



Jul 1st, 12:00 AM

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Holzkämper, A.; Surridge, B.; Paetzold, A.; Kumar, Vikas; Lerner, D. N.; Maltby, L.; Wainwright, J.; Anderson, C. W.; and Harris, R., "A consistent framework for knowledge integration to support Integrated Catchment Management" (2008). *International Congress on Environmental Modelling and Software*. 73.

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A consistent framework for knowledge integration to support Integrated Catchment Management

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Abstract: The European Water Framework Directive (WFD) sets out an integrated perspective to water management in river catchments and river basin districts and is a key driver in the movement towards Integrated River Basin Management. Integrated river basin management must deliver objectives related to the WFD in the wider context of various other stakeholder interests, for example related to flooding, water resources, employment and cost. In managing such complex systems, a specific objective can be achieved through different management actions. Likewise, a specific management action can have implications for multiple objectives. Synergies or conflicts between specific objectives and between specific actions are likely to occur, and need careful consideration in order to increase the efficiency of planned management actions. However, such integrated decision making is a very difficult and highly complex task, which cannot easily be accomplished by either single or groups of planners. Integrated modelling tools to facilitate and enhance communication within a group of decision-makers and inform a more objective and evidence-based multi-criteria decision-making process are required. The scope for the development of such an integrated tool is being tested by the Catchment Science Centre (CSC) at The University of Sheffield. The CSC and the Environment Agency are jointly developing a tool termed the Macro-Ecological Model (MEM). 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 enables knowledge from various different resources to be integrated, including empirical data, model results and even expert knowledge using a Bayesian Belief Network (BBN) approach. BBNs have the advantage of representing system understanding in an intuitive, graphical format. Furthermore, the approach provides the ability to explicitly account for uncertainties in model predictions. Therefore, the model framework provides a good tool for visualising system understanding and communicating uncertainties. Applied in a participatory process, it can support robust decision making in river basin management. The conceptual model framework is illustrated with examples from the prototyping study. The prototype model captures the process interactions affecting the management objectives “Ecological Status” (composed of both Biological Quality and Physico-chemical Quality) and “Flood Risk”. It is planned to be later extended to incorporate further environmental, and also social and economic objectives.

Keywords: Integrated Catchment Management; Integrated Modelling; Decision support; Bayesian Belief Network

1. INTRODUCTION

The actions of many stakeholders influence the processes occurring in a catchment, and as a consequence many of the objectives that are valued within a catchment. For example, flood risk managers, water quality managers and land use planners all have different sets of objectives and they apply different set of measures to achieve these objectives. As the processes in a catchment are connected, it is very likely that interactions between different actions occur. These interactions can either be conflicting or synergetic with respect to the different management objectives. By considering these interactions in integrated management, the opportunity is provided to make management more efficient by focusing on synergetic effects and avoiding conflicting effects. New and innovative solutions can be found to make management more sustainable [Pascual, 2007]. However, integrated management also represents a great challenge. Complex system interactions are involved that are beyond the ability of individual planners and decision makers to grasp. Planners need to work together and objective tools are required to assist planners in making their management decisions [Reichert et al., 2007]. Decision support tools such as integrated models can enhance communication and support decision making by providing insights into the possible impacts of planned management interventions on multiple objectives [Matthies et al., 2007]. Integrated planning takes place at different spatial levels (e.g. national, regional, local). Therefore, integrated modelling tools are required at different spatial scales to support integrated management at these different levels.

This paper presents a conceptual framework, termed the Macro-Ecological Model (MEM), for the integration of knowledge and information about environmental, social and economic processes and process-interactions that are affected by management actions, and that have impacts on multiple management objectives. The conceptual model framework is illustrated with examples from the prototyping study. The prototype model captures the process interactions affecting the management objectives “Ecological Status” and “Flood Risk”. The model is planned to be later extended to incorporate further environmental, and also social and economic objectives. The full implementation of the MEM would be designed to support the decision-making process in integrated river basin management. The tool is envisaged as a means to enhance communication and system understanding within fora of high-level decision makers in the second and third cycles of the river basin planning under the Water Framework Directive.

2. MODEL CONCEPT

High-level decision making deals with identifying appropriate sets of broad scale management actions whilst considering multiple management objectives in a catchment. The Macro-Ecological Model (MEM) is planned to incorporate a range of different environmental, social and economic management objectives that represent the interests of multiple stakeholders in a catchment. The model will capture the processes and process interactions affecting these different objectives, and it will allow us to make predictions regarding how different management scenarios could affect the status of these objectives in a catchment (Fig. 1).

