Integrated hydro-economic modelling: experiences from an Australian catchment

Abstract:

Integrated catchment policies are used worldwide to manage catchment natural resources. Catchment management decision support tools are often limited in their integration of environmental processes with socio-economic systems. Fully integrated models are required to support assessments of the environmental and economic trade-offs of catchment management changes. A Bayesian Network (BN) model is demonstrated to provide a suitable approach to integrate environmental modelling with economic values. The model considers hydrological, ecological and economic systems in the George catchment in Tasmania. Information about non-market costs and benefits is elicited using Choice Experiments, allowing an assessment of the efficiency of alternative management scenarios.

Keywords: Integrated catchment modelling; Hydro-economic modelling; Bayesian networks; Uncertainty; Non-market valuation; Choice Modelling.

1 Introduction

Catchment natural resource managers are faced with complex decision problems that involve multiple systems and stakeholders, varying from environmental and ecological issues to social and economic concerns. Mono-disciplinary analytical methods and models that aim to predict the impacts of alternative policy decisions are typically insufficient to capture the complexities in the multiple catchment systems. *Integrated catchment management* is increasingly aimed at addressing the wide variety of catchment objectives and interests, including water quality and quantity, conservation of natural resources, agricultural production, recreation and other economic activities (Heinz et al., 2007). Modelling tools are increasingly developed that aim to support integrated catchment management (Argent, 2004). However, despite the policy interest in integrated catchment management (NWI, 2004, EU Commission, 2000), and the identified need for decision support tools (Liu et al., 2008, Acreman, 2005) there is still limited experience in developing catchment models that evaluate environmental and economic trade-offs in one framework (Heinz et al., 2007, Reinhard and Linderhof, 2006). Many of the existing tools have limited flexibility to deal with the multitude of systems and linkages between them. The scientific underpinning of economic studies is often limited (Brookshire et al., 2007) and environmental models generally lack appropriate economic system models (Brouwer and Hofkes, 2008).

Economics provides methods to better inform decision makers about the effects of alternative management strategies. *Economic valuation* studies are particularly useful to show how catchment management actions may impact non-market values. The study reported in this paper aims to demonstrate how biophysical science can be linked with non-market valuation in one integrated framework[1]. An integrated catchment model is developed for a case study of the George catchment, Tasmania.

The central processes considered in the integrated framework include catchment management actions, hydrological response, effects on river and estuary water quality, ecological changes and impacts of changes on economic values (Figure 1).

[1] This study is part of two larger research programs. The Landscape Logic project (http://www.landscapelogic.org.au/index.html) aims to develop decision support tools that simulate the impacts of land use changes on water flows and quality in selected catchments in Tasmania. The Environmental Economics Research Hub (http://www.crawford.anu.edu.au/research_units/eerh/) aims to address Australia's major environmental management challenges through integrated economic research encompassing the establishment of markets to achieve environmental goals, environmental valuation and the assessment and development of government intervention in environmental management.

A suite of models was developed to predict how changed catchment management may impact biophysical and socio-economic systems:

1) A process-based water quality model that enabled an assessment of nutrient and sediment loadings in streams and estuary;

2) Probability based ecological models to predict how changes in water quality would impact selected ecosystem assets;

3) An economic valuation study using Choice Experiments (CE) aimed at estimating the marginal values associated with changes in multiple catchment assets (called 'attributes' in a CE).

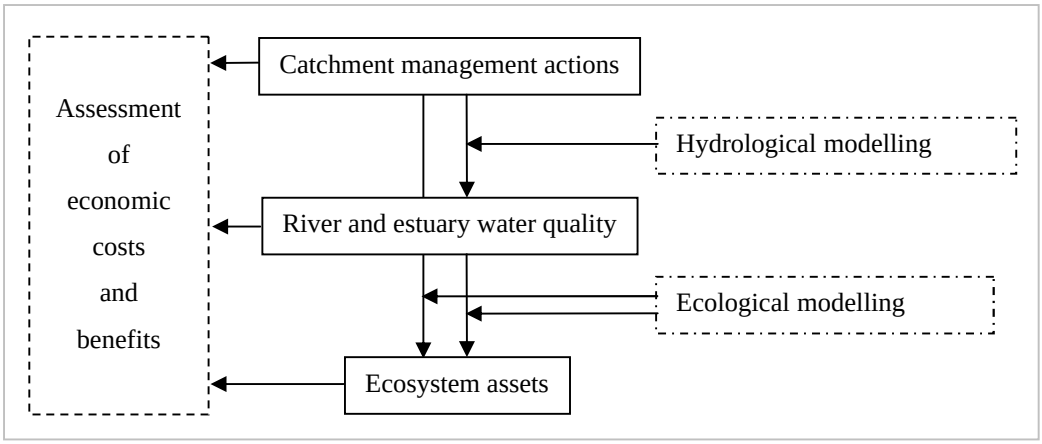


Figure 1 Catchment processes considered in the George catchment integrated modelling framework

Parallel development of the various models ensures corresponding management context and tailored information exchange between models. Biophysical modelling provides an increased scientific foundation for the environmental valuation study than is typically available (Brookshire et al., 2007). The biophysical and economic systems are integrated in a comprehensive Bayesian Network model that will enable decision makers to analyse the tradeoffs between catchment environmental conditions and the costs and benefits associated with changes in catchment management.

In this paper, an overview is given of the study progress to date and the research' issues that have been encountered. The next section of this paper provides a short review of integrated catchment models, followed by an introduction to Bayesian Networks in Section 3. A consensus needed to be reached between natural scientists and economists on the study area, the management changes and the variables considered in the integrated model. The selection process and the George catchment that was chosen as a case study for this research are described in Section 4. The development of management scenarios and the selection of variables are also discussed. In Section 5, details of the three model components – water quality, ecology and economics – are provided, followed by a description of the integration approach taken to link these different model components in Section 6. In Section 7, some of the lessons learned from this study are discussed. A final section provides conclusions and directions for further work.

2 Integrated catchment modelling

Integrated models that combine natural science and economic knowledge can contribute to more efficient catchment management by allowing an assessment of multiple values. Of particular interest here, is the growth in the number of 'hydro-economic' models, that aim to combine traditional engineering and hydrological models of water management with economic analyses (Brouwer and Hofkes, 2008, Heinz et al., 2007). A wide range of hydro-economic models exists, with different foci and objectives.

