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Water quality modelling for decision-making: the drinking-water watersheds of Sydney, Australia

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Abstract

Water quality modelling for decision-making occurs at a disciplinary divide between science and management. Workers in science and management operate in fields that traditionally have different objectives, priorities and expectations. These differences can create barriers to the effective use of scientific models by watershed managers. This paper reports on two methods that are being used to overcome barriers that inhibit the successful use of models in watershed planning and decision-making. The first is the use of generic evaluation criteria that both scientists and managers may use to critique water quality models from a decision-maker's perspective. The second

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is an activity in which water quality modelling is embedded into a water management organisation's planning and management processes.
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Introduction

The Sydney Catchment Authority (SCA) is a state government agency responsible for the health of the watersheds that supply drinking water to four million residents of Sydney, Australia. The SCA's area of operations is extensive (Figure 1), comprising

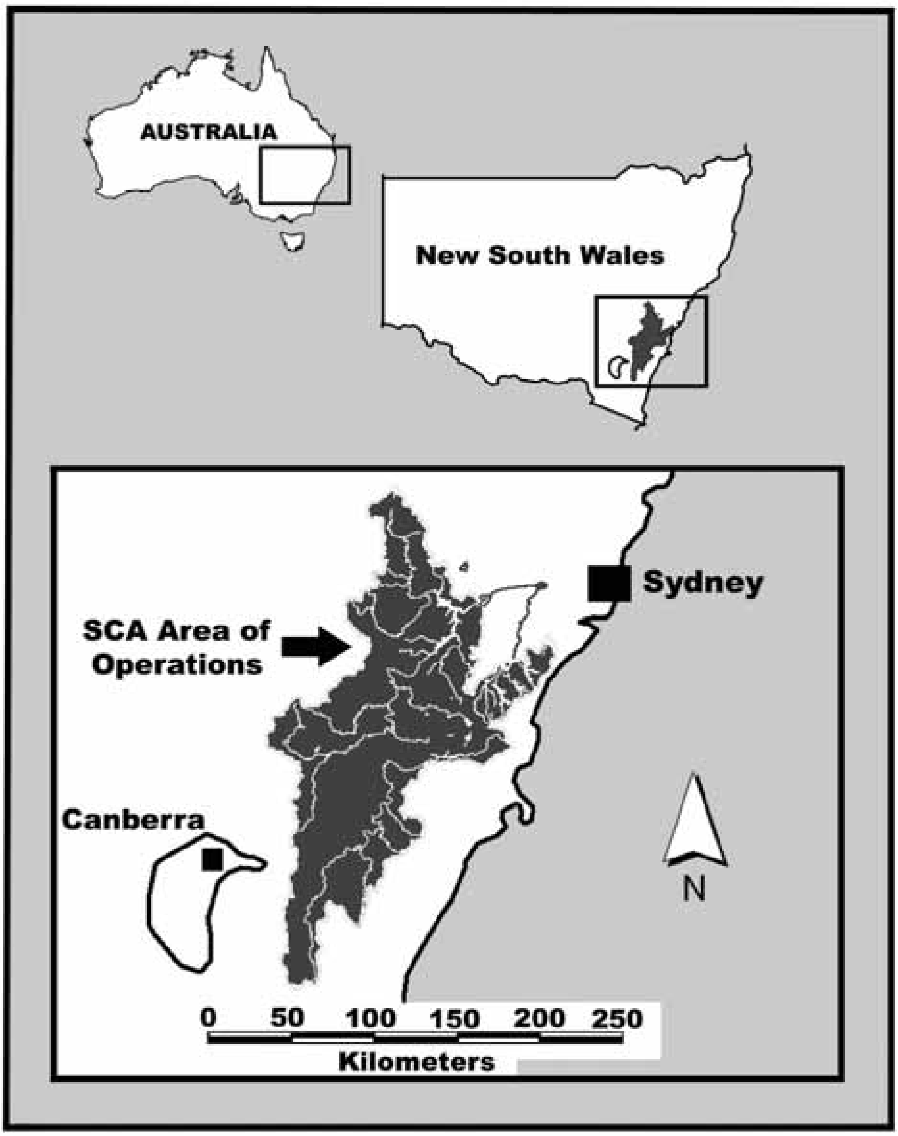

Figure 1. The Sydney Catchment Authority's area of operations

an area of 16,000 km^2 and a population of 110,000 people. A plan for the future management of Sydney's drinking-water watersheds is outlined in a draft regional environmental planning document entitled 'Sustaining the Catchments' (SCA and DIPNR 2004). Under the plan, the SCA will use models and decision support systems as assessment tools to support consideration of development proposals. More generally, models will also be used to test alternative land management scenarios and support watershed management decision-making. An important role for such models will be to identify nonpoint sources of nutrient pollution (nitrogen and phosphorus), such as rural and urban land, and estimate and predict nutrient loads delivered to streams.

The SCA and other agencies interested in environmental and watershed health have been undertaking computer modelling of water quantity and quality in Sydney's drinking-water watersheds for several years. Some examples of predictive models that are capable of modelling nonpoint sources of pollution, and have been used in SCA watersheds, include CMSS (Cuddy et al. 1994), ANSWERS (Armstrong, Mackenzie and Edwards 1995), HSPF (AWT 2000), IQQM (Young et al. 2000), AnnAGNPS (AWT 2003), and SedNet (Olley and Deere 2003). A brief overview of most of these models is found in Letcher et al. (1999). Despite considerable effort expended modelling nonpoint source pollution, there is limited integration of previous research with current research and management-planning activities. There seem to be barriers that have inhibited the transfer of information and knowledge produced by water quality scientists and water quality models into decisive watershed policies and management actions.

