decision-support in ICM. The study undertaken by the Catchment Science Centre at the University of Sheffield in a project called the Macro-Ecological Model (MEM) in collaboration with the Environment Agency of UK. The MEM is developed as a consistent framework for the integration of knowledge and information about environmental, social and economic processes and process-interactions that are affected by management actions and have impacts on multiple management objectives. The MEM combines the advantages of "soft" techniques of stakeholder participation for problem structuring, interdisciplinary communication and negotiation with the "hard" predictive capabilities for analysing the likely outcomes of different management scenarios. The meta-model could serve as a learning and decision-support tool to be applied within a group of decision-makers and stakeholders.

Keywords: Bayesian Network; Decision-support; Integrated catchment management; Meta-model; Water Framework Directive.

1. INTRODUCTION

Integrated Catchment Management (ICM) is a complex interdisciplinary area, with scientific and socio-economic sides to it, which intersects various knowledge domains, and acts at various levels of abstraction. ICM takes a holistic approach to all the interconnected water-related issues, while also considering the activities of various stakeholders [Holzkaemper et al., 2010a, 2009].The practical applicability of integrated models to support ICM depends on many factors. The many different kinds and sources of information have to be condensed to support decision makers in handling the management problem. Effective decision making depends on the power of knowledge abstraction: the ability to draw back one or more layers from the complex system around us, and then assemble piece by piece different processes, system linkages, management hypothesis into a desired level of abstraction. A framework for effective abstraction can help to organizing, analysing, and ultimately "operationalizing" information—integrating system functioning and decision-making processes into an analytical tool. The process of analysis obviously involves thinking, but while the human brain is capable of highly complex thought patterns, there is a limit to how far out a person can abstract, or how many concepts one can juggle in his mind at once. An integrated meta-model can be considered as a conceptual analytical tool for multi-source information integration and abstraction which can be used to help human abstraction processes for the purpose of decision making or Meta scale analysis.

Over the last two decades increasing numbers of model-based decision support tools have been developed to support Integrated Catchment Management. Two fundamentally different approaches to integration have been used namely model couplings and conceptual network models. These differ in their primary focus of integration. The main focus of conceptual network models is to facilitate interdisciplinary communication and structure the management problem based on the knowledge and views of different stakeholders. Whereas the model coupling approach can be described as a "hard" approach to integration, aiming to integrate quantitative process descriptions. Its main focus is on analysing different management scenarios to rank the possible solutions. A detail discussion has been provided in our paper or project report Holzkaemper et al. [2010a, 2009], which also reviewed the requirements of such tools in the context of ICM and concluded that they need to: (i)integrate a wide range of objectives and processes, (ii) aggregate system complexity to the level that is appropriate in the decision-making context, (iii) represent and communicate prediction uncertainties, (iv) be fast and easily applicable as exploratory learning tools, and (v)be easily transferable to new regions.

Different methods for knowledge abstraction or facilitating analysis have emerged, for example hierarchical based methods that create and harnesses different layers of abstractions. Other methods frequently used are multi-attribute utility analyses, Bayesian Networks, decision trees and influence diagrams, stochastic optimal control theory, partially observable Markov decision processes, neural network, rule-based cognitive architectures etc. In the last decade Bayesian networks (BNs) have increasingly been applied to environmental management problems under uncertainty, and recently also to integrated water management issues [Ames et al., 2005; Barton et al., 2008; Kumar et al., 2008]. BNs are graphical probabilistic approaches, based on Bayesian probability theory, which are commonly used as a decision analysis framework. BNs allow the integration and abstraction of qualitative and/or quantitative information with exclusive consideration of uncertainties associated with that information. The BN approach involves describing a system in terms of variables and linkages, or relationships between variables, at a level appropriate to the decision maker. This is achieved through representing linkages as conditional probability tables and propagating probabilities through the network to give the likelihood of variable outcomes. BNs are increasingly being used as decision support tools to aid the management of the complex and uncertain domains of natural systems [Barton et. al., 2008].Common to these studies is the use of BNs to integrate probabilistic information derived from data sets, model simulations and expert opinion in the study of water allocation or pollution problems. As an alternative to extensive scenario analysis using deterministic models [e.g. Hein, 2006], BNs hold the promise of a more complete accounting of integrated model uncertainty. In some cases, BNs are used as data testing or analysis framework for example to study the properties of integrating a number of sub-models for purposes of targeting data collection or joint risk analysis [Borsuk et al., 2004]. In other cases, BNs are extended to include uncertainty regarding the scenario analysis of management decisions in what is known as influence diagrams [Barton et. al., 2008].