2.1 Optimisation models

Many of the existing hydro-economic models aim to identify the optimal combination of management actions that maximise a certain goal, subject to environmental and economic constraints. Such optimisation models often focus on estimating the water needs of the physical environment and analyse how production and extraction decisions might impact water flows. See, for example, the models developed by Thornes and Rowntree (2006), Martín de Santa Olalla *et al.* (2005), Lanini *et al.* (2004) and Rosegrant *et al.* (2000). These approaches typically include a hydrological component, models of agricultural water demand and an economic component that estimates the financial benefits from irrigation. Optimisation techniques are employed to assess the allocation of water between users that maximises the expected social and economic gains from different ways to use the water, subject to technical and environmental constraints (eg. land and water availability). Whereas such models integrate hydrology and economics, the representation of impacts of changed allocation and efficiency in water use on water quality, ecology or non-market values remains limited.

2.2 Hydro-ecological models

Decision makers need information about the impacts of management changes on catchment ecosystems. Hydro-ecological models are aimed at assessing such changes by explicitly considering hydrological and ecological processes, and the interactions between them. Such models may focus on the ecological impacts of eutrophication and acidification of surface water (Fujita et al., 2007), impacts of changes in river flows (Kennen et al., 2008) or effects of varying ground and surface water levels (van den Bergh et al., 2001). Not many of these models assess the economic impacts of ecosystem changes.

An example of a hydro-ecological model that incorporates economic effects is the NELUP model (Moxey et al., 1995, Rushton et al., 1995). NELUP considers how rural land use changes in the River Tyne catchment, UK, affect surface water and groundwater flows using hydrological models. An ecological modelling component predicts changes in plant community and species composition in response to land use changes. The economic module assesses the impacts of changes in land use policies and prices on agricultural production. Although NELUP considers a range of activities

associated with land use, the modelling does not assess the non-market effects of changed ecological conditions associated with alternative land uses.

2.3 Economic valuation

Optimisation models and hydro-ecological models are often limited to changes in biophysical systems. An integrated representation of a catchment system needs to encompass a range of systems, allowing assessments of environmental and socio-economic values. Many economic valuation studies have aimed to assess the non-market values impacted by changes in catchment environmental conditions. An Australian example includes a study on environmental protection in a sugar-cane growing region in the Herbert River catchment, Queensland, aimed at identifying the land-use options that maximised regional profits of sugar cane farming and minimised environmental externalities (Mallawaarachchi and Quiggin, 2001). The benefits of cane production were estimated using a linear programming approach. Community values for the protection of natural vegetation in areas suitable for cane production were estimated through a CE survey. Scenarios of clearing natural vegetation for cane expansion were described by changes in four attributes: the area of vegetation along rivers and in wetlands, the area of teatree woodlands, regional income from cane production, and an environmental levy. The levels of the environmental attributes were chosen based on a literature review and expert advice, rather than on underlying biophysical modelling. The criterion was to present an 'acceptable range' of attribute levels (Mallawaarachchi et al., 2001). Another example is Whitten and Bennett (2003a), who present an integrated bio-economic model of wetland management on the Murrumbidgee River Floodplain (MRF) in New South Wales. Choice experiments were used to measure the non-market values of the MRF, including values for healthy wetland areas, bird populations and native fish populations. The projected impacts of different management scenarios on these characteristics of the MRF wetlands were based on a literature review and expert consultations. There were no natural science models underlying the prediction of attribute levels. Bennett *et al.* (2008) use a non-market valuation study to estimate the economic value of improved environmental health in Victorian rivers. An expert panel defined a list of indicators that were used to describe river health. These indicators included the population of native fish, the length of riverside vegetation and the populations of native birds and animals. The levels of each of these variables were estimated by staff members of catchment management authorities in Victoria, rather than through the use of quantitative, scientific evidence.

Because of their focus on monetary trade-offs of environmental changes, economic catchment valuation studies often have a limited representation of the complexity of underlying hydrological or ecological systems. A sound scientific underpinning to estimating the impacts of management changes on the catchment environment, and an integration of ecological and hydrological models could improve the rigour of the valuations.

2.4 Integrated hydro-economic modelling

Many existing catchment models are science or engineering based models focusing on environmental system processes, rather than on socio-economic values. Catchment valuation models, on the other hand, often lack a thorough biophysical foundation that could improve the representation of the complex environmental systems underlying valuation studies. To the authors' best knowledge, only two other studies have been undertaken that link comprehensive biophysical models to estimations of market and non-market costs and benefits. The 'Catchment hydrology, Resources, Economics and Management' (ChREAM) project aims to assess the economic impacts of implementing the EU Water Framework Directive on rural communities in the Humber catchment, UK (Bateman et al., 2006a, 2006b). The study uses a combination of biophysical models and GIS techniques to assess how different management scenarios might alter water flows and water quality, as well as the biological responses they may trigger in river ecosystems. The biophysical modelling provides inputs for parallel socio-economic assessments. Changes in agricultural production are estimated using farmers' surveys and socio-economic models of farming behaviour (Bateman et al., 2006a). Travel cost and CE surveys are employed to elicit the non-market values that individual visitors attach to the Humber catchment. ChREAM is a multidisciplinary project linking biophysical and socio-economic modelling outcomes. There is, however, no documentation of how the various model outcomes may be integrated into one comprehensive framework.

Another study that aims to integrate hydrological and ecological modelling with non-market valuation is underway in two catchments in Arizona, USA (Brookshire et al., 2007). This study focuses on the impacts of changes in groundwater levels on water flows, riparian vegetation and, subsequently, habitat provision for birds. Natural science-based models provide information about changes in flows, vegetation and birds as inputs into Contingent Valuation (CV) and CE studies that aim to elicit the values people place on varying catchment conditions. A major focus of the project is the degree of scientific detail that can be presented in the valuation surveys, while taking into account the cognitive burden on respondents. No results have been published yet, but the researchers have highlighted the complexity involved in creating an integrated scientific/economic framework (Dixon et al., 2008).

Available integrated modelling often concentrates on either biophysical or economic systems. Where multiple systems and processes are considered, integration into a single comprehensive modelling framework is limited. The study described in this paper proposes a Bayesian Network approach as a method to link biophysical science to nonmarket valuation outcomes in a single catchment model.

3 Bayesian Networks

A major challenge in any integrated modelling study is to combine the knowledge from different academic disciplines into a logically consistent framework. Some processes (for example, in catchment hydrology) may be clearly described by deterministic models or can be derived from

observational data. However, many ecological and socio-economic processes are not well understood and are inherently subject to uncertainty. Using a deterministic model that relies on quantitative data will not be useful when there is limited information about a system. A Bayesian Network model (BN - sometimes called belief network) quantifies uncertainty by representing the impacts from alternative management actions as (discrete) probability distributions. Through this probability definition, BNs enable an analysis of the risks associated with catchment management changes[2].