To improve this situation, University of Western Sydney researchers are working with the SCA to investigate the range of nonpoint source-modelling tools that may be appropriate as watershed planning and decision-making aids, and explore how they may be used more effectively. This paper reports on that work, and some of the theory underlying the approach. The research involves the development of generic evaluation criteria that will enable SCA decision-makers to assess the utility of nonpoint source watershed models in the planning and decision-making process. A related activity is a pilot project in which a model will be integrated or 'embedded' into a planning process. Through the embedding activity, researchers and the SCA hope to be able to identify and overcome some of the institutional, technical and ideological barriers between science and management that inhibit the efficient and effective conversion of scientific knowledge into watershed management decisions and actions.

Limitations of modelling for decision-making

When considering ways of achieving water quality improvements, including reductions in nutrient loads to streams, watershed managers often turn to computer-based mathematical models (Caminiti 2002). Watershed simulation and prediction models are useful to scientists because they help them advance scientific knowledge by testing their understanding of processes in natural systems. For decision-makers, models hold the promise of allowing them to predict the environmental impact of human activities and evaluate or prioritize management interventions (Rizzoli and Young 1997). Decision-makers expect that by undertaking simulation- and prediction-based scientific analyses of a decision-making problem, they will reduce the uncertainty associated with the decision-making process.

However, there is relatively little quantitative knowledge of environmental processes at scales appropriate to management, and the assumptions that are built into simulation and prediction models are always subjective and will rarely, if ever, be agreed upon by all scientists or stakeholders (Cullen 1990). In any case, models usually do not include all of the biophysical and socio-political variables that are needed to make a water management decision (Cullen 1990; Loucks 1992; Rizzoli and Young 1997). Scientific models therefore are imperfect and incomplete decision-making tools.

Despite improvements in scientific knowledge of environmental processes and better characterization of landscapes through remote sensing and geographical information systems, water quality model outputs are inherently uncertain. Uncertainty can be the result of a lack of knowledge of important biophysical processes that need to be modelled and/or a lack of data to parameterize a model. Information that might improve model inputs and reduce uncertainties, such as more or better environmental monitoring or experimentation, is often costly and time-consuming to obtain. Additionally, there is inherent uncertainty in predictive model outputs resulting from natural environmental variability, in rainfall for example (Beck 1987).

