18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Making the most of modelling: A decision framework for the water industry

J.M. Blackmore[1,2], **G.C.Dandy**[1,3], **G.Kuczera**[1,4], **J.Rahman**[1,5]

1: eWater Cooperative Research Centre; 2:CSIRO Sustainable Ecosystems; 3:University of Adelaide, 4: University of Newcastle, 5: CSIRO Land and Water
Email: jane.blackmore@csiro.au

Abstract - Increasingly, water management models are being used in decision making contexts that involve selecting a “preferred” course of action by weighing performance against competing objectives. The role of models within the decision process is often poorly articulated, uncertainty is not well accounted, and risk only evaluated after the selection has been made. For example, the technical performance of alternative integrated urban water management options are evaluated using various models, and the results presented in a technical report. The decision makers base their selection on the predicted performance, and the preferences of the stakeholders around the table. Risk assessment is then undertaken to identify and control any areas of high risk, which might be costly or even unachievable. A well structured decision process might have resulted in a different choice.

eWater CRC is delivering a range of new tools to support decision-making in the water industry, ranging from selecting water sensitive design of new urban allotments to exploring policy options for Australia’s large regulated rivers. Central to this effort is a user requirement to incorporate uncertainty analysis, risk analysis, optimisation and prioritisation into the tools.

This paper describes a decision making framework that places models, and other sources of knowledge, into a decision making context. The framework articulates the role of optimisation, risk analysis and prioritisation in the decision making process and clarifies the pervasive role of uncertainty. The framework provides a guide for the inclusion of these decision elements into modelling products, either as generic software elements that can be applied to multiple models, or as supporting material such as documentation or training.

Using the framework, water-management stakeholders articulate problems by iterating around a cycle that defines objectives based on an initial problem statement, and determines what metrics will be used to ascertain that the objective has been achieved within the context of a well-defined system. Different proposed solutions are then evaluated in terms of the agreed metrics, and the outcomes are compared to select the “best” solution.

Selection of “best” option is achieved by including considerations beyond the direct outputs of performance prediction models. By tracking uncertainties and providing assessment methods for risk and optimisation in an environment of compound considerations, a rational and scientifically justified suite of preferred options can be generated. These preferred solutions in turn inform a multi-objective decision process, which allows stakeholders to express preferences and assign weightings to make their final choice, while making full use of the outcomes of detailed scientific analysis. An understanding of the quality of the evidence used to support each step of the process enhances the value of the decision support.

The decision framework complements a common model structure that is used to integrate the various component models developed by eWater CRC. Together the decision framework and the common model structure form the conceptual architecture of the eWater product offering.

.

Keywords: *eWater CRC, decision framework, water management models, uncertainty, optimization, risk*

1. INTRODUCTION

eWater Co-operative Research Centre’s core business is building tools to assist in water management decisions. The eWater product portfolio includes tools for operating river systems, tools for evaluating integrated urban water management options, tools for managing catchments in varying climate and land-use and tools for assessing ecological response to management decisions (eWater CRC 2009). Increasingly, such tools and models are being used in decision making contexts that involve selecting preferred courses of action, by comparing the performance of different options against competing objectives. Such decisions are not easy to make, even when the “performance” of various options has been simulated using computer models. Additional information, either derived from the model outputs or drawn from other sources, can greatly improve the quality of the decision. Are the uncertainties in the model outputs well understood? What are the risks that different courses of action will fail to work? How can we make sure we have considered all possibilities, and select optimal solutions across many competing objectives? And how can we consider scientifically verified or calibrated model outputs alongside the diverse views and interests of many stakeholders? The way that scientific knowledge is presented to decision makers is critical; the value of decision support tools can be greatly increased if outputs are presented in ways that are relevant to the decision context and easily understood by all stakeholders, including those with non-technical backgrounds. A structured decision process, that is easy to use and makes maximum utility of modeling capability, combining model quantification with more qualitative but none-the-less influential considerations, can result in better understanding and hence more sustainable choices. A key component of the eWater endeavour is to add value to its portfolio by incorporating aspects of “decision science” into the toolkit.

Integrated water management decisions require holistic consideration of different concerns and objectives, available water resources, needs and uses, and the multitude of physical, social and economic influences that affect the performance of the entire water system. Effective tools to assist in such decisions must therefore have the ability to represent critical aspects of the system, combining sciences from different disciplines to work together at various geographic and temporal scales. A common model structure that is used to integrate various hydrological and ecological component models has been developed by eWater CRC. The common model structure, together with the decision framework described in this paper, forms the conceptual architecture of the eWater product offering. The challenge facing the decision science group is to identify generic capability in risk, uncertainty, optimisation and multi-criteria assessment that can be integrated into the modeling platform and toolkit, so that it can be usefully applied to the variety of water management decisions that eWater is seeking to support.