The processes and process interactions need to be simplified as far as possible to develop a feasible model of the extremely complex catchment system. To accomplish this, the tool must integrate knowledge and information on processes and process interactions from many different disciplines. This knowledge and information will very likely be available in different forms. For example, process-relationships can be derived from empirical data. If no empirical data is available, process relationships could also be derived from existing models or from expert knowledge.

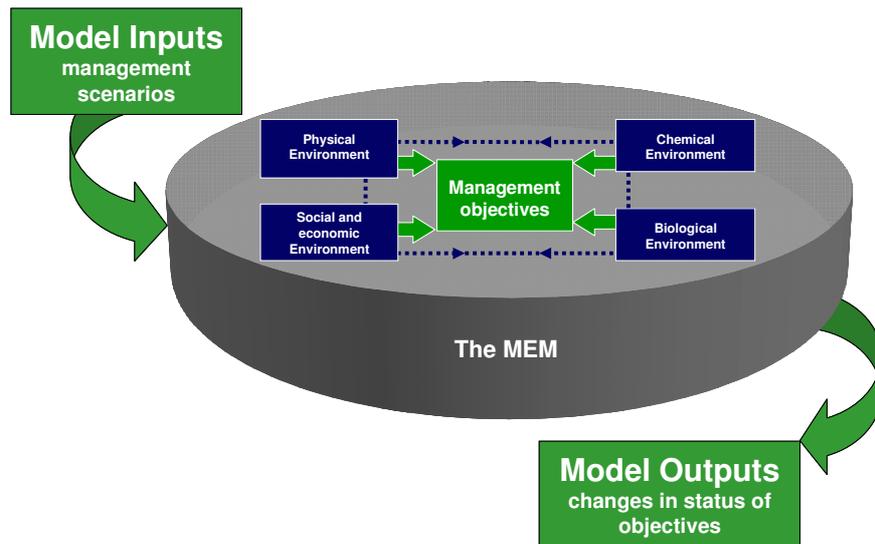


Figure 1. Schematic diagram of the Macro-Ecological Model.

3. MODEL APPROACH

The Macro-Ecological Model is implemented as a Bayesian Belief Network (BBN). A BBN is a graphical cause-effect network, where variables are linked together according to their dependencies [Jensen, 2001]. Associated with each variable is a conditional probability table (CPT), which specifies how this variable is affected by its influencing variables. The CPTs can be derived from data, external model results or expert knowledge, which provides the opportunity to integrate and combine information from different sources in one model. The BBN can be built to any level of detail and thus allows us to simplify complex relationships. Further advantages of the BBN approach are that uncertainties in model predictions can be explicitly considered, and rapid scenario analyses can be performed. The explicit consideration of uncertainties is an important challenge to decision making, particularly in the complex systems involved in integrated river basin management.

4. MODEL CONSTRUCTION

A conceptual framework for the development of the MEM was developed which involves six major steps that are detailed below:

4.1 Identification of index variables

Index variables represent relevant aspects of management objectives within the MEM. The definitions of index variables are ideally based on classification schemes that are currently used within the Environment Agency (EA) in the UK to evaluate the status of management objectives. The index variables must also be a useful basis for decision making. To ensure that these requirements are met, all index variables are defined in consultation with experts from different management functions within the EA during the prototype study. In a full implementation of the MEM the collaborative definition of index variables would be extended to all stakeholders in a catchment. Figure 2 shows the index variables that were identified to represent aspects of the objectives “Ecological status” and “Flood risk” that were chosen to be included in the prototype model to test the development of the MEM.

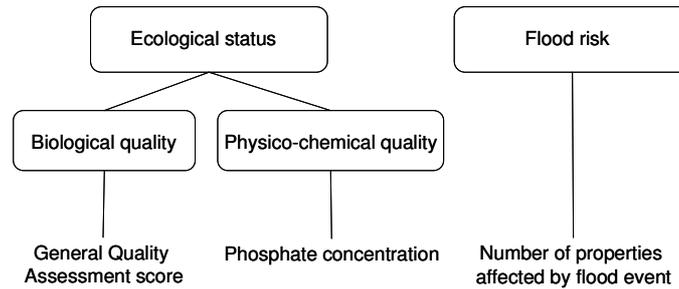


Figure 2. Derivation of index variables to represent relevant aspects of the management objectives “Ecological status” and “Flood risk” in the MEM prototype. The General Quality Assessment score for biology indicates how much the community of macroinvertebrates in the river is affected by organic pollution. The score is currently used in the UK as a basis to the assessment of biological quality as part of ecological status assessments under the WFD.