Decision-makers must also contend with socio-political and economic uncertainties, such as those relating to government policy, community values, or the financial and opportunity cost of pollution abatement measures. Decisions are not always based on biophysical outcomes such as pollutant load, pollutant concentration or ecological impact (Cullen 1990; Loucks 1992).

The limitations associated with predictive modelling have caused some investigators (e.g. Loucks 1992; Pielke Jr., Sarewitz and Byerly Jr. 2000) to question the extent to which models and the science of simulation and prediction can benefit decision-making. Model use (or misuse) may sometimes have the effect of making the complexities and uncertainties associated with an environmental issue more conspicuous, increasing political controversy and producing a false perception of a need for more research rather than management intervention.

The science–management interface

Despite acknowledgment of the limitations of models, most managers and scientists agree that they play an important role in watershed management (Rizzoli and Young 1997; Caminiti 2002; Newham et al. 2004). However, problems can arise because water scientists and water managers operate within different disciplines or 'knowledge cultures' and have different professional priorities. Traditionally, the culture of science emphasizes the acquisition of disciplinary knowledge, and quality is determined through a process of publication and peer review. Management however, is focused on the application of knowledge, and requires the integration of information from several disciplines to achieve management objectives. The quality of management decisions is subject to public scrutiny and is judged by a much wider group that includes all affected stakeholders.

The disciplinary differences between scientists and managers have contributed to the development of barriers that inhibit the translation of scientific knowledge into watershed management decisions and actions. These include difficulty communicating and integrating information and knowledge from different professional disciplines within and outside watershed management organizations, uncertainty about the roles and limitations of science in watershed management, confusion about the range of scientific models and modelling methodologies and their appropriate use as decision support tools, policies and systems that are unable to reconcile scientific uncertainty with the need for management intervention, and difficulty reconciling socio-political and environmental values (see Cullen 1990; Loucks 1992; Bosch, Ross and Beeton 2003; Cash et al. 2003). If watershed models are to provide decision-makers with decisive information, modelling needs to be undertaken in an environment that acknowledges the needs of the decision-maker, the strengths and weakness of the models being used and the scientific knowledge that underpins them. This can be achieved by managing the boundary between science (knowledge) and managers (action) (Cash et al. 2003).

In order to overcome barriers between scientists and managers, and facilitate more effective utilization of models in decision-making, two research activities are being undertaken. Firstly, a set of model evaluation criteria are being developed that will be used, in conjunction with conventional technical criteria, to help model developers, analysts and model users evaluate models from the perspective of a decision-maker. In the second activity, an interactive and participative modelling process involving both water quality scientists and watershed managers is being piloted. The process is designed to 'embed' a model within a broader planning and decision-making framework to facilitate the conversion of knowledge to action.

Model evaluation from the manager's perspective

There are a plethora of watershed-scale water quality and quantity models, and these are often reviewed and compared against various criteria (e.g. Ghadiri and Rose 1992; Singh 1995; Shoemaker et al. 1997; Letcher et al. 1999; Borah and Bera 2003; Merritt, Letcher and Jakeman 2003). Most reviews are written in the 'language' of science, and focus on technical aspects of model development and use, including model structure, parameterization, calibration, sensitivity analysis and more recently validation, and uncertainty analysis. In contrast, there has been relatively little study into the utility of scientific modelling and prediction in environmental and water management (Cullen 1990; Beck 2001). For watershed managers, technical aspects of model design and use may not reflect the value of a model as a tool to support watershed management and planning processes (Pielke Jr., Sarewitz and Byerly Jr. 2000; Loucks 1992).