BNs are probabilistic graphical models, widely used for knowledge representation and reasoning under uncertainty in natural resource management (NRM) (Castelletti and Soncini-Sessa, 2007). A BN consists of a directed acyclic graph of variables (called 'nodes'), that can represent management scenarios, states or utilities. The values each variable can assume are classified into mutually exclusive, 'states'. These states can be defined in quantitative levels (e.g. <50, 50-150, 150-300 and >300mg/L) or in qualitative terms (e.g. 'decrease', 'no change', and 'decrease'). That means that BNs are able to accommodate different data sources, including expert opinion when observational data is not available (Pearl, 1988, Jensen, 1996). The range of states should be wide enough to cover all possible levels. The 'discretisation' of states can reflect the precision of the value estimates by using more or less states to cover the range of values. The conceptual links between nodes are described by conditional probability distributions. For example, in Figure 2, State variable 2 can assume five different states. The probability that each of these states occurs is conditional on the state the Decision variable is in. The value of the Utility variable is determined by the combined states and probabilities of State variables 1 and 2. Bayesian Networks rely on Bayes' theorem of probability to propagate information between nodes. Unlike most integrated approaches where models are linked, BNs thus use probabilistic, rather than deterministic, expressions to describe the relationships between variables (Borsuk et al., 2004).

There is a rising interest in BNs as tools for ecological and water resource modelling[3]. Applications of BNs in catchment modelling range from catchment-wide assessments of agricultural point-source pollution (Dorner et al., 2007) or dryland salinity (Sadoddin et al., 2005) to eutrophication of river estuaries (Borsuk et al., 2004, Hamilton et al., 2007) and degradation of coastal lake-catchment systems (Ticehurst et al., 2007). BNs of stakeholder participation in catchment management are presented in Bromley et al. (2005) and Hendriksen et al. (2007).

[2] See Brouwer and DeBlois (2008) for a discussion on risk and uncertainty in water quality modelling.

[3] See, for example, McCann et al., 2006, Castelletti and Soncini-Sessa, 2007b, and Kragt, 2009, for an overview.

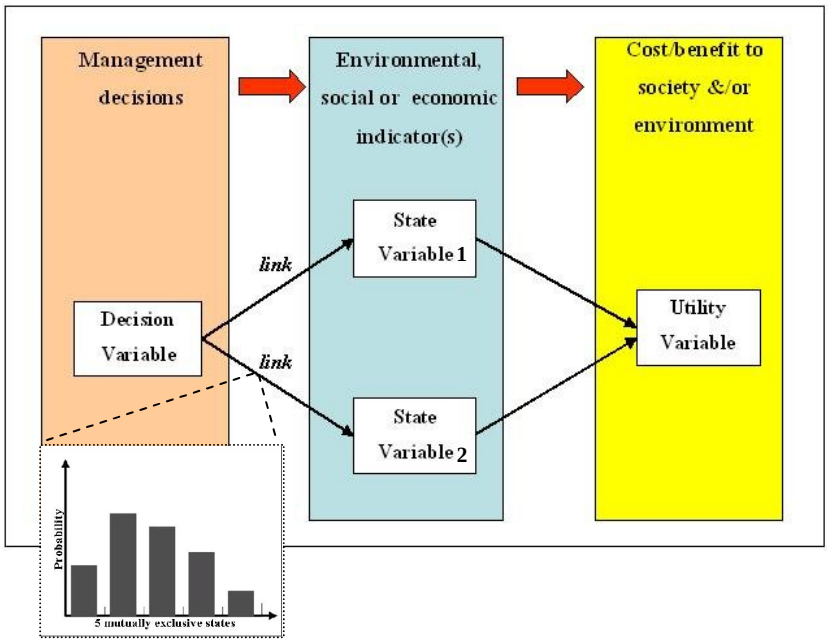


Figure 2 Bayesian Network modelling basics (Source: Merritt et al., 2006)

There are few BN applications focusing on economic impacts of environmental changes. Only one BN study has been published to date that incorporates non-market costs and benefits of catchment management changes (Barton et al., 2008). The authors used a BN approach to integrate existing economic information on the costs of nutrient abatement measures with modelled impacts of changed land management practices on lake water quality in the Morsa catchment, Norway. This enabled a cost-effectiveness ranking of measures based on the expected costs and environmental effects. The benefits of improved water quality on recreation were also evaluated, using results from a 1994 CV survey. Combining the economic valuation of water quality to the abatement costs allowed a cost-benefit analysis of alternative management scenarios in the catchment. The study showed the benefits of using a BN approach compared to deterministic cost-effectiveness or cost-benefit analyses. However, the economic studies were not developed in concordance with the biophysical models. Doing so could have improved the information exchange between models and the integration of biophysical and economic knowledge. Furthermore, using CV restricted the value estimate for bathing water suitability to a binary variable. An estimation of the *marginal* values of changes in multiple environmental attributes was not possible with the employed environmental valuation approach.

4 Case study and scenario development

Each modelling process starts at the level of issue definition, including an identification of the system that is to be studied, the objectives of the model and the changes under consideration (Jakeman et al., 2006). In an integrated model, various stakeholders or scientific disciplines may consider a multitude of issues related to the system under consideration, which could lead to different modelling objectives for different stakeholders. Even a definition of the system itself may differ between model developers. In this section, the definition of the scales and scope of the George catchment integrated modelling study are described.

4.1 Selecting a case study area

The first step in our integrated modelling study was the selection of a case study catchment that was suitable for both the scientific and socio-economic research. This consensus-based process involved researchers from various disciplines. The focus of the study was on Tasmanian catchments and the analyses of river and estuary changes. As such, the selection process started with an assessment of 34 coastal catchments in Tasmania. The aim of the biophysical modelling component was to assess the linkages between catchment management, hydrology and impacts on freshwater and estuary water quality and ecology. Therefore, there needed to be a demonstrated impact of management actions on receiving waters and aquatic systems. Catchments without identified environmental issues were excluded from the selection process. Another important criterion for biophysical modelling was the availability of quantitative data on meteorology, catchment hydrology, soil composition, land use distribution, and the presence of monitoring sites for stream-flow and river and estuary water quality. Catchments with large perturbations such as hydro electric structures, dams, mining activities or major urban developments were excluded to avoid confounding with catchment management impacts.

This process resulted in a ‘short-list’ of 13 catchments in which environmental concerns had been demonstrated, for which adequate monitoring data were available and that did not have major catchment modifications. This shortlist was scrutinised based on criteria for the socio-economic research component.