This paper describes the eWater decision support framework, and the interconnections between components of decision science and simulation models, that are being developed and tested by the eWater decision science group. The paper has five sections; Section 2 outlines the eWater decision process, which provides a context for selecting suitable models and methods for comparing and choosing different options; in Section 3 individual elements of decision science are considered in more detail, and their interactions and roles within the decision process are discussed in Section 4; concluding remarks are provided in Section 5.

2. THE EWATER DECISION PROCESS

The first step in enhancing the value of eWater models for decision makers was to understand their role within the decision process. A generalised decision framework based on common practice in many different disciplines and professional experience was developed by the architecture team. The framework represents a generic process that is suitable for addressing the kind of problems facing water managers, and similar frameworks can be found in, for example, the discipline of systems analysis (Gibson et al 2007a, Dandy et al 2008). It was tested on a number of integrated water management problems during the course of an eWater science workshop. Hypothetical problems ranged from finding optimal catchment restoration options in rural riparian environments with diminishing river flows, to selecting options for long-term, integrated urban water planning for cities. The decision process was refined and finalised using experience gained at the workshop.

The eWater decision process starts with problem definition, which involves articulating the problem, setting goals, and agreeing what performance measures and methods will be used to demonstrate that the goals have been met. Although goal-setting is not the subject of specific research within eWater CRC, the importance of getting this first step right cannot be overstated. Advice on how to go about agreeing goals and setting objectives can be found in the literature of various disciplines. For example, an easily digested process is described in (Gibson et al 2007b). Decisions made in water management will often have multiple goals, and each of these should be clearly articulated. For example, while supply security might be paramount in times of water scarcity, flood prevention and protection of the environment will also matter to stakeholders. With multiple goals it is likely that measures will relate to a number of different disciplines; for example, sustainability goals might require measures from the social, environmental and economic domains. There is no need to reduce these to a single value; the sophistication of techniques now available in the decision science arena provides help for decision makers in multi-objective environments. In order to constrain the solution space, the context of the problem must be well defined for each discipline; spatial and temporal scales, limits and system boundaries must be agreed. Dependency relationships are identified and possibly some initial analysis is undertaken to help understand the extent of the problem, and hence the nature of possible solutions, in more detail. Possible actions, represented by variables that can be adjusted to produce different solutions (decision variables) are agreed; these are to some extent dependent upon the responsibilities and powers of stakeholders, who should be involved throughout the decision process. Initially the problem definition process was depicted as a sequence of events, but eWater researchers from different disciplines found that it is a highly iterative process, with no pre-defined starting point.

Once the problem is understood and the ways in which performance measures are to be calculated have been agreed, data are collected and system performance under different scenarios is modelled. Alternative solutions are developed (these represent different combinations and values of decision variables), modelled and evaluated. With knowledge of the performance of different solutions, decision variables can be adjusted and outcomes compared. Generally a shortlist of those options that appear most promising is prepared and further evaluation undertaken. A final comparison results in the selection of one option for implementation that is acceptable to all stakeholders. As with the problem definition process, evaluation and selection is iterative, and understanding gleaned along the way will often influence earlier steps, sometimes feeding back as far as problem definition.

The eWater Decision Framework is shown in Figure 1.