The ability to evaluate models from the perspective of a manager will empower managers and planners by giving them a better understanding of their own modelling needs, and help them convey these needs to scientists who develop and run models on their behalf. It will also allow scientists to understand the needs of managers better, so that they may tailor models and modelling activities to managers' needs. It is appropriate that watershed managers who use models to support decision-making evaluate models according to criteria that emphasize aspects of model selection and use that are important in the field of planning and management. The development of these criteria is occurring through a review of literature, and through the model-embedding workshop process.

Embedding a model in decision-making

Researchers are working with the SCA using both theory and practical experience to derive methodological lessons on how to incorporate models better into the planning and decision-making process in their organization. The embedding activity was conceived as an action research initiative (see Kolb 1984) in which a watershed-scale model will be used to identify diffuse nutrient pollution sources and calculate nutrient loads using a participative process.

The modelling component of this activity is accompanied by a series of three workshops aimed at identifying the modelling needs of decision-makers and planners in the SCA, and delivering to them a model and model outputs that meet their needs. A respected expert in water quality modelling and management has been hired to facilitate each workshop. At the time of writing, the first two workshops had been held.

The first workshop was open to SCA managers and was designed to clarify their thinking about what they expect from models, and determine what is needed to embed a model into their decision-making process. Scientists and analysts from within and outside the SCA attended the second workshop. This workshop was structured to ensure that the research team used the most appropriate and sufficiently rigorous scientific method to meet the needs of the managers and planners. This workshop also provided an opportunity to identify significant differences/conflicts between the needs, wants and expectations of the management group and science group. These differences provide insights into how barriers to communication between the two knowledge cultures can be overcome and may later assist in the development of model evaluation criteria. Participants at either of the first two workshops will be invited to attend the third workshop. Here, the modelling process and results will be presented to participants. As completely as practicable, all of the inputs and assumptions used in the model will be explained to those present. The third workshop will include an opportunity for managers and scientists to evaluate the process and the modelling outputs so that future modelling activities more effectively meet the managers' needs. Key personnel that do not attend the workshops will be approached to take part in interviews.

Early outcomes

Sixteen SCA managers and planners attended the first workshop. Participants were asked what they thought were the barriers to embedding models in their decision-making roles, and what evaluation criteria should be considered to ensure that models met their needs. A wide range of technical and institutional barriers was identified. Technical barriers included access to modelling expertise within the organization, limited data availability, difficulty choosing appropriate models, lack of suitable modelling tools for specialized applications, difficulty understanding how some models work, inadequate or user-unfriendly interfaces, difficulty linking models, and difficulty quantifying uncertainty in model input data, algorithms and outputs. The major institutional barriers to embedding models in decision-making were seen to be the absence of guidance material, or a consistent organizational policy, on the selection and use of models. The form that such guidance might take was debated, and suggestions included a 'standard operating procedure' manual, a decision tree, a flow chart, a checklist or a combination of these. The lack of appropriate training regimes and organization of the SCA's in-house modelling capability were also cited as institutional barriers. Another issue that was the subject of some interest and discussion was the need for a 'champion' within an organization to support a push to make better use of models, and to better integrate models into the planning and decision-making processes.

With respect to the evaluation criteria that they considered important to decision-makers, participants said that it was important that managers understand how models worked, and in particular to understand the assumptions upon which models are based. They wanted model developers and analysts to provide a clear statement of the scope of applicability of models to ensure that models were outcome-focused and 'fit for purpose', and they wanted models that were flexible and preferably upgradeable so that they would meet future SCA needs and long-term objectives. Some participants thought that it was also important for operational reasons that models had conceptual consistency at different temporal and spatial scales, and that models applied across different parts of the organization were also based on a consistent conceptual foundation.