4.2 Development of conceptual networks

Conceptual cause-effect networks are developed around each identified index variable. Based on literature reviews and in consultation with EA experts as well as experts from the University of Sheffield and other institutions, conceptual cause-effect networks are developed to capture knowledge on processes and process interactions that could have impacts on the index variables. The aim is to reduce the chance that relevant pathways are neglected in the final MEM model. Also, the conceptual models developed can be the basis for a later expansion of the MEM if further data and knowledge become available, or if new management actions need to be integrated. Figure 3 shows the conceptual model that was developed for the index variable “phosphate concentration”. The network summarises which processes influence the phosphate concentration in a river and how certain interventions, such as introducing restored wetlands, introducing riparian buffers or applying P-fertilisers in agriculture, could affect the phosphate concentration in the river.

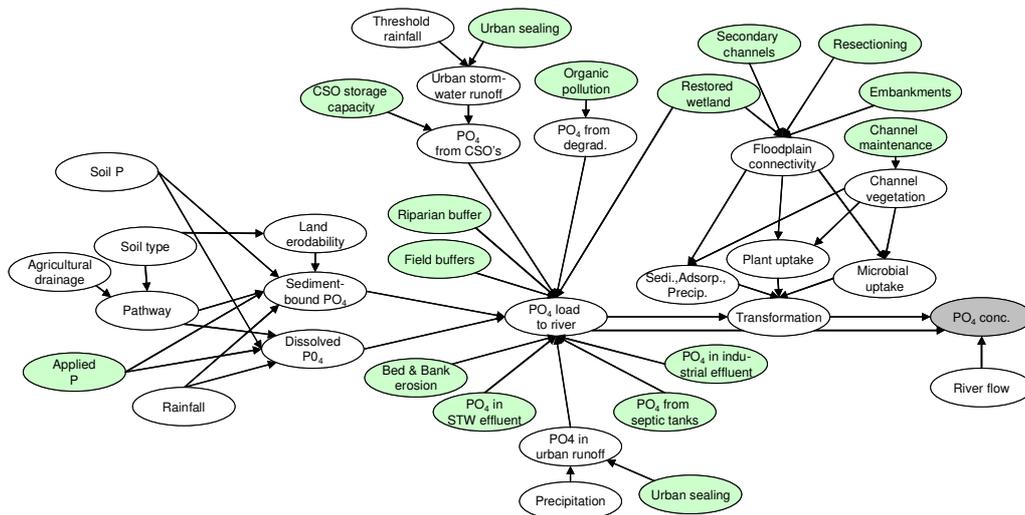


Figure 3. Example of a conceptual cause-effect network linking management variables (green bubbles) to index variable (grey bubble) via a network of intermediate variables (CSO = combined sewer overflow, STW = sewage treatment work).

4.3 Simplification of conceptual networks

To enable the implementation of sub-networks as Bayesian Belief Networks (BBNs), the conceptual models need to be simplified. To do that, cause-effect links and variables with minor relevance are excluded, as well as links and variables that are not influenced directly or indirectly by any of the management actions under consideration. This process of simplification was conducted in collaboration with stakeholders to ensure that they remained confident in the conceptual basis of the MEM. Appropriate management actions to be considered in the MEM prototype are identified in consultation with EA planning experts. Other links and variables that are excluded from the network are those that can not be specified due to insufficient data and knowledge. If such data and knowledge become available at a later stage, the BBN structure could be extended according to the conceptual network (Fig. 3). Current data and knowledge gaps that limit an approach such as the MEM will be documented and reported as a record of the potential barriers to a full implementation of the MEM. Figure 4 shows the simplified network which describes how phosphate concentration is affected by agricultural land management, riparian buffers, phosphate inputs from point sources (i.e. combined sewer overflows and sewage treatment work effluents) and morphological modifications, such as introducing restored wetland, embankments or channel resectioning.