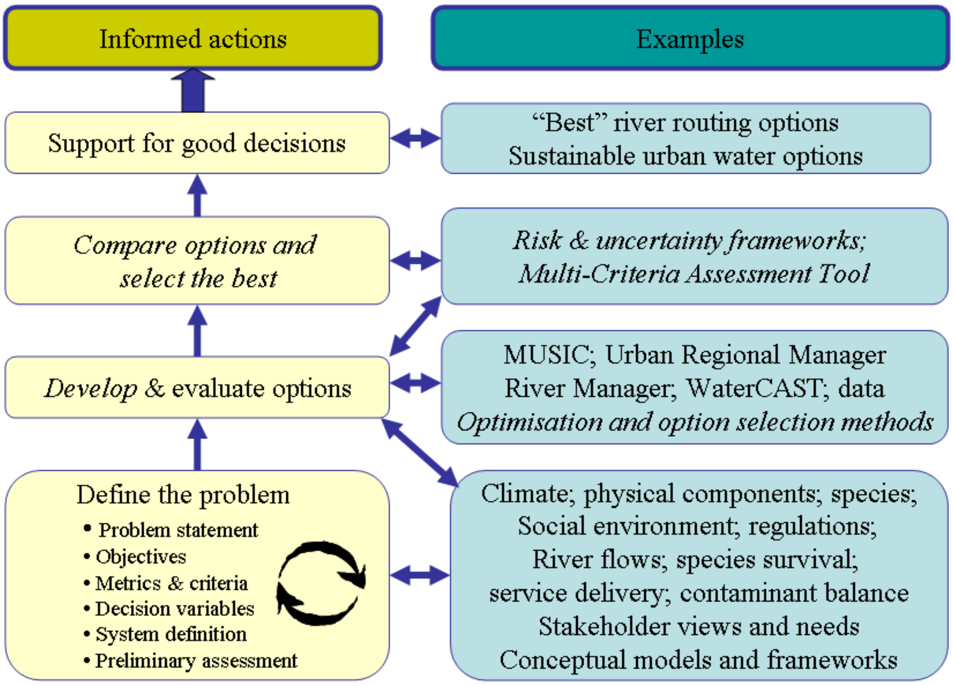

Figure 1: The eWater Decision Framework: a simple representation of a highly iterative process

3. ELEMENTS OF DECISION SCIENCE

Current awareness of the need for good decision support systems for the water management industry has led to the development of a multiplicity of tools. Many of these reflect an understanding of the need to either optimize solutions, evaluate risks, involve stakeholders or, to a lesser extent, acknowledge and work with a great deal of uncertainty. Few if any consider how these techniques can be brought together, to make maximum use of the power of simulation models and provide scientifically sound input to a decision process that might itself be part of an adaptive management process. The eWater decision science group focuses on methods to develop and compare options and select the "best", the activities shown in italics in Figure 1. In this section, we look at the value of these individual components of decision science.

3.1. Risk and Resilience

Good management decisions do not simply focus on the way a system performs when all is going well. They take into account the risk of the system failing, and its inherent resilience. Risk has two components, frequency (or likelihood) and consequence (or impact), which together inform our expectation of undesirable outcomes. From the risk point of view, a system is made up of interacting components, forces and influences, some of which can be controlled or adjusted by stakeholders (often called "controls", and represented in models as decision variables), and others (often exogenous, such as climate change, and sometimes referred to as "drivers") which cannot. Adjusting controls leads to different outcomes, and the aim of adaptive management is to preempt failure and adjust system controls (or choose less risky options) when risks become unacceptably high. Controls and the consequences of adjusting them follow a causal path (or impact chain). For example, dam releases are calculated, instructions relayed, valves are opened, water flows, sediment is transported changing the geomorphology of the river, and habitat and food availability are altered impacting on species survival. If flows and feedbacks along the causal path are understood, points along it can be identified and appropriate control measures taken when the situation becomes too risky. Simulation models provide an ideal tool for calculating response to multiple scenarios and testing the effects of different control strategies (Yum et al 2007).

While current risk assessment methods are useful where frequencies and consequences are well understood, they have their shortcomings when dealing with low probability, very high consequence events, a situation often encountered in water management. Low probability events have the added disadvantage that accurate data are often hard to come by. Where consequences are extremely high, stakeholders are often concerned with avoiding or controlling impacts, however unlikely or unknown the causal path. This perception is reflected in the Precautionary Principle, which states that "Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation" (United Nations 1992). "Value at risk", a technique used to evaluate critical risks in the domain of financial risk assessment (Jorion 2007), shows promise of providing a method for incorporating special consideration of risks of high consequence rare events into the eWater modeling platform. Other techniques used in financial decision making, such as options approaches, might further enhance the eWater decision process (Dixit and Pindyck 1994).