The main aim of this paper is to report the outcome of the feasibility study of a new framework for developing an integrated meta-model for decision-support in ICM based on BNs approach which we recently developed at Catchment Science Centre (CSC) at the University of Sheffield.

2. INTEGRATED META-MODEL DEVLOPMENT FRAMEWORK

We have recently completed a scoping study [Holzkaemper et al. 2009] of developing an integrated meta-model for decision-support in ICM, called the MEM (Macro Ecological Model). A number of design principles were adopted which make the MEM a novel and ambitious approach for developing a decision-support model. We sought to integrate across traditional domains (e.g. linking ecology, hydrology, water quality and socio-economics) and across sources of knowledge (e.g. combining empirical data with the outputs of existing models). The final model was designed to be simple enough to be used by non-experts within decision-making and negotiation meetings, and to explicitly communicate the uncertainties associated with predictions. Bayesian Networks and model coupling techniques were used, and the prototype was built from a combination of numerical models, data analysis, and expert knowledge in a way that, we believe, has rarely been attempted before. The framework and techniques are currently being used to build similar tools in a research project on urban river corridors (www.ursula.ac.uk).

Detail of proposed framework has been discussed in Holzkaemper et al. [2010a, 2009] and summarised in Figure 1. The framework combines the advantages of "soft" techniques of stakeholder participation for problem structuring, interdisciplinary communication and negotiation, alongside the "hard" predictive capabilities for analysing the likely outcomes of different management scenarios. The integrated modelling cycle has been envisioned as a four phase model development framework with close engagement of three different groups of people. It makes a broad distinction between three groups of people with different roles and expertise: stakeholders, domain experts and system modellers. The stakeholders, including policy-makers and various interest groups, make the final decisions and have responsibility for the outcome. The domain experts are subject knowledge experts and help in model development from the problem from Phase 1 into an integrated conceptual model (Phase 2) and finally into a functional integrated model (Phase 3). The system modellers provide the continuity between the phases, have the expertise to elicit the knowledge and assemble the various models with help from the other groups and finally to create the simplified meta-model (phase 4) for use by the stakeholder or user group.

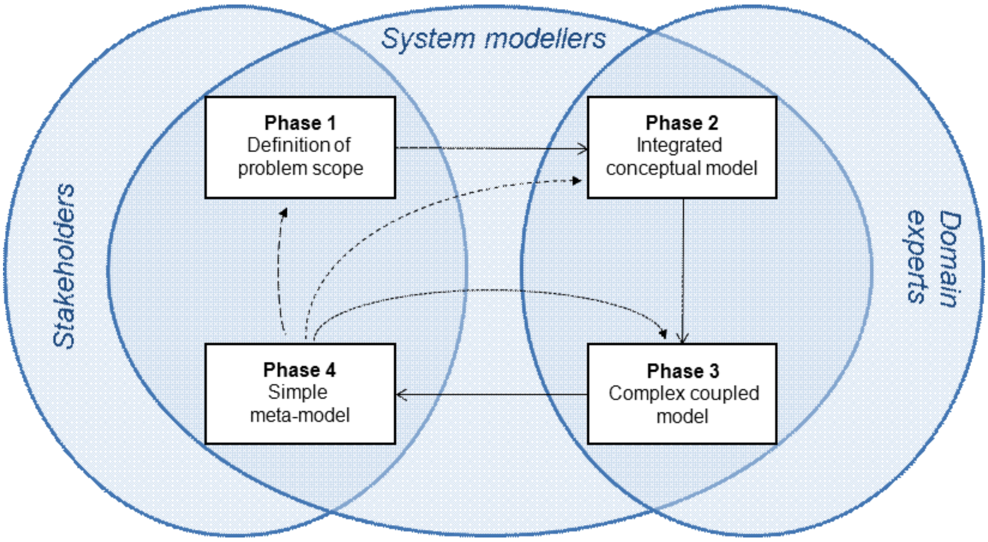


Figure 1. The four phases of participatory model building framework developed in MEM project.