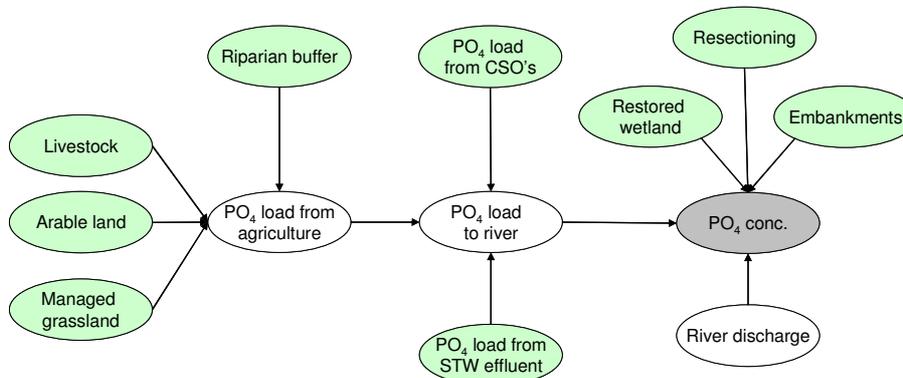


Figure 4. Example of a simplified network suitable for implementation as a BBN (CSO = combined sewer overflow, STW = sewage treatment work).

4.4 Specification of sub-networks

The BBN sub-networks are specified based on information and knowledge from different resources. Where empirical data is available, this will be used to specify network components. If no data, but existing and well-tested models are available, these can be used to generate synthetic datasets, which can then be used to populate parts of the BBN. If only expert knowledge is available to inform network components, CPTs can be elicited from experts to specify the links. If data become available at a later stage, they can be used to update the model and knowledge-based network specification. Experts from various disciplines are consulted to identify data availability, model availability, and finally to gather expert knowledge for the network specification. The network specification can differ for different river types to take into account the fact that many processes are affected by relatively local-scale characteristics (e.g. altitude, soil type, geology). In this way, the definition of a river type would account for significant differences in processes and process relationships due to local-scale characteristics. Suitable river typologies for the MEM are under consideration. For example, the WFD-defined river typology could be included, which is based on the three characteristics “altitude”, “geology” and “catchment size”. This typology would be based on commonly available data and it could also be an intuitive basis for expert knowledge elicitation.

Figure 5 shows the phosphate sub-network, which is planned to be specified based on model simulations of two external models: the PSYCHIC model [Davison et al., 2008], which predicts how land management affects phosphate loads from agriculture and the SIMCAT model [EA, 2006], which predicts how the phosphate concentration in a river is affected by diffuse and point sources of phosphate, and by the river discharge. These two models do not take into account the effects of riparian buffers, restored wetlands, embankments and channel dredging. Therefore, knowledge on the influences of these variables on phosphate loads from agriculture, and on phosphate concentration in the river, respectively, will be elicited from experts. This sub-network has been used to test the approach of using existing mechanistic models to specify a BBN, and to combine results from these mechanistic models with expert knowledge in a single BBN. Other sub-networks being developed as part of the MEM project are testing different approaches to specification of the BBN, including the combination of data-based and expert-knowledge based networks.

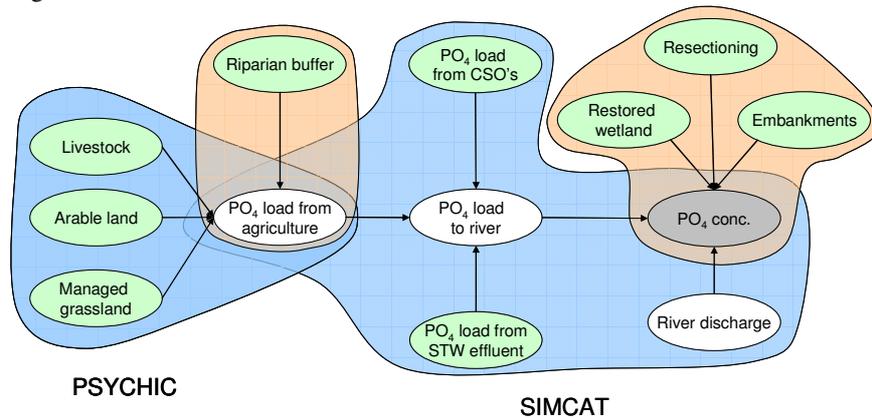


Figure 5. Example of a simplified network to be specified based on external model simulations (blue background) and expert knowledge (red background); (CSO = combined sewer overflow, STW = sewage treatment work).