The presence of environmental assets in the chosen catchment was an important criterion, as potential attributes for the valuation survey. Furthermore, natural resource degradation needed to be related to local catchment management and the catchment estuary needed to have economic significance through its contribution to production, recreation or non-market values. Four Tasmanian catchments were proposed for final selection: the Duck, George, Inglis and Port Sorell catchments. From these four, the George catchment was selected as a suitable case study area because hydrological and water quality data were available and because the catchment has significant socio-economic values through its environmental assets, aquaculture production and recreational values. Another advantage was the support the study received from local and regional NRM bodies.

The George catchment is a coastal catchment of about 557 km^2 on the North-East coast of Tasmania (Figure 3). The total length of rivers in the catchment is approximately 113km, with the main rivers being the Ransom and the North and South George Rivers. The George River flows into the Georges Bay estuary (22 km^2) near the town of St Helens (population 2,200 - Census 2006). Continuous water quality monitoring data is available for the Ransom and George river (DPIW, 2007) and ongoing research in Georges Bay provides monitoring data on estuary water quality and ecology (Crawford and White, 2005). The region is a popular holiday destination, and Georges Bay is intensively used for recreational activities including boating, swimming, sailing and recreational fishing. There is also extensive aquaculture in Georges Bay, with 10 marine farming licenses (DHHS, 2008). In 2006, approximately 3,000 dozen of oysters were commercially harvested in Georges Bay (DEWR, 2007)[4].

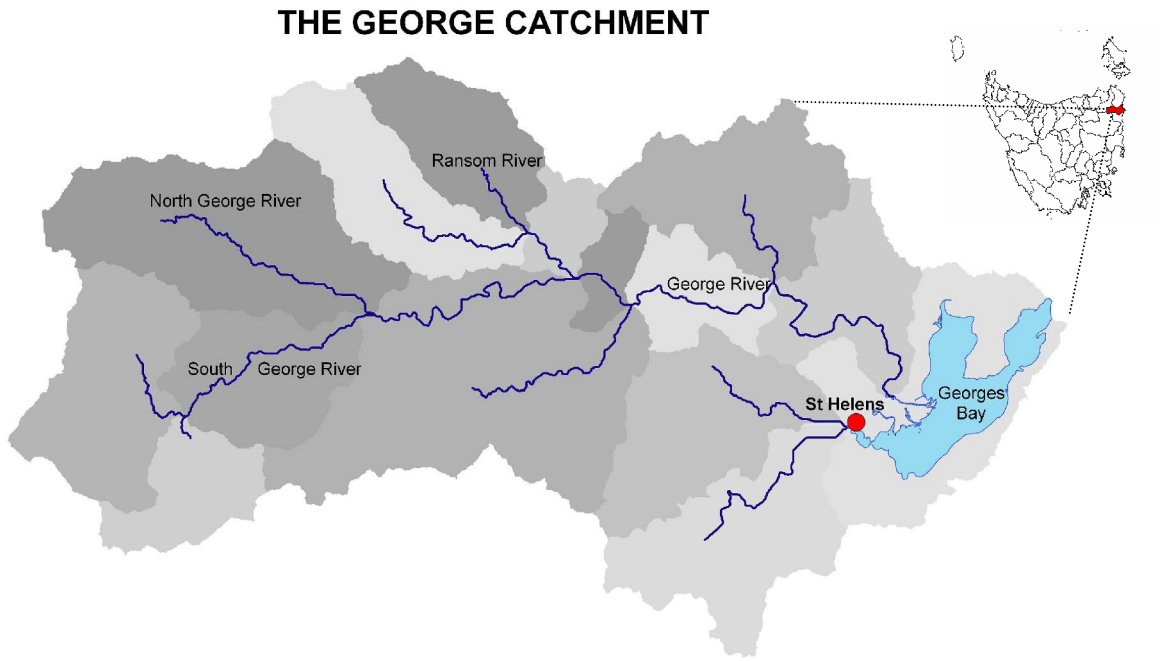


Figure 3 The George catchment

Land use in the upper catchment is a mix of native forestry and forest plantations along with dairy farming, while the lower catchment is used for agriculture and contains most of the rural and urban residences. Although the catchment environment is currently in good condition (Walker et al., 2006, Davies et al., 2005),dairy runoff, forestry operations and urban pollution are affecting water quality in the George catchment (NRM North, 2008a and 2008b). There are significant concerns about degradation of the catchment environment (BOD, 2007, Sprod, 2003, Rattray, 2001). Local management is aimed at preventing a quality decline of the natural resources in the George catchment. Current NRM actions include limiting stock access to rivers, removing weeds along river banks, developing riparian buffer zones, recovery of dairy effluent and improved wastewater treatment.

[4] More recent (commercially sensitive) production data is not publically available.

4.2 Scale and management scenarios

In any integrated model, the various modelling components should consider the same management issues on the same spatial and temporal scales. The geographical scale in this study was based on the catchment contours of the George catchment, delineated using digital elevation models. A projection of water quality changes in the next twenty years was considered an appropriate time frame from both a biophysical and socio-economic modelling perspective.

The management scenarios to be considered were limited to local NRM activities, and variables that could be incorporated in the biophysical modelling. Scenarios were specified using literature analysis and interviews with science experts, local stakeholders and decision makers. Management actions included in the George catchment model are targeted at:

1) Changed catchment land use;
2) Controlling erosion and point-source pollution through fencing and instream engineering works;
3) Riparian management through establishing riparian buffer zones, weeding and revegetation of riparian zones.

Some of these actions are already being implemented in the George catchment on a small scale, which increases the plausibility of the management scenarios for respondents to the valuation study. Changes that cannot be influenced by local management, such as climate change, were not considered.

4.3 Attribute selection

The next step in model development involved defining the scope of the system in terms of the assets or values that would be considered in the modelling. From an integration perspective, the scientific information should predict the changes in environmental attributes of interest for socio-economic research. Choosing science-based indicators of catchment condition that were important to policy makers ánd suitable to be included as attributes in the choice experiment was a challenging task in this study.

The selection of attributes was an iterative process. 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. A review of the literature on ecosystem indicators in Australian catchments (e.g. NLWRA, 2008, Beeton et al., 2006, NLWRA, 2001, White and Ladson, 1999) aided the identification of variables important in catchment and aquatic processes. Discussions with local policy makers and a review of George catchment management plans (BOD, 2007, DPIW, 2005b, Mount et al., 2005, Sprod, 2003, Lliff, 2002, Rattray, 2001, McKenny and Shepherd, 1999) provided additional focus on attributes that are significant in the George catchment. These were discussed during several science workshops with experts on river and estuary health.