The model development starts with an iterative procedure of specification of problem definition (a description of the nature and scope of a specific problem that needs to be addressed) with close engagement of decision-makers and stakeholders (**phase 1**). The cognitive mapping approach is applied to identify the objectives and management actions that represent the major interests and activities of the stakeholders and decision-makers. In **phase 2**, an integrated conceptual model is developed, linking the identified management actions to the objectives under consideration. The cognitive mapping approach is applied on a more detailed level in collaboration with domain experts to integrate knowledge from different disciplines. Data requirements and availabilities according to conceptual model are also analysed at this stage. Once the scope for the decision-making problem is agreed, and knowledge on possible system interactions is integrated, an operational model is developed in **phase 3** to quantify the impacts of the management interventions on management objectives as specified in the conceptual model. This integrated model would couple existing process based models with empirical and knowledge-based models. This allows for system components to be included in the integrated model even if process-based models are unavailable for these components. In this way, important interactions, non-linear effects or spatial or temporal dynamics are not neglected. Engagement of domain experts is required, especially for the development of knowledge-based sub-models. In **phase 4**, the integrated operational model developed in the third phase is abstracted to result in an integrated meta-model that resembles the behaviour of the complex coupled model and adapts the information about the complexity of the system to the decision-making level. Multiple simulations with the coupled model are usually required to generate outputs for various management scenarios and derive uncertainty estimates. The BN approach provides a promising possibility for implementing the meta-model and is especially interesting in the context of representing uncertainties. Abstract information along with prediction uncertainties would be quantified and represented. The operationally simple meta-model developed could be used to inform decision-making in ICM. Decision-makers and stakeholders could test their ideas for management strategies and explore synergies and trade-offs between different objectives.

The stakeholders, including policy-makers and various interest groups, make the final decisions and have responsibility for the outcome. They will be most interested in framing the problem (Phase 1) and having access to an-easy-to-use model with which to explore the options (Phase 4). The domain experts have the knowledge of the cause-effect relationships in the catchment. They can help translate the problem from Phase 1 into an integrated conceptual model (Phase 2) and assist in converting the conceptual model into a full model (Phase 3). The system modellers provide the continuity between the phases, have the expertise to elicit the knowledge and assemble the various models with the help from the other groups, and finally to create the simplified meta-model for use by the stakeholder group (Phase 4). Once the stakeholders have reached a decision, the more complex model developed in phase 3 can be used for more detailed analyses.

3. CASE STUDY

The framework developed in the MEM project was implemented for the Don catchment in North East England, UK. The Don catchment comprises an area of ~1800 km^2 and it is located in the Humber River Basin District (RBD). Alongside eight other RBDs, the Humber represents the administrative unit for which River Basin Management Plans are developed as part of the implementation of the WFD in England and Wales. The upland and downstream rural parts of the catchment contrast with the middle reach which contains the previously heavily industrialised urban conurbations of Sheffield, Rotherham and Doncaster, now undergoing regeneration and redevelopment. It incorporates a rich mixture of geological, topographical, soil and land use types, and is representative of many catchments in the UK.

The development process and outcomes of the prototype MEM have been described in detail by Holzkaemper et al. [2010b, 2009]. The stakeholders were a mixture of policy, operations and science staff in the Environment Agency of England and Wales (EA). The system modellers were researchers from the CSC. The domain experts were academics and researchers in the CSC and science staff in the EA. There was some overlap between the stakeholder and expert groups.

In Phase 1, agreement was reached that the model would investigate a selection of catchment management options related to agricultural land, urban drainage and flood management, and that options would be compared using the objectives of water quality (with phosphate and BOD as indicators), biological quality (biological general quality assessment score, GQA_{bio}, as indicator) and flood risk (flood damage costs as indicator). This is a relatively small set of options and indicators compared to those that would be needed to populate a full model. They were selected as examples which were sufficient to show whether the method could link indicators for the Water Framework Directive with those for other objectives such as flood risk, and whether the framework and technical solutions being proposed would be suitable. In Phase 2, an integrated conceptual model was constructed of the relationships between the management options and indicators, as shown in Figure 2. In simple terms, four sub-models, one for each indicator, were developed, integrated together and the resulting network simplified by eliminating unimportant or unspecified links; this phase was iterative and collaborative with the domain experts.

In Phase 3, the conceptual model was translated into a fully functional model of the system. Three different types of information (numerical models, data analysis, and expert knowledge) were used to populate the links shown in Figure 3 in order to create the model. The existing numerical models Psychic and SIMCAT were loosely coupled and used to simulate phosphate loads and transport from diffuse and point sources, while SIMCAT also simulated inputs of BOD from point sources. The effects on water quality caused by changes in travel times due to flood management were simulated in SIMCAT. Results from an existing flood modelling study [Hankin, 2008] were used to estimate flood damage. Expert knowledge was used to define the relationships between the flood management options and both the flood protection standard and the travel time changes which affected water quality. A combination of data analysis and expert knowledge was used to define the biological quality sub-model. A complex integrated model was the product of this third phase of the modelling building framework. This was the longest phase of the work, with many tasks to be completed, including: acquiring, coupling and calibrating models; acquiring, cleaning up and analysing datasets; eliciting knowledge from experts; and finally coupling all the different aspects together.