4.6 Merging of sub-networks

Once the different sub-models for biological quality, phosphate and flood risk are specified and tested, they are merged into a single network. For the prototype model, sub-networks for phosphate, biological quality and flood risk will be linked together. A subset of the combined network is shown in Figure 6. Links between sub-networks are provided via index variables and management variables. For example, the index variable “phosphate concentration” is an input to the biological quality sub-network. Management actions such as introducing embankment, restored wetlands and resectioning have impacts on the biological quality component, the phosphate sub-model and the flood risk sub-model.

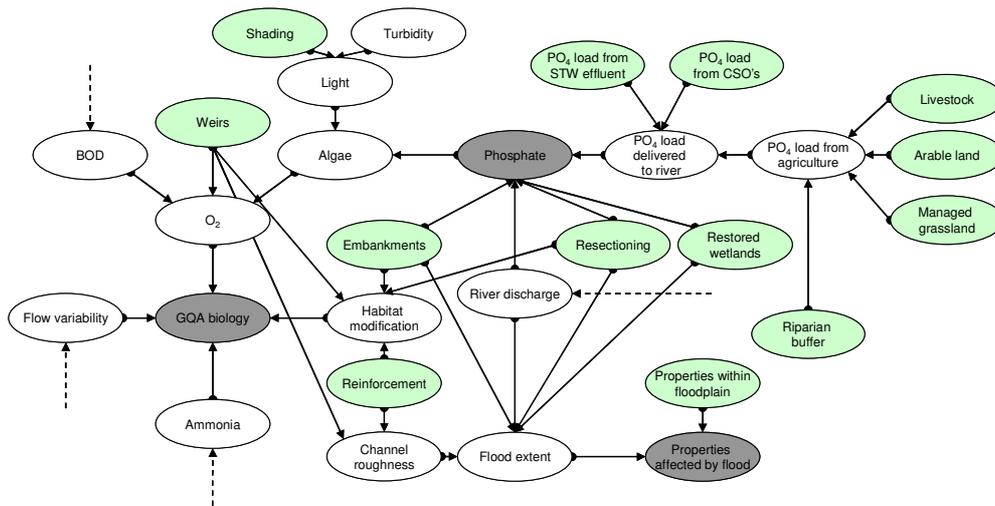


Figure 6. Subset of the MEM prototype network showing how the sub-networks developed for the three index variables are linked together (green bubbles indicate management variables; grey bubbles indicate index variable; dashed arrows indicate connections to further model components; BOD = Biological Oxygen Demand, GQA biology = General Quality Assessment score for biology; CSO = combined sewer overflow; STW = sewage treatment work).

4.6 Model evaluation and updating

The predictions of model components that were specified based on empirical data will be evaluated based on test-datasets. Model parts that were specified based on external model simulations or expert knowledge and for which no data are available will undergo a plausibility analysis that involves an evaluation of model predictions by groups of experts. As the model development is an iterative process, the model specification can be updated as further information and knowledge becomes available. For example, if empirical data become available for a model part that is specified based on expert knowledge, this empirical data can be used to update the conditional probability tables for that model part, which will decrease the prediction uncertainties.

5. MODEL APPLICATION

To predict changes at the catchment scale, the predictions of the river-type specific models have to be aggregated. In a simple approach, each river type-specific model would be applied once and the predictions would be aggregated by assigning weights to the predictions according to the frequencies of the river types in the catchment. In the most realistic case, the model would be applied for every single water body within a catchment. This would allow us to estimate the catchment's response to a highly disaggregated management scenario, because different combinations of management actions could be assumed in each water body. The catchment-scale outputs could then be represented either as averages (e.g. average General Quality Assessment score for biology in a catchment or Basin), or as numbers of exceedences of a certain threshold (e.g. number of water bodies with good biological quality in a catchment or Basin). The model could finally be applied to compare a baseline scenario to different management scenarios for a catchment. In different scenarios the impacts of management actions, such as, introducing wetlands in 20% of the lowland water bodies or reducing livestock numbers by 10%, could be tested and evaluated with respect to the multiple management objectives.

6. CONCLUSIONS

The Macro-Ecological Model project has developed as a consistent framework for knowledge integration, using BBN technology. 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 Bayesian Belief Network 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 BBN 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.

ACKNOWLEDGEMENTS

The Macro-Ecological Model project (SC060039) is funded by the Environment Agency and the University of Sheffield. We would like to especially thank all experts from the Environment Agency, the University of Sheffield and other academic institutions who volunteered to support the development of the MEM during various group discussions.

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