Fourteen scientists attended the second workshop, including 7 from the SCA. The remaining participants came from the University of Western Sydney, the Australian National University, the New South Wales Environment Protection Authority and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). At the commencement of the workshop, the SCA provided a brief presentation discussing why they needed nonpoint-source nutrient pollution modelling, and how the model would be used to support management and planning. Participants then set about identifying the assumptions and limitations of a simple modelling approach based on export coefficients, similar to that used by McNamara and Cornish (2004), and how it might be enhanced or substituted with a different modelling approach.

The workshop revealed that although the factors driving nutrient mobilization, transport and delivery to streams are relatively well understood (eg rainfall, land use and management, land cover, antecedent soil moisture, nutrient concentrations in soil, soil erosion and streambank and gully erosion), the relative importance of each factor in the watersheds that form the SCA's area of operations, and at temporal and spatial scales appropriate for management, are generally unknown. This uncertainty made it difficult for researchers to reach a consensus about the most appropriate modelling methodology and highlighted the need for local research at hill-slope and small watershed scales.

The participatory process as a whole has led to a number of changes in direction for the modelling component of the project. Whereas the original expectation of the SCA was that researchers would deliver an export coefficient-based model to calculate annual nutrient exports from different land uses and sub-watersheds in the whole of the SCA's area of operations, the consultation process has revealed that this approach may not meet the SCA's needs. Instead, a more adaptable approach based on average concentrations of nutrients in runoff water is now preferred. Because of the lack of appropriate monitoring data, pollutant loads will mostly be estimated using a simple empirical relationship between soil nutrient concentration and the concentration of nutrients in runoff water, and modelled runoff volumes. Modelling will be more strategically focussed on hill slopes and small watersheds containing critical land uses. This redirection of effort has ensured that the scientists and managers involved in the project are focussed on the same goal, and that effort is not spent on a model that is not 'fit for purpose'.

Discussion and conclusion

Three questions are important when evaluating models (Beck 2001):

1. Peer review: Has the model been constructed of approved materials?
2. Matching history: Does the behaviour of the model approximate that observed in respect of the real thing?
3. Fulfilling a designated task: Does it serve its intended purpose?

Much work has been done to evaluate models according to the first two of these questions, yet these questions may be the least critical when evaluating models used to support decision-making (Loucks 1992; Pielke Jr., Sarewitz and Byerly Jr. 2000). There has been relatively little research aimed at answering the third question (Beck 2001; Cullen 1990). This investigation helps address that research need.

An important outcome of the first workshop was that it demonstrated a desire amongst SCA managers and planners for formal guidance material on model selection and use. Both workshops have demonstrated a need for better communication between the scientists who run models and the managers that use their outputs to support watershed management plans and actions. The evaluation criteria that are currently being developed could readily be included in formal guidance material, and the process of involving managers and planners in modelling is facilitating an interdisciplinary dialogue.

For this effort to continue, attention will need to be focussed on managing the science-management interface over the longer term. Although not stated in these terms at the time, participants at the first workshop identified this need and proposed a solution in the form of a ‘champion’. Cash et al. (2003) discuss the importance of ‘boundary management’, and describe those who operate at the interface as ‘boundary managers’. The research team involved in this work are acting as boundary managers, and this role could be passed on to a champion or through other individuals as a result of a reorganization of the SCA’s modelling expertise, an activity also proposed by participants at the first workshop.

The development of new model evaluation criteria can provide lasting assistance to SCA managers and planners to guide the selection and use of models. An additional benefit of these criteria is that they should be useful to both scientists and managers since they will provide a tool that workers in both disciplines can use to tailor modelling products and processes to managers’ needs. Cash et al. (2003) describe tools that are adaptable to different viewpoints and maintain their identity across different knowledge cultures as ‘boundary objects’.

Nonpoint source pollution is a policy issue in which science has an important role to play. In order to achieve effective use of watershed models, the information models produce must be useful and take into account the cultural and institutional settings in which decision-makers operate. Managing the boundary between water science and water management, and providing scientists and managers with tools that encourage interdisciplinary dialogue can help achieve a more effective conversion of scientific knowledge into management action.

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