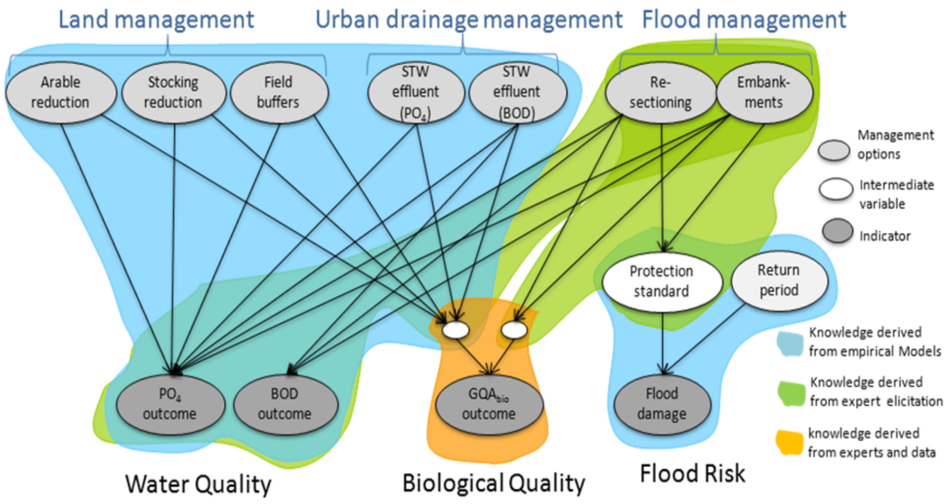
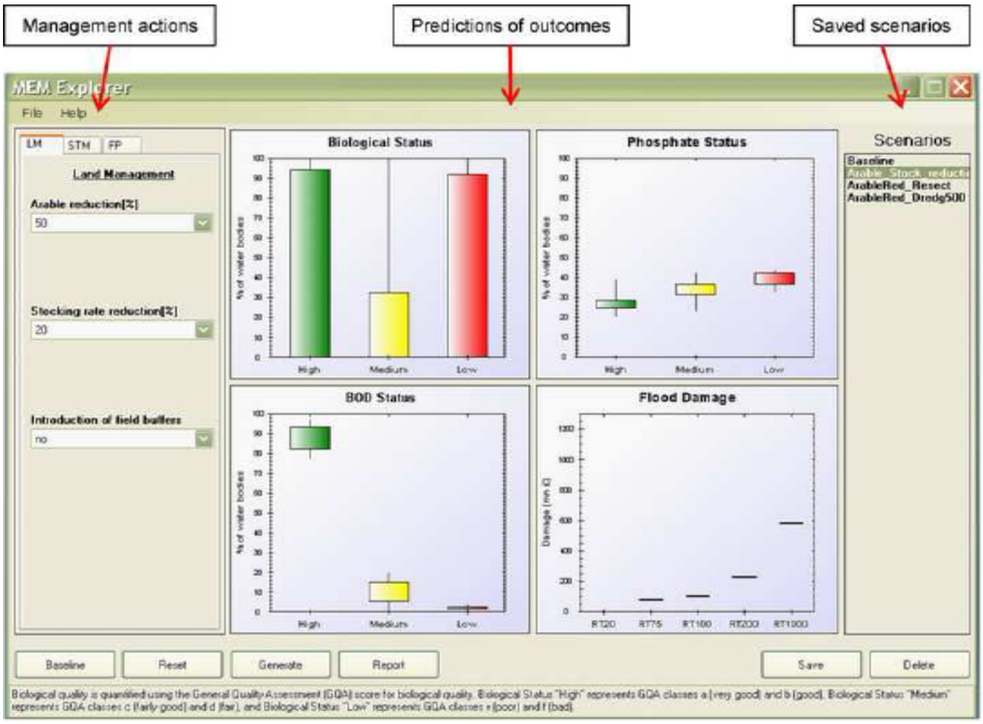


Figure 2. Integrated conceptual model underlying the MEM prototype, showing management options examined (top), intermediate variables and indicators (bottom).

The model produced within phase 3 is too complex to run in planning meetings or by non-experts such as the original stakeholder group. In Phase 4, a meta-model was created to emulate the full model in a way that was rapid, easy to use, and retaining the confidence of stakeholders. It relates closely to the conceptual model (Figure 2), and was created as a Bayesian Network derived from a set of runs of the full model. Finally the BN-based meta model was packed in a user friendly graphic user interface (GUI) to make it more intuitive to operate for non-specialist users (i.e. managers and stakeholders; Figure 3).The meta-model predicts indicator values and their uncertainty for combinations of management options. Estimates are considered accurate enough for decision-making; once a scenario has been chosen, the more detailed model of phase 3, or the initial specialist models, would be used for detailed design.



Arable reduction[%]: 50

Stocking rate reduction[%]: 20

Introduction of field buffers: no

Biological quality is quantified using the General Quality Assessment (GQA) score for biological quality. Biological Status "High" represents GQA classes a (very good) and b (good), Biological Status "Medium" represents GQA classes c (fairly good) and d (fair), and Biological Status "Low" represents GQA classes e (poor) and f (bad).

Figure 3. User Interface of the MEM prototype.

4. EVALUATION OF PROPOSED FRAMEWORK AND PROTOTYPE MODEL

At the end of the prototyping study, a workshop was held with the potential users of the tool (EA staff involved in the development of River Basin Management Plans for the WFD and members of the project board). Detail discussion on evaluation has been provided in Holzkaemper et al. (2010b). The perceived benefits of the MEM were:

- It provides a structured approach to address complex planning issues and integrate knowledge from different domains.
- The visualisation of cross-benefits between management measures enhances the effectiveness of planning.
- The presentation of uncertainties allows for systematic review and identification of robust measures.
- Limiting the level of complexity and detail enhances the applicability for non-specialist users.
- The tool could support communication and social learning in participatory planning.

However, there are some limitations to the prototype model and development framework. Technical and institutional challenges that were encountered during the prototyping study are discussed in detail in Lerner et.al. [2010] and Holzkaemper et al. [2010b, 2009]. Major technical challenges in building such a tool include the difficulties of coupling disparate models of components of the catchment system, and the conversion of a complex coupled model into a simplified meta-model. The model will have to be customised to each basin in which it is used. Validation of an integrated catchment model is difficult because there are few, if any, suitable sets of field observations which could be used to test it against. Moreover, the prototype model does not represent all uncertainties. For example, uncertainties about the efficiency of buffer strips were not considered in the prototype model, as this uncertainty analysis would have required a large effort because the source code of the underlying model (Psychic) was not accessible which prohibited a tight coupling and automated uncertainty analysis. Limited access to data and models because of issues surrounding intellectual property rights presents significant barriers to any integrated modelling exercise. This issue will remain a significant barrier to future development of integrated decision-support tools.

The institutional challenges are more severe, starting with the question of whether individuals and institutions accept the overall concept of integrated catchment management through collaboration and new ways of open and participatory working. Developing integrated model at large scales will have major resource implications within the sponsoring organisations under the participatory route we propose. Continuity and availability of personnel is a key challenge when developing a framework that involves long-term, intense engagement between scientists and potential users. Identifying relevant individuals within organisations that have complex structures, particularly individuals with sufficient power to promote frameworks such as the one described in this paper, is also a significant challenge. Will a model such as the one discussed here be acceptable to all the groups and vested interests involved, and will the project team get the cooperation over data, current models and input of stakeholder time that it needs? Such a project is ambitious and risky enterprise, but has potentially high rewards for sustainable development of catchments in the UK and beyond.

5. CONCLUSION

Within the Macro-Ecological Model project we developed a consistent framework for integrated meta-model for decision-support in ICM based on a BN knowledge integration approach. The framework seeks to reduce some of the current limitations and promote the development of modelling tools that can support ICM both by providing an integrated scientific evidence base and by facilitating communication and learning processes. The results of the scoping study suggest that this approach, although challengingly difficult in its own right, could help to support the implementation of river basin planning and other activities based on philosophies such as ICM.

As such, it is designed to be a tool for high-level decision support in integrated catchment management, which brings together knowledge from different disciplines to support a more holistic evaluation of planning alternatives. The BN approach is well suited to integrating knowledge from different resources. It also provides the opportunity to perform rapid scenario analyses, which makes it a very practicable tool to be applied in a planning context. The possibility to take modelling uncertainties explicitly into account enables robust decision support [Schlüter & Rüger, 2007]. Previous research in the area of decision-support systems has pointed out that decision-support tools are only accepted by their potential users if these users are involved in the model development from the beginning [Borowski & Hare, 2007]. Therefore, a close interaction between the model developers and the potential users is promoted in the development of the Macro-Ecological Model. The intuitive model structure of the BNs and the integration of information from trusted sources (e.g. EA data, models and expert knowledge) should support the acceptance of the model amongst its potential users.

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