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

A Bayesian Network approach to integrating economic and biophysical modelling

Kragt, M.E.[a,b], **L.T.H. Newham**[a] **and A.J. Jakeman**[a]

[a] *Integrated Catchment Assessment and Management (iCAM) Centre, The Fenner School of Environment and Society, The Australian National University, Canberra, ACT 2600, Australia*
[b] *The Crawford School of Economics and Government, The Australian National University, Canberra, ACT 2600, Australia*
Email: marit.kragt@anu.edu.au

Abstract: It has been recognised that the complex interrelationships between environmental processes and socio-economic systems require integrated approaches to catchment management (Cai et al., 2003; Jakeman and Letcher, 2003;). Until recently, integrated modelling tools were often limited to either biophysical processes to assess environmental changes, or to economic models focussing on socio-economic systems. Despite the policy interest in integrated catchment management, there is still limited experience in linking environmental and socio-economic systems in one modelling framework (Heinz, 2007; Reinhard, 2006).

The study reported in this paper aims to demonstrate how biophysical science can be linked with economic non-market valuation in an integrated Bayesian Network (BN) framework. In the context of this study, a BN was deemed a suitable modelling technique to integrate the various systems impacted by catchment management changes. The model can incorporate data of different types and quality, and its structure provides an explicit depiction of the uncertainties in environmental and economic systems. We develop an integrated model for a case study of the George catchment in northeast Tasmania, Australia. The modelling framework incorporates a water quality model, ecological information and economic data (Figure 1). The major innovations of the research reported here are the parallel development of the various models, enabling increased integration, and the use of an environmental valuation technique known as Choice Experiments (CE) to elicit economic information on the non-market costs and benefits of catchment management changes. To the best of our knowledge, CE data has not previously been linked to biophysical modelling in a BN framework. Furthermore, the biophysical modelling provides more scientific foundation for the valuation study than is typically available (Brookshire, 2007).

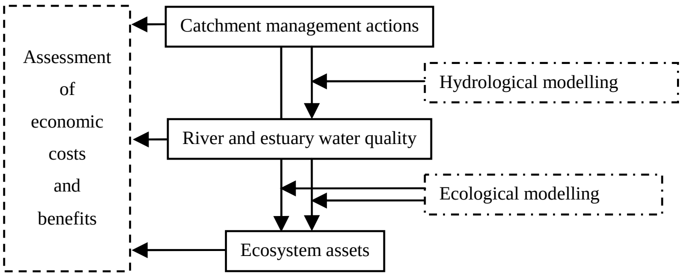

Figure 1. Processes considered in the integrated biophysical-economic model

In this paper, an overview is given of the BN development process that integrates CE with natural science modelling. Specific issues related to linking economic and biophysical knowledge include the selection and description of catchment environment indicators relevant for all research components, and matching the variables' states in the BN to the levels of the environmental attributes in the CE survey. Several of the challenges in developing an integrated, multidisciplinary model are discussed in this paper.

Keywords: *Knowledge integration, Bayesian networks, catchment modelling, integrated modelling, non-market valuation*

1 INTRODUCTION

Integrated catchment management aims to maintain the wide variety of catchment values, including those associated with water quality and quantity, conservation of natural resources, agricultural production, recreation and other economic activities (Heinz, 2007). An increasing number of modelling tools are being developed that aim to support integrated catchment management (Argent, 2004). However, despite the policy interest in integrated catchment management, and the identified need for decision support tools (e.g. Liu, 2008), there is still limited experience in developing catchment models that evaluate environmental and economic trade-offs in a single framework.

The study reported in this paper aims to demonstrate how biophysical science can be linked with economic non-market valuation in an integrated Bayesian Network (BN) framework. An integrated catchment model was developed for a case study of the George catchment, Tasmania. In this paper, an overview is given of the integration process to date, and the challenges that have been encountered in linking economic and biophysical knowledge.

2 METHOD

The central processes considered in the integrated framework developed here include catchment management actions, hydrological response, effects on river and estuary water quality, ecological changes and impacts of changes on economic values (Figure 1). A suite of models was developed to predict how changed catchment management may impact biophysical and socio-economic systems[1]: (1) a process-based water quality model enabled assessment of nutrient and sediment loadings; (2) probability-based ecological models predicted how changes in water quality impact selected ecosystem assets; and (3) an economic valuation study using Choice Experiments (CE) estimated the marginal values associated with changes in several catchment environmental assets (called ‘attributes’ in a CE).

Synchronous model development, rather than using existing models, ensured tailored information exchange between models. The biophysical and economic systems are integrated in a Bayesian Network (BN) model that enables decision makers to analyse the tradeoffs between catchment environmental conditions and the costs and benefits associated with changes in catchment management.

2.1 Bayesian Networks

A major challenge in any integrated modelling study is to combine knowledge from different disciplines into a logically consistent framework. Most integrated catchment models employ holistic and/or coupled component modelling techniques to link the various systems under consideration. However, these techniques require substantial data and their complexity can restrict widespread application of integrated models (Ticehurst, 2007). Moreover, many environmental and socio-economic processes are not well understood and are subject to uncertainty. Using a deterministic model that relies on quantitative data will not be useful when there is limited information about a system. BNs can be used to represent knowledge and reasoning under uncertainty (Castelletti, 2007). A BN consists of a directed acyclic graph of system variables (called ‘nodes’). The values each variable can assume are classified into mutually exclusive ‘states’. These states can be defined as quantitative levels or as qualitative categories, enabling the use of different data sources, including expert opinion when observational data are not available (Jensen, 1996). The propagation of information between nodes is described by conditional probability distributions. Unlike most integrated modelling approaches, BNs thus use probabilistic, rather than deterministic, expressions to describe the relationships between variables (Borsuk, 2004).

There is a rising interest in BNs as a modelling tool in a catchment management context (McCann, 2006; Castelletti, 2007; Kragt, 2009). BN models can represent the uncertainty that inherently arises from the variability in natural systems (Walker, 2003) as well as the imperfect knowledge and information about ecosystem functioning. There are, however, few BN applications that link environmental changes to economic impacts. Only one BN study has been published to date that incorporates non-market costs and benefits of catchment management changes (Barton, 2008). However, the biophysical modelling in that study was restricted by the nature of the available economic information. Synchronous collection of data would have been more useful, to improve information exchange between models and to increase the integration of biophysical and economic knowledge.

[1] Details of each model and how they have been used to generate probability distributions will be published elsewhere

2.2 Choice Modelling

The economic non-market valuation study used CEs to elicit community preferences towards changes in catchment environmental conditions. In a CE survey, respondents are presented with a series of choice questions describing several possible alternative futures, each with different levels of environmental attributes. Respondents are asked to choose their preferred option in each choice question. This allows analyses of the trade-offs that respondents make between attributes. If cost is included as one of the attributes, these trade-offs can be used to estimate the marginal value of each environmental attribute in monetary terms.

For the present study, a CE survey was developed using a combination of literature review, interviews with science experts and regional natural resource managers, biophysical modelling and feedback from focus group discussions (Kragt, 2008). An example choice question is shown in Figure 2. The survey was administered in Hobart, Launceston and St Helens between November 2008 and March 2009.

Question 4

Consider each of the following three options for managing the George catchment.
Suppose options A, B and C are the **only ones** available.
Which of these options would you choose?

Features	Your one-off payment	Seagrass area	Native riverside vegetation	Rare native animal and plant species	YOUR CHOICE
Condition now		690 ha (31% of total bay area)	74 km (65% of total river length)	80 rare species live in the George catchment	
Condition in 20 years					Please tick one box
OPTION A	$0	420 ha (19%)	40 km (35%)	35 rare species present (45 no longer live in the catchment)	☐
OPTION B	$60	815 ha (37%)	81 km (70%)	50 rare species present (30 no longer live in the catchment)	☐
OPTION C	$30	690 ha (31%)	74 km (65%)	65 rare species present (15 no longer live in the catchment)	☐

Figure 2. Example CE choice question

3. SCALE AND SCOPE

3.1 Selecting a study area

The study reported here focussed on coastal catchments in Tasmania, Australia. The first step in the modelling process was the selection of a case study area that was suitable for both the scientific and socio-economic research. For the biophysical modelling component, there needed to be a demonstrated impact of catchment management actions on freshwater and estuary water quality and ecology. Another important criterion was the availability of quantitative biophysical data. For the socio-economic research, the presence of environmental assets was important, as potential attributes for the valuation study. Furthermore, natural resource degradation needed to be related to local catchment management and the catchment estuary needed to have economic value.

Figure 3. Location of the George catchment, TAS

The 557 km^2 George catchment, located on the north-east coast of Tasmania (Figure 3), was selected as a suitable study area because hydrological and water quality data were available and because the catchment has significant socio-economic significance through its production, recreation and non-market values. Although the catchment environment is currently in good condition (Walker, 2006), dairy runoff, forestry operations and urban pollution are affecting water quality in the George catchment (NRM North, 2008). There are significant concerns about degradation of the catchment environment (BOD, 2007; Lliff, 2002). Local natural resource management actions include limiting stock access to rivers, treatment of dairy effluent, improving wastewater treatment, revegetation of riparian buffer zones and weed management.

3.2 Selecting variables

In the integrated BN, scientific modelling was to predict changes in environmental attributes of interest for the socio-economic research. The chosen indicators of catchment condition needed to be relevant from a natural science perspective, important to policy makers and suitable to be included as attributes in the CE.

Important environmental indicators of catchment condition were identified based on extensive literature review (e.g. BOD, 2007; DPIW, 2005; Lliff, 2002), discussions with local policy makers and science workshops with experts on river and estuary health[2].

The catchment management actions modelled were: land use changes, erosion and pollution control and riparian management. Scientists sought to represent all the processes related to catchment management changes in extensive detail, resulting in a conceptual framework with nearly eighty variables. It was not feasible to collect data on that many variables and to specify the relationships between all of them. A balance needed to be found between model parsimony and detailed representation of catchment processes. The in-depth biophysical information envisaged by natural scientists would have been impossible to present in a non-market valuation survey. Additional rounds of workshops and expert consultation therefore aimed to identify the *most important* variables that scientists expected to be impacted by catchment management. The final set of variables included in the BN represent a compromise between the detailed depiction of system complexities sought by biophysical scientists and the parsimony desirable from a modelling perspective (Figure 4).

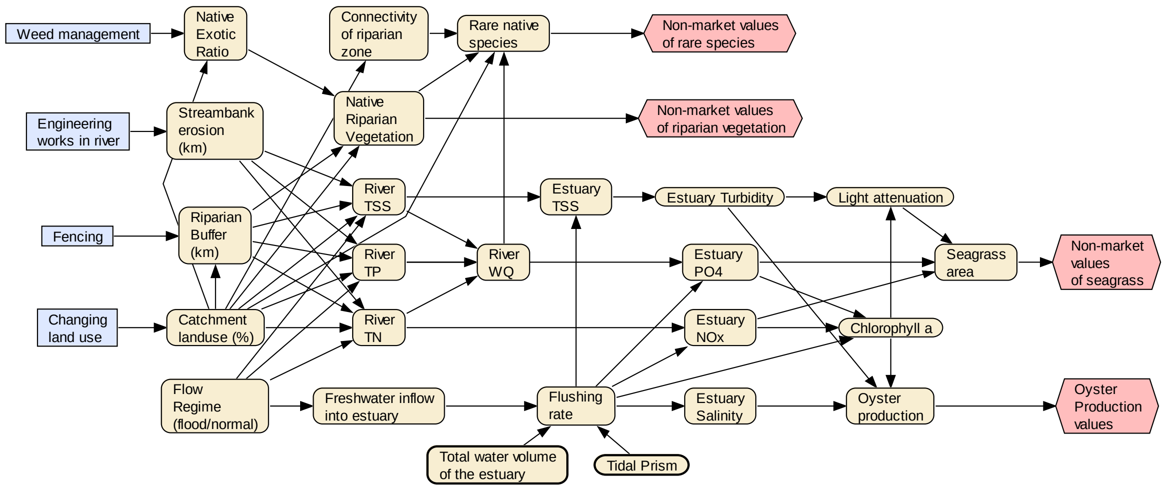

Figure 4. Graphical representation of the integrated BN model for the George catchment

Scientists were challenged to define ecological indicators of water quality and catchment conditions that would be appropriate to include in the valuation study. Experts initially found it difficult to think beyond chemical indicators (such as salinity or nutrient concentrations), or the abundance and species composition of benthic macro-invertebrates as indicators of water quality. However, more 'visual' assets were needed to represent catchment conditions to respondents in the valuation survey. Expert consultation and focus group discussions were used to select environmental attributes. Because scientific data was not available for all suitable attributes (for example, there was no information on fish populations), the three final attributes selected as indicators of environmental conditions in the George catchment were seagrass, rare animal and plant species and riparian vegetation.

3.3 Describing variables

The selected attributes for the valuation study were also the final output nodes in the overall BN framework (Figure 4). The output nodes and environmental attributes needed to be evaluated in identical terms. Natural scientists and economists needed to agree on the description of each attribute, the units of measurements and the potential levels that each attribute could assume. Similar to experiences reported by Brookshire (2007), natural science experts sought to describe each variable in extensive detail. However, the attribute description in the CE survey, whilst based on scientific predictions, needed to be simple and brief to convey information to survey respondents in a readily digestible manner. Measuring attributes in quantitative units (desirable from an environmental valuation perspective) posed an additional challenge, as deterministic ecological information was difficult to obtain. A broad range of measurement units and attribute levels were discussed with natural science experts, economists and focus groups. The final description of the attributes is a compromise between scientific views and the economic valuation requirements (Table 1).

[2] Interviews were conducted with experts on river health, threatened species, bird ecology, forestry management, riparian vegetation and estuary ecology.

Table 1. Output nodes, their units of measurement and description in the George catchment model

Output node	Measurement units	Description in the choice experiment survey
Native riparian vegetation	The percentage of total riparian zone in the George catchment with intact vegetation, of which at least 70 percent is native vegetation	Native riverside vegetation in healthy condition contributes to the natural appearance of a river. It is mostly native species, not weeds. Riverside vegetation is also important for many native animal and plant species, can reduce the risk of erosion and provides shelter for livestock.
Rare native animal and plant species	The number of different native Tasmanian flora and fauna species listed as vulnerable, endangered or critically endangered listed under Tasmania's *Threatened Species Protection Act*, with more than one observation in the Natural Values Atlas (DPIW, 2008).	Numerous species living in the George catchment rely on good water quality and healthy native vegetation. Several of these species are listed as vulnerable or (critically) endangered. They include the Davies' Wax Flower, Glossy Hovea, Green and Golden Frogs and Freshwater Snails. Current catchment management and deteriorating water quality could mean that some rare native animals and plants would no longer live in the George catchment.
Seagrass area	The area in hectares of dense seagrass (*Heterozostera tasmanica* and *Zostera muelleri*) beds mapped in the estuary	Seagrass generally grows best in clean, clear, sunlit waters. Seagrass provides habitat for many species of fish, such as leatherjacket and pipefish.

4 INTEGRATED MODELLING RESULTS

The main objective of the study described in this paper was to provide a method for integrating economic analyses and environmental modelling into a single, comprehensive framework. The study goes beyond simply linking the outputs from multiple single-disciplinary models. Water quality, ecological and economic models were 'translated' into Bayesian networks, resulting in one integrated BN framework. In this section, the linkages between the economic valuation study and the BN model are described.

Results from the water quality model, CatchMODS (Newham et al. 2004), provided predictions of changes in river flow, sediment and nutrient concentrations. Ecological changes were predicted using a combination of observed data, expert consultation and assumptions in separate probabilistic BN models for each environmental attribute included in the CE survey.

The levels of the environmental attributes presented in the CE survey were based on predictions from the ecological modelling. Although realistic, the attribute levels predicted by the biophysical modelling were not ideal from an econometric modelling perspective. CE modelling is advanced when an equally distributed' range of levels is used. The attribute levels were therefore a compromise between the economic requirements and natural science predictions.

The CE technique was considered the most appropriate environmental valuation technique in this context, as it presents multiple levels for separate environmental attributes. These attributes and levels could readily be linked to the output nodes in the BN model, with discrete node states directly corresponding to the attribute levels presented in the CE survey (Table 2). Estimating the *marginal values* of a change in these attributes is currently underway. Such values will be linked to the BN model to present the costs and benefits of environmental changes in one framework.

Table 2. States and levels of the BN final nodes and CE attributes

Node Variable	BN states	CE levels*
Native riverside vegetation (%**)	< 40 40 - 60 60 – 70 > 70	35 (40km) 50 (56km) **65 (74km)** 75 (84km)
Seagrass beds in Georges Bay(ha)	< 490 490 – 620 620 – 760 > 760	420 560 **690** 815
Rare native animals and plant species (number)	< 40 40 – 60 60 - 70 > 70	35 50 65 **80**

* Observed levels in bold, ** levels were presented as the % of total river length as well as the absolute length in km.

5 DISCUSSION

Several challenges that apply to interdisciplinary research and the development of integrated models were revealed in this study. Frequent communication was required between various academic disciplines and with non-academic participants, such as NRM bodies and community members. The study challenged scientists to think beyond disciplinary boundaries. The use of different languages between the natural sciences and economics (e.g. 'asset' versus 'attribute', or 'node' versus 'variable') and sometimes limited understanding of other disciplines posed a challenge for model developers. Hydrological modellers, ecologists and economists all had their own idea of how detailed the model should be. Although ecologists wanted to capture the complete system processes, the level of detail needed to be limited for practical purposes. Discussions between scientists also involved the data compatibility between the different sub-models. The spatial and temporal dimensions of the various models as well as the variables and their units of measurement needed to be the same. The variables needed to be relevant to all stakeholders, including scientists, economists, decision makers and CE survey respondents. Many disparities were encountered between what qualified as key indicators from a biophysical perspective and what were relevant assets from an economic valuation point of view. Furthermore, the *description* of variables in the CE survey needed to match natural science definitions, while the measurement *units* needed to suit the valuation exercise. For example, natural scientists favoured qualitative ways to describe environmental changes, while quantitative attribute levels would benefit the CE study. The final set of variables and their description represent a compromise between science and economics.

Developing a conceptual model with the most *relevant* variables, defining the relationships between variables and describing their levels based on sound scientific predictions was a lengthy and iterative process. Considerable efforts were made to collect as much appropriate information as possible within the time frame of this study. However, the availability of data about biophysical and socioeconomic processes in Tasmanian catchments is limited. Obtaining detailed, quantitative information about the environmental attributes was limited by the availability of current scientific knowledge.

The model development described in this paper was a science-driven process. This was considered appropriate for demonstrating a modelling technique to link environmental and economic variables. It is worth mentioning that for development of a *decision support tool*, further involvement of policy makers and (local) stakeholders would be desirable.

6 CONCLUSION AND FURTHER STEPS

Catchment decision-makers face a wide range of management issues that involve complex environmental and socio-economic systems. To support efficient catchment management and investment in protection and remediation, biophysical modelling tools need to be integrated with economic techniques. There are currently few studies that integrate natural science models with non-market economic valuation. This research addresses this knowledge gap by demonstrating modelling techniques that combine science-based biophysical modelling and non-market valuation in a single framework. An integrated model was developed for the George catchment, but the techniques are straightforward enough to apply in other catchments.

In the context of this study, a BN provided a suitable modelling approach to integrate economic valuation and biophysical modelling. The graphical representation of a BN displays the links between different system components. This facilitated discussions of the conceptual model structures with various scientists and decision makers. The BN accommodates source data of differing type and quality and represents uncertainties in the form of probability distributions. This approach provides a more explicit depiction of system uncertainty than is usually the case in integrated models. However, defining the probability distributions can be a lengthy and difficult process.

The use of a CE enabled a valuation of changes in multiple environmental attributes on a stepwise scale. Results from the CE study could readily be linked to the output nodes of the BN, through a matching of attribute levels and node states. Contrary to previous BN studies that aimed to integrate valuation and environmental modelling, the biophysical and economic models were jointly developed, enhancing the data compatibility between models. The use of biophysical models to predict changes in the CE attributes thus provided a better scientific foundation than is typical in environmental valuation studies.

Work is continuing to ‘validate’ the models through comparison with observed data and additional rounds of expert reviews. Additional monitoring data and advanced modelling of the ecological components is required to achieve a more sophisticated representation of the interactions between natural systems and their subsequent impacts on socio-economic systems. Sensitivity and uncertainty analyses are required to aid further evaluation of the integrated model. It is important to assess the sensitivity of the outcomes to changes in model parameters, and the propagation of uncertainty in the linkages between models. There are currently no prescriptive guidelines about how to conduct an assessment of accumulated model uncertainties (Brouwer, 2008). Further work is formulating an approach to perform structural uncertainty analyses of the model.

ACKNOWLEDGEMENTS

This research is supported by the Environmental Economics Research Hub and Landscape Logic, both of which are funded through the Australian Commonwealth Environmental Research Facility.

REFERENCES

Argent, R.M. (2004), An overview of model integration for environmental applications--components, frameworks and semantics. *Environmental Modelling & Software*, 19(3), 219-234.

Barton, D.N., T. Saloranta, S.J. Moe, H.O. Eggestad and S. Kuikka (2008), Bayesian belief networks as a meta-modelling tool in integrated river basin management -- Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. *Ecological Economics*, 66(1), 91-104.

BOD (2007), Break O'Day NRM Survey 2006 - Summary of Results. Break O'Day Council, St Helens.

Borsuk, M.E., C.A. Stow and K.H. Reckhow (2004), A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. *Ecological Modelling*, 173(2-3), 219-239.

Brookshire, D.S. et al. (2007), Integrated Modeling and Ecological Valuation: Applications in the Semi Arid Southwest, Workshop "Valuation for Environmental Policy: Ecological Benefits". US Environmental Protection Agency, Washington DC.

Brouwer, R. and C. De Blois (2008), Integrated modelling of risk and uncertainty underlying the cost and effectiveness of water quality measures. *Environmental Modelling & Software*, 23(7), 922-937.

Cai, X., D.C. McKinney and L. Lasdon (2003), An Integrated Hydrologic-Agronomic-Economic Model for River Basin Management. *Journal of Water Resources Planning and Management*, 129(1), 4-17.

Castelletti, A. and R. Soncini-Sessa (2007), Bayesian Networks and participatory modelling in water resource management. *Environmental Modelling & Software*, 22(8), 1075-1088.

DPIW (2005), Environmental Management Goals for Tasmanian Surface Waters. Dorset & Break O'Day municipal areas. In: W.a.E. Department of Primary Industries (Editor). Department of Primary Industries, Water and Environment, Hobart, pp. 38 pp.

DPIW (2008), Natural Values Atlas, http://www.naturalvaluesatlas.dpiw.tas.gov.au. Department of Primary Industries and Water, Hobart.

Heinz, I., M. Pulido-Velazquez, J. Lund and J. Andreu (2007), Hydro-economic Modeling in River Basin Management: Implications and Applications for the European Water Framework Directive. *Water Resources Management*, 21(7), 1103-1125.

Jakeman, A.J. and R.A. Letcher, (2003), Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling & Software*, 18(6), 491-501.

Jensen, F.V. (1996), An introduction to Bayesian networks Springer, New York

Kragt, M.E. and J. Bennett (2008), Developing a Questionnaire for Valuing Changes in Natural Resource Management in the George Catchment, Tasmania, Crawford School of Economics and Government, Australian National University, Canberra.

Kragt, M.E. (2009), Bayesian Network Modelling for Integrated Catchment Management, Landscape Logic Hobart.

Liu, Y., H. Gupta, E. Springer and T. Wagener (2008), Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modelling & Software*, 23(7), 846-858.

Lliff, G., 2002. George River Catchment: Plan for Rivercare Works for the Upper Catchment, North George and South George Rivers, St Helens.

McCann, R.K., B.G, Marcot and R. Ellis (2006), Bayesian belief networks: applications in ecology and natural resource management. *Canadian Journal of Forest Research*, 36(12), 3053-3062.

Newham, L.T.H., R.A. Letcher, A,J. Jakeman and T. Kobayashi (2004) A framework for integrated hydrologic, sediment and nutrient export modelling for catchment-scale management. *Environmental Modelling & Software*, 19(11), 1029-1038.

NRM North (2008), State of the Region: Water Quality and Stream Condition in Northern Tasmania 2006, Northern Water Monitoring Team, Launceston.

Reinhard, S. and V. Linderhof (2006), Inventory of economic models, Institute for Environmental Studies, Amsterdam.

Ticehurst, J.L., L.T.H. Newham, D. Rissik, R.A. Letcher and A.J. Jakeman (2007), A Bayesian network approach for assessing the sustainability of coastal lakes in New South Wales, Australia. *Environmental Modelling & Software*, 22(8), 1129-1139.

Walker, J., T. Dowling and S. Veitch (2006), An assessment of catchment condition in Australia. *Ecological Indicators*, 6(1), 205-214.

Walker, W.E. et al. (2003), Defining Uncertainty: A conceptual basis for uncertainty management in Model-Based Decision Support. *Integrated Assessment*, 4(1), 5-17.