Scientists expressed a desire to capture a complete and detailed representation of the processes related to catchment management changes, resulting in a conceptual model framework with nearly eighty variables (Appendix 1). It is practically impossible to collect data on so many variables and to specify the relationships between all of them. A balance needed to be found between model parsimony and scientific representation of catchment processes. Furthermore, the detailed model information envisaged by natural scientists would have been impossible to present in a non-market valuation survey. Additional rounds of workshops and expert consultation[5] were therefore aimed at identifying the *most important* variables that scientists expected to be impacted by land use changes, erosion and pollution control and riparian 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 (Appendix 2).

The output nodes in the model deserved particular attention, as these would serve as the environmental attributes in the environmental valuation study. An important attributes that was identified by natural scientists was general 'water quality' in the rivers and in Georges Bay. From an economic perspective, 'water quality' was not a desirable attribute because of its potential to act as a 'causal attribute' in the choice experiment. Causal attributes are seen by CE respondents as being indicators of an array of other -consequential- attributes such as biodiversity and recreational use. The inclusion of a causal attribute such as 'water quality' in the valuation task tends to preclude other catchment attributes from playing a role in respondents' choice processes. Scientists were therefore challenged to define ecological indicators of 'water quality'. Experts initially found it difficult to think beyond chemical indicators such as nutrients, sediment, salinity or dissolved oxygen concentration. The most important *ecological* indicator of water quality changes for ecologists was the abundance and species composition of benthic macro-invertebrates (see, for example, Haase and Nolte, 2008, Parsons et al., 2002, and Ladson et al., 1999). However, macro-invertebrates were not a useful attribute to represent catchment environmental conditions in the valuation study, as survey respondent were expected to be relatively unfamiliar with macro-invertebrates and their ecological significance. Rather than 'educating' respondents about food webs and ecosystem functioning, it was considered desirable to represent catchment conditions by attributes of higher trophic levels. After several consultation rounds, experts agreed that algal growth, fish, oysters and seagrass were reasonable ecological indicators of water quality[6]. Given that there are currently no observations of algal blooms

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

[6] Elevated nutrient and sediment levels can trigger excessive algal growth, making the occurrence of algal blooms a suitable indicator of declined water quality. Changes in water quality, salinity, aquatic vegetation and especially subsequent effects on in dissolved oxygen levels can impact fish abundance. Seagrass generally grows best in unpolluted waters with low turbidity, making the extent of seagrass beds another appropriate water quality indicator.

in the George catchment, seagrass area, fish and oyster populations were considered as attributes for the valuation study.

Ecological indicators of catchment environmental conditions other than water quality were also discussed with scientists. Ecologists argued that a complete understanding of species and vegetation composition was needed to measure natural resource conditions in the George catchment. The aim was to find the attributes that can represent the highest level in an ecosystem and thus serve as indicators of ecosystem health. Two attributes were selected to represent the George catchment environmental conditions: threatened species and riparian vegetation.

All the attributes were discussed during focus group meetings with survey respondents in Hobart, St Helens and Launceston[7]. Respondents reacted positively to the riparian vegetation and species attributes. With respect to the water quality indicators, both oyster and fish populations were considered valuable George catchment assets. However, a lack in scientific information about the relations between catchment management and oyster growth, and a lack in observed data on fish populations impeded the use of these attributes. Seagrass area, riparian vegetation and rare animal and plant species were chosen as environmental attributes to be modelled and to be included in the valuation study.

4.4 Attribute states

The selected attributes are the final output nodes in the overall integrated Bayesian modelling framework. Biophysical modelling was to predict how changed catchment management would impact the attributes and a decision needed to be made about the measurement units that would represent the attribute levels. All model components should evaluate attributes in identical measurement units. Natural scientists and economists therefore needed to agree on the description of each attribute, the units of measurements and the potential levels that each attribute could assume. In the BN, the discrete states of the output nodes were to match the range of attribute levels presented in the CE survey. It is worthwhile noting here that being able to use node states that directly correspond to attribute levels is an added advantage of integrating CE results into BNs.

Observations of current catchment conditions were available. Scientists were, however, reluctant to predict changes without detailed information about all the biophysical processes that could affect the environmental attributes (Appendix 1). Initially, qualitative descriptions were used to define the states of each attribute (e.g. ‘increase’, ‘no change’ or ‘decrease’). However, the valuation task is advantaged when attribute levels are specified as quantitative levels. Using quantitatively attribute levels can reduce the subjectivity that is associated with individual respondents’ interpretation of a

[7] Four focus group discussions were organised in Hobart and St Helens in February 2008, and a further four in Launceston and Hobart in August 2008. For further details about the focus groups and the attribute selection process, see Kragt and Bennett (2008).

qualitatively defined attribute. Quantitative levels also improve the capacity of valuation results to be used in benefit transfer exercises (Desvousges et al., 1992).

The available biophysical data and preliminary modelling outputs were discussed during several expert workshops. Similar to experiences reported by Brookshire (2007), natural science experts wanted to describe each variable in much scientific detail. However, the attribute description in the CE survey needed to be simple and short to convey the information to survey respondents. The final description of the attributes are a compromise between these two views (Table 1).

A broad range of measurement units and attribute levels was considered. Both quantitative and qualitative measures were discussed during the CE focus groups. Given the subjectivity of qualitative measures, quantitative levels were chosen to depict changes in seagrass, riparian vegetation and rare animal and plant species.

Table 1 Attributes / output nodes, their units of measurement and description in the George catchment model

Attribute / output node	Measurement units	Description in the choice experiment
Native riparian vegetation	The percentage of total riparian zone in the George catchment that is more than 80 percent vegetated, with at least 70 percent 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 observed 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 George estuary	Seagrass generally grows best in clean, clear, sunlit waters. Seagrass provides habitat for many species of fish, such as leatherjacket and pipefish.

5 Modelling components

In this section, the biophysical and economic models that were developed for the George catchment are described[8]. The various models provide inputs for the final integrated BN framework.

5.1 Water quality modelling

The impacts of alternative catchment management actions on river and estuary water quality were modelled in a spatially semi-distributed framework called CatchMODS (Catchment Scale

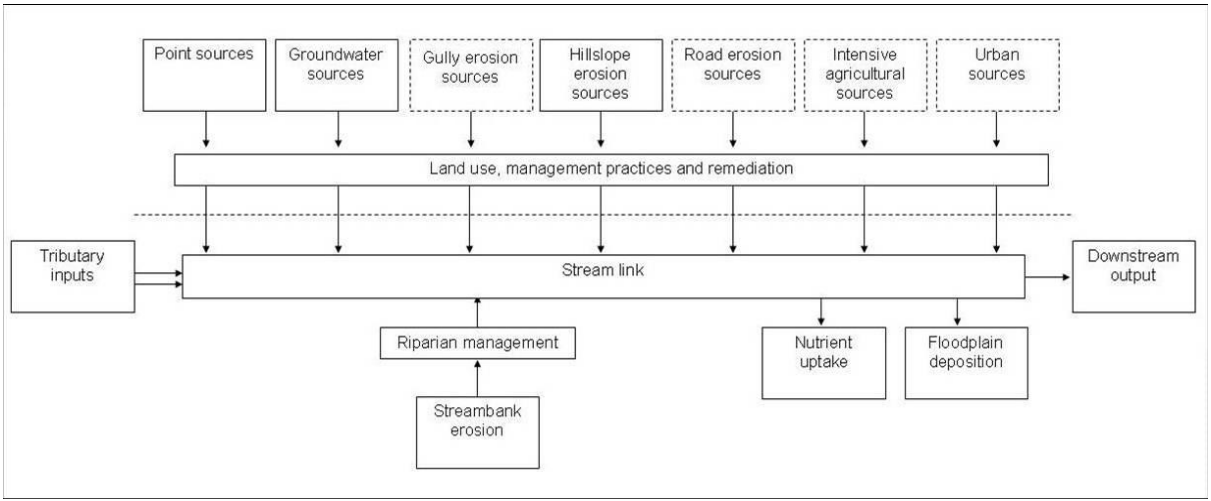


Figure 4 CatchMODS reach structure

Management of Diffuse Sources; Newham et al., 2004). The CatchMODS framework is based on a node-link structure where loadings from upstream sub-catchments provide inputs to the downstream reaches (Figure 4). Physically-based sub-models simulate the hydrological processes and sediment and nutrient export. These are linked with additional models of pollutant trapping and decay to enable a predication of average annual flows, sediments and nutrient loads into receiving waters. Stream reach and catchment data input is coded using GIS mapping software to produce a spatial disaggregation pollutant loads.

The development of a CatchMODS framework for the George catchment built on experiences of CatchMODS water quality modelling in New South Wales and Victoria (Newham et al., 2008 and 2004). Data input requirements included information about climate, hydrology, soil nutrient concentrations and land use in the George catchment. The collection of reliable data involved inputs from literature values, scientific experts, monitoring information and results from on-site sampling. The model predicts annual average sediment and nutrient loads into the George catchment rivers and Georges Bay. Results are presented as a map, which makes the output easy to understand and identifies which subcatchments contribute most to pollutant loadings, aiding targeted natural resource management (Figure 5).

[8] Kragt and Newham (forthcoming), Kragt and Bennett (2008) and Kragt and Bennett (2009) provide additional information about the water quality, ecological and economic modelling.

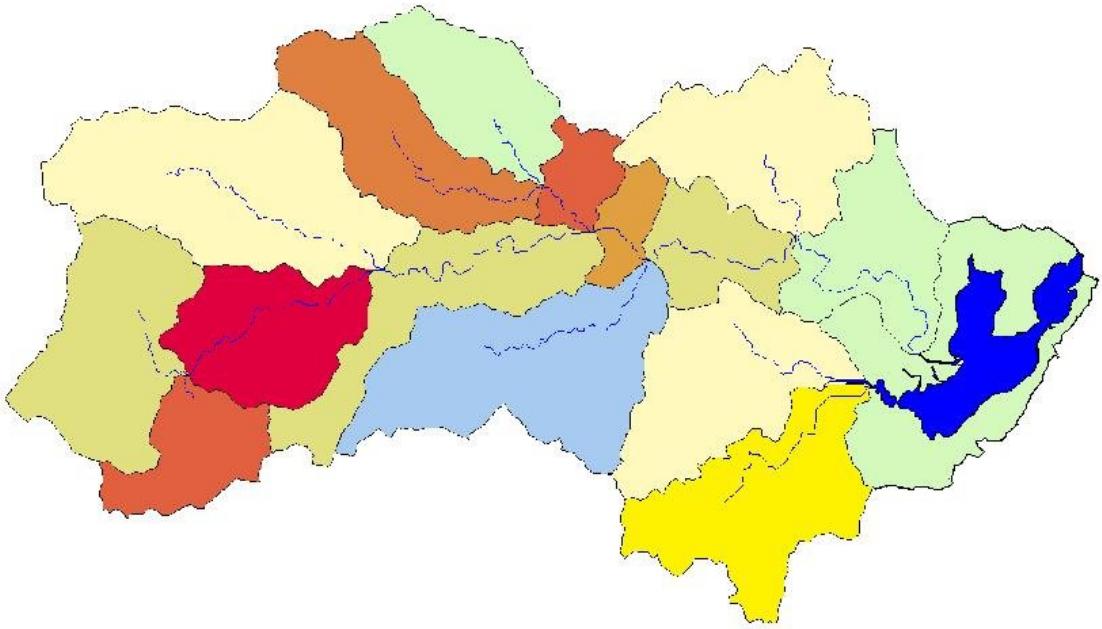


Figure 5 Example of George CatchMODS output (different colours presening different sediment yields)

5.2 Ecological modelling

The ecological modelling in this study focused on the three environmental attributes that were to be included in the CE survey. Various combinations of the management actions (land use changes, erosion and pollution control, riparian zone and weed management) were modelled to predict changes in the levels of these attributes in the George catchment in 20 years time.

A specific challenge in the ecological modelling was the uncertainty that inherently arises from the variability in natural systems (Walker et al., 2003) as well as the imperfect knowledge and information about ecosystem functioning in the George catchment. The modelling needed to deal with this uncertainty. Information was collected about the current status of riparian vegetation, native species and seagrass in the George catchment and Bay. In the absence of quantitative scientific studies and limited long-term monitoring data about ecological changes in Tasmanian catchments, no deterministic models could be developed to simulate changes in the George catchment ecosystems. The approach taken in this study therefore followed the strategy of assigning probabilities to the uncertain states of each variable (Brouwer and De Blois, 2008). A combination of observed data, expert consultation and assumptions was used to predict changes in riparian vegetation, native species and seagrass in a probabilistic BN model. The quantification of uncertain relationships between variables as probability distributions and the graphical representation of these probabilities provided a more explicit depiction of system uncertainty than is usually the case in integrated models. Furthermore, the formalisation of ecosystem processes in this manner provided an increased scientific foundation for the CE than is typical in environmental valuation studies.

The available data for riparian vegetation, seagrass and species were reviewed by a team of natural scientists and local and regional NRM organisations. The most important management actions impacting upon the environmental attributes were also discussed.

Information about riparian vegetation in the George catchment was derived from digital vegetation mapping (DPIW, 2005c), river health modelling (DPIW, 2005a), interviews with local NRM officers, agricultural and forestry practitioners and natural scientists. Native riparian vegetation was defined as percentage of total riparian zone in the George catchment that is more than 80 percent vegetated, consisting of at least 70 percent native vegetation (Table 1). The current percentage of riparian zone with native vegetation is approximately 65%, or 74km, of the total river length in the George catchment. Management actions that were most likely to impact riparian vegetation are changes in land use, fencing of riparian zones and weed management actions. Information about rare species was obtained from the Natural Values Atlas (DPIW, 2008) and was discussed with flora and fauna experts at the DPIW Threatened Species Unit. The variables assumed to impact the number of rare native animals and plant species were length of native riparian vegetation, land use, habitat connectivity and water quality. A total number of 68 rare flora species and 34 rare fauna species has been observed in the George catchment, of which about 80 could directly be affected by the considered local management changes. The area of healthy seagrass beds in Georges Bay was assessed using monitoring data and digital mapping of the Bay (Mount et al., 2005). The current area of healthy seagrass beds is approximately 690ha, or 31% of the total estuary area. Changes in estuary water quality, predominantly sediment concentration, nutrient loadings and turbidity, were assumed to impact seagrass beds.

The elicitation of probability distributions for the ecological variables followed approaches described by Ticehurst *et al.* (2008) and Merrit *et al.* (2006). Structural interviews with various natural scientists and local NRM officers were used to predict ‘worst case’ and ‘best case’ scenarios for each environmental attribute. Preliminary results of this elicitation process are summarised in Table 2. The *likelihood* that each output node is in a certain state needs to be further refined by probability distributions. A wide probability distribution was used for the initial modelling, to represent the uncertainty in the ecological information.

Table 2 Preliminary results of ecological modelling

Output node	Worst case scenario	Lowest attribute level	Best case scenario	Highest attribute level
Native riparian vegetation	Decrease in natural areas, increase in agricultural areas and limited weed management	35% (40km) of the total river length	Increase in conservation area, large-scale weed management and increase in vegetation density in the riparian zone	75% (84km) of the total river length
Rare native plants and animals	Decrease in native riparian vegetation, land conversion, limited habitat connectivity and degraded water quality	35 rare animal and plant species	Current situation	80 rare animal and plant species
Seagrass area	Increased sediment and nutrient loadings	420ha of seagrass beds	Improved water quality and reduced turbidity	815ha of seagrass beds

An increase in the number of observed rare species in the George catchment was considered unlikely by natural scientist. Because an increase in the number of rare species was also confusing to respondents in the CE, only a decline in species was modelled. The assumptions for the seagrass modelling were based on estuary models developed for mainland Australia (Baird et al., 2002). Estuary scientists stressed that the ecological response of seagrass to water quality changes is currently not well understood in Tasmanian estuaries. More accurate predictions and refining probability distributions will require further modelling of estuary hydrodynamics and detailed mapping of changes in seagrass beds in Tasmanian estuaries. Unfortunately, results from current research in this field[9] were not available to be included in the present study.

5.3 Economic modelling

The economic component of this research consisted of a non-market valuation study using Choice Experiments (CE) to elicit community preferences towards the George catchment environment. In a CE, respondents are presented with a series of choice questions describing several possible alternative futures, each with different levels of the attributes. Respondents are asked to choose their preferred option in each choice question. This allows the researcher to analyse the trade-offs respondents make between attributes. If cost is included as one of the attributes, these trade-offs can be used to estimate

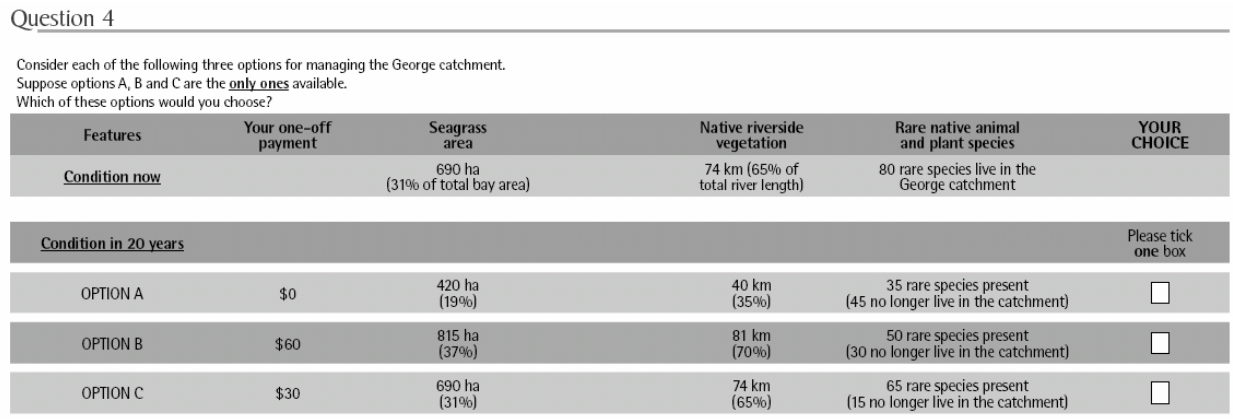
[9] http://www.landscapelogic.org.au/projects/project4.html

the marginal value (implicit price) of each attribute.[10] A CE was considered the most appropriate environmental valuation technique in this study, as it enables an estimation of marginal values for separate environmental attributes. These marginal values can then readily be linked to the output nodes in the BN model, with node states matching the CE attribute level ranges. It is implausible from a scientific perspective to predict the condition of the George catchment in terms of the exact number of species, riparian vegetation length or seagrass area. In the ecological BN modelling, this uncertainty is acknowledged by defining attribute levels in terms of the probability that an attribute is in a certain state. In the CE survey, this uncertainty was acknowledged by describing the outcomes of implementing new management actions as the "likely outcomes in 20 years time". Four attribute levels were used for each environmental attribute in the CE survey, based on the highest and lowest states and two intermediate states, of the BN output nodes.

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 various focus group discussions (Kragt and Bennett, 2008). The description of the attributes and their levels was, whilst based on scientific predictions, kept simple to make the survey comprehensible for respondents. Information about natural resource management in the George catchment and the environmental attributes was presented on a poster that accompanied the survey questionnaire The George catchment mapping and the described management changes were derived from the water quality modelling and were identical to the catchment scale and changes modelled in the BN.

Each choice question presented to respondents consisted of three choice alternatives. A base alternative was included in each choice question describing a degradation of catchment conditions over the next 20 years if no catchment management actions were to be undertaken. In this base scenario, the attributes would be degrading to the lowest level predicted by the water quality and ecological modelling. Two other options in each question depicted the outcomes if new management actions were to be implemented and showed improvements in attribute levels, compared to the base. An example of a choice question is shown in Figure 6.

[10] See Hensher *et al.* (2005), Alpizar *et al.* (2001), Bennett and Blamey (2001) or Hanley *et al.* (1998) for more information about Choice Experiments.



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 6 One of the choice questions included in the George catchment CE

The survey was administered in Hobart, Launceston and St Helens in November and December 2008. A limited number of surveys were collected in Hobart and St Helens. To increase the sample size, a second sampling wave will be carried out in February 2009. As such, the results reported here are preliminary. Analysis of the surveys collected to date showed that respondents, in general, hold positive values for the environmental attributes in the George catchment. Results from a mixed logit, random-effects model suggest that respondents are, on average, willing to pay $0.13 for an additional ha increase in healthy seagrass beds, $4.46 for a km increase in the length of native riverside vegetation and $9.35 for a species increase in rare native plants and animals (Table 3).

Table 3 Average marginal willingness to pay for environmental attributes in the George catchment (Source: Kragt and Bennett, 2009)

Attribute	Mean marginal WTP*	95% confidence interval
Seagrass (ha)	0.13	(0.04 0.22)
Riverside vegetation (km)	4.46	(3.27 5.66)
Rare species (#)	9.35	(7.96 10.74)

* Marginal WTP for a unit increase of the environmental attribute with the base alternative as the reference level

6 Bayesian Network modelling

The main objective of the study described in this paper is to integrate economic analyses and environmental modelling in one comprehensive framework. The study goes beyond simply linking the outputs from multiple mono-disciplinary models. The water quality, ecological and economic models are 'translated' into Bayesian networks, resulting in one integrated catchment framework. Different techniques are being used to define the conditional probability distributions that characterize the relationships between variables.

6.1 The water quality network

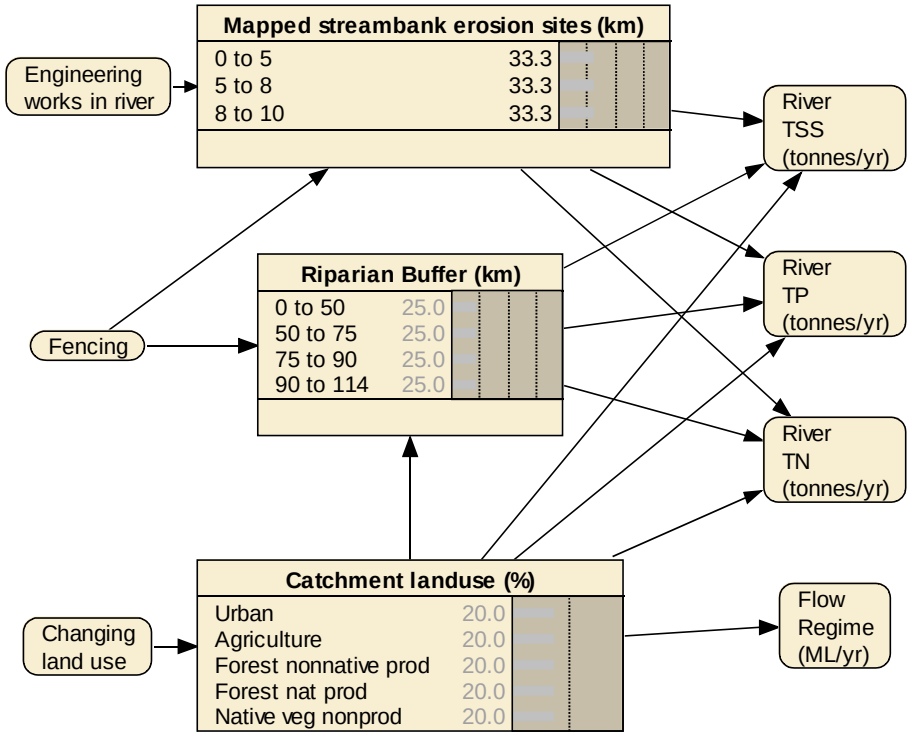


Figure 7 Bayesian Network structure of the water quality sub-model in the George catchment framework

The complex, process-based water quality model will be converted into a BN-structure that serves as a water quality sub-model in the Georges catchment integrated BN. Figure 7 shows the structure of the water quality BN (no findings have been entered in the network). Changes in management actions (engineering, fencing or land use changes) alter streambank erosion, the length of riparian vegetation that serves as a nutrient and sediment trapping zone and the percentages of different land uses in the catchment. Results from CatchMODS will provide predictions of changes in river flow, sediment and nutrient concentrations. The BN structure does not capture all the hydrological processes modelled in CatchMODS, but focuses on the management actions and their impacts on water quality. This BN presents a simpler representation of the water quality model than the complex CatchMODS framework and can be used to identify which management actions have the largest impact on water quality parameters. The conditional probabilities that describe the links between catchment management actions and water quality will be generated using Monte Carlo simulations of management scenarios in CatchMODS. As such, the BN water quality model is conditional on the information used in CatchMODS. Extensive documentation of all assumptions and data is included to enable model verification and testing.

6.2 The ecological network

A BN sub-model was created for each output node, based on the ecological modelling outcomes. A combination of empirical observations, biophysical modelling and theoretical knowledge about ecosystem processes was used to predict the states that each node can assume in the BN. The likelihood that different combinations of management actions would result in a change in nodes' states was captured by a conditional probability distribution for each node. Initially, a uniform distribution was used to capture ecosystem uncertainty, ranging from a maximum to minimum level of each environmental attribute. These distributions then needed to be refined in the ecological modelling to improve the models' predictions. Proposed conditional probability distributions are currently being scrutinised by Tasmanian scientists to increase knowledge integration in the model.

The seagrass and riparian vegetation sub-networks are shown in Appendix 3 and the rare species sub-network is shown in Figure 8. The probabilities that a node is in a certain states are based on the current observations in the George catchments, with wide confidence intervals to represent the uncertainty in the system. For the example in Figure 8, the probability that the number of