Resilience is a term that has different meanings within different disciplines, but in general it can be considered to be a desirable property of a system that enables it to respond to shocks and return to a satisfactory state of functionality within a reasonable time. Attempts have been made to quantify or predict the resilience of hydro-ecological systems, with limited success. Efficiency, another property that is often seen as desirable and sought after by system managers, is in a sense a counterpart to resilience, and moves towards achieving efficiency can unwittingly lead to system collapse. A simple example, albeit more closely related to risk than resilience, is that of increasing pressure in reticulation pipes to achieve higher flows, leading to an increased number of burst pipes and possible catastrophic failure of the system. In more complex systems the gradual removal of redundancy (for instance, alternative pathways to find new habitat) can remove flexibility for mitigation when disaster strikes. Performance indicators that flag when management decisions are potentially undermining the resilience of the system could be incorporated into risk assessment to provide a valuable addition to the option selection process (Blackmore and Plant 2007). eWater is seeking to identify such indicators for inclusion in risk assessment (Wang and Blackmore 2009)

3.2. Uncertainty

Little of the knowledge that we bring to the decision table is entirely certain. Uncertainties can be intrinsic (the result of natural randomness), epistemic (limited by the amount of available data or our limited knowledge of a particular process), or the result of something that has not yet been thought of (Donald Rumsfeld's "unknown unknowns") (Rumsfeld 2002). While in some circumstances it might be sufficient to make decisions based on fixed (often mean) values, very different choices might be made if the extent of uncertainty on inputs to the decision process and its impact on outcomes was better understood. Uncertainty can be expressed as a probability distribution function, and the ability to track uncertainty through eWater's models is currently being built into the modeling framework (Perraud et al 2007).

Understanding uncertainty is a necessary part of risk assessment. Without uncertainty there is no risk; the risk of an event occurring that has a defined outcome is simply the probability of its occurring; and the risk of possible events to a vulnerable population depends upon the probability (and hence uncertainties) of the event occurring and its impacts. For example the risk of a dam running out of water is simply the probability of that event. The risk to the town of sourcing its water supply from a single dam, however, has a range of undesirable consequences (for example, the number of months spent in restrictions, loss of recreation amenity, loss of biodiversity), each of which has a different probability of occurring. In both cases simulation modeling is used to understand the impact of events; in the second case uncertainty is only part of the risk assessment process, and risk is expressed as a matrix or risk curve.

3.3. Optimisation

Selecting the "best" option from a multitude of possible solutions, in the face of many and possibly conflicting objectives, is a challenge faced by many water managers. For example, in the urban planning area the question might be asked "how many houses should be connected to a stormwater reuse system to give the most effective performance in terms of water supply reliability, energy consumption and capital cost?", or, in river management, "how can we operate our dams so that the months per year over which water levels are less than 20%, the months per year over which water restrictions apply, and the operating cost, are optimized?" Without guidance and a rigorous process in place, viable options can be overlooked and "guesses" can result in sub-optimal solutions. Computational approaches to optimization can provide comprehensive consideration to the whole decision space (thus avoiding missed opportunities), rejecting solutions that are obviously less satisfactory than others and generating a "Pareto front" of optimal solutions that satisfy multiple objectives (Kingston et al 2008, Broad et al 2005). Solutions selected from the Pareto front can then be taken to the decision makers to consider for final selection.

eWater is building generic optimization capability, using genetic algorithms, into its core simulation models. Metamodelling techniques are being considered to increase the efficiency of the optimisation process. Visualisation of the Pareto Front, allowing the user to understand the properties of the alternatives represented, will be an important component of this work.

3.4. Stakeholder Involvement and Multi-criteria Assessment

Water management decisions are likely to succeed only if the proposed changes are accepted and implemented by all relevant stakeholders. This can be achieved by gaining acceptance through a transparent decision making process, and acknowledging and valuing the experience of all stakeholders. Ideally, consultation will take place throughout the decision making process. Stakeholder agreement is especially important at the start of a project when goals and objectives are being set and options selected, and again at the conclusion when a final choice is being made. There is a period however when options have been agreed and detailed evaluation of system performance is underway, during which consultation might not be needed as the analysts and modelers go about their business.

CSIRO, in conjunction with eWater, has developed a decision support tool, MCAT that uses multi-criteria analysis to assist in selecting a preferred option where several are available, and to help select the most beneficial actions from a list where there are budget constraints (Marinoni et al 2009). Decision options are first identified and criteria set. Criteria are then weighted, and options ranked according to their utility score. MCAT offers linear and non-linear transformations for obtaining criteria score values.

4. COMBINING ELEMENTS OF DECISION SCIENCE

There is clear evidence that each element of decision science described above can assist in the selection of significantly better options, and hence improve the sustainability of water management decisions. The challenge facing eWater is to bring the techniques together within a single framework. At the core of the framework are the simulation models, which each decision science component uses in a different way. With uncertainty protocols included in the models, multiple runs (for example, Monte Carlo simulation) can provide evaluation of the consequences and probabilities of events. Model outputs can inform a wider risk assessment, providing better understanding of "worst case" scenarios, for example; and genetic algorithms can be linked to the models to progressively adjust decision variables to achieve optimal levels of performance. The performance of different options generated by the models can help inform stakeholders of risks and consequences during a multi-criteria assessment process.

Figure 2, which represents the activities highlighted in italics in Figure 1, shows a representation of the various components and the links between them. The core models use input data to predict system performance (P1 – Pn in Fig. 2). Different aspects of performance are then optimized, and a Pareto surface of optimal solutions is generated. From this, a shortlist of possible solutions is selected, any additional analysis is undertaken if required, and knowledge of how each option will perform is considered in the multi-criteria assessment process for the selection of a preferred option. If probability distribution functions (or any understanding of likelihood) are available for the model input data, risks associated with each of the shortlisted options can be calculated (R1 – Rn), and considered as performance measures in the multi-criteria assessment. Additional data and knowledge might be needed to assess all the risks that are of interest to the stakeholders, and stakeholders' views and personal experience provide additional input to the multi-criteria assessment.

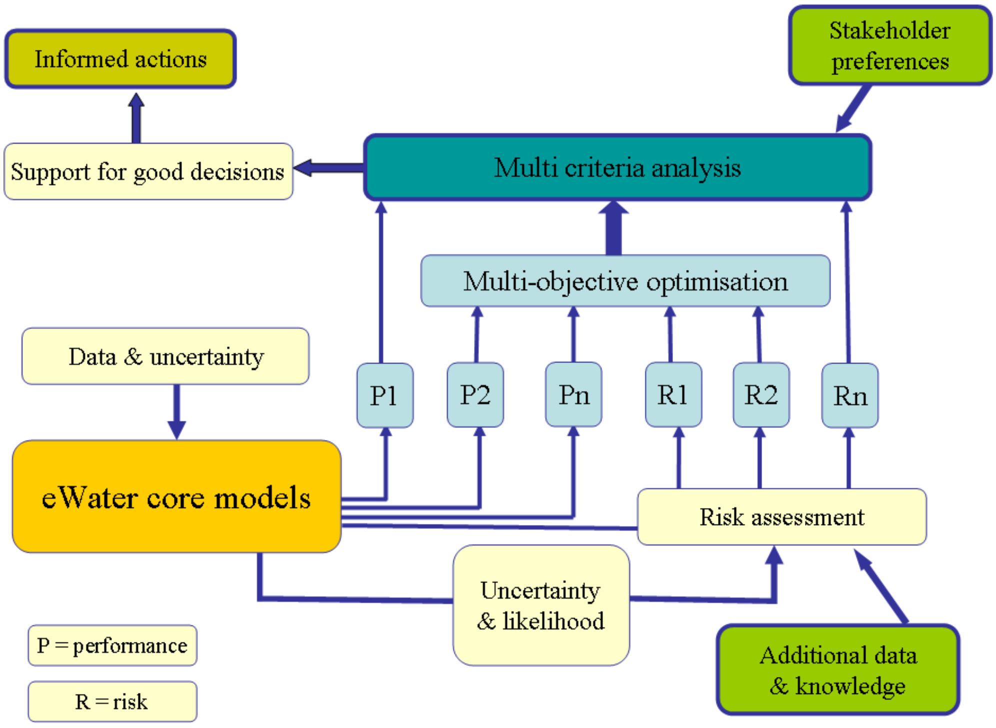

Figure 2: Integrating Components of Decision Science (feedbacks not shown)

The eWater decision science group has capability in each of the fields described above, and is linking the necessary functions into the eWater modeling framework. Individual and linked components will then be tested in real-world problems, in eWater Focus Catchment projects. Questions that are currently being explored include:

- Should risk be considered as an objective function and included in the multi-objective optimization, or should risk assessment only be undertaken on options that are already considered optimal?
- Are there aspects of system performance, either predicted by the simulation models or understood in other ways, that should not form part of the multi-objective optimization process but nonetheless be included in multi-criteria assessment?
- The Pareto Surface generated by the multi-objective optimization represents numerous acceptable solutions. Can we generate rules or processes to identify which of these should be shortlisted and taken to the multi-criteria assessment process? And how do we handle uncertainty in the points on the Pareto Surface?
- Stakeholder involvement is desirable throughout the process (Fig 1), if the final choice is to be well received by all involved. It is critical at the problem definition stage, in selecting a shortlist and for final selection. Can we further define the roles of and boundaries around stakeholder input in our decision process?
- Aspects of decision science require multiple runs of simulation models, which can lead to prohibitively long run times. Can Artificial Neural Networks and other metamodelling techniques be used to speed up the sampling process used to optimize decision variables and identify high impact events for risk assessment?
- Can aspects of decision science share computational functionality, to add efficiency and help speed up the process?

5. DISCUSSION AND CONCLUSIONS

Decision making is a dynamic, anthropogenic process that is, at most, *informed* by scientific analysis. While simulation models can provide valuable assistance, the accuracy of their outputs and the way in which they are presented and used can substantially alter the decision being made and the value of the outcome. For example, optimization of urban water pipework systems has been demonstrated to save up to 50% of capital cost on major projects (Dandy 2009).

eWater is developing powerful simulation models to assist the water management industry in its decision processes. Without incorporation into transparent decision frameworks, much of the value of the modeling will not be realized. The common computing framework in which these models are built and interact lends itself to incorporation of generic decision science capability. The eWater decision framework, together with readily available components of decision science for risk assessment, optimisation and multi-criteria analysis within the eWater toolkit, and the integration of different components to provide a total decision process, will greatly enhance the value of the models.

ACKNOWLEDGMENTS

The Authors would like to thank eWater CRC for funding this work, and members of the Decision Science group at CSIRO Sustainable Ecosystems, the University of Newcastle and the University of Adelaide.

REFERENCES

Blackmore, J.M and Plant, R.A.J (2008), Risk and resilience to enhance sustainability with application to urban water systems, *Journal of Water Resources Planning and Management*, American Society of Civil Engineers, 134 3, May, 224-233

Broad, D, Dandy, GC and Maier, HR. (2005), Water distribution systems optimisation using metamodels, *Journal of Water Resources Planning and Management*, American Society of Civil Engineers, 131 (3), May, 172-180

Dandy, G.C. (2009), Personal correspondence with J. Blackmore

Dandy, G, Walker, D, Daniell, T and Warner, R (2008), Planning and Design of Engineering Systems, Second Edition, Taylor & Francis, London, 51-88

Dixit, A.J. and Pindyck, R.S. (1994), Investment Under Uncertainty, Princeton University Press, 468 pp, Princeton, New Jersey, USA

eWater CRC (2009), http://www.ewatercrc.com.au/

Gibson, J.E, Scherer, W.T. and Gibson, W.F. (2007a), How to do Systems Analysis. John Wiley, New Jersey, USA 29 - 48

Gibson, J.E, Scherer, W.T. and Gibson, W.F. (2007b), How to do Systems Analysis. John Wiley, New Jersey, USA 55 - 85

Jorion, P. (2007) Value of Risk: The New Benchmark for Managing Financial Risk, Third Edition, McGraw-Hill, 602 pp, New York

Kingston G.B., Dandy G.C. and Maier H.R. (2008) Review of artificial intelligence techniques and their applications to hydrological modeling and water resources management Part 2 – optimization. In Robinson, L.N. (ed), Water Resources Research Progress, Chapter 2, Nova, 67-99.

Marinoni, O., Hajkowicz, S., Higgins, A., Collins, K., (2009) An investment decision support system for improved water management, *Environmental modelling and software.* 153-164.

Perraud, J.-M, Kuczera, G. and Bridgart, R. (2007), Towards a software architecture to facilitate multiple runs of simulation models, *MODSIM 2007* International Congress of Modelling and Simulation, Christchurch, New Zealand, December 10 -13

Rumsfeld D.H. (2002) USA Department of Defense news briefing, Feb. 12

United Nations (1992) The "Rio Declaration", United Nations Conference on Environment and Development, Rio

Wang, C-S and Blackmore, J (2009) Resilience Concepts for Water Resource Systems, *Journal of Water Resources Planning and Management*, American Society of Civil Engineers, accepted for publication April

Yum, K.-K., Blackmore, J. (2007) Systems Modelling for Sustainable Performance - a Risk Management Approach, Systems Engineering Test and Evaluation Conference – Complex Systems and Sustainability, Sydney, Australia, September,24-27

Yum, K.-K., Blackmore, J., Wang, X., Diaper, C., Zhou, M., Wang, C.-H., McGregor, G., Anticev, J. (2007) Integrating Risk Management into Water Planning and Management Industry. eWater CRC Technical Report, Canberra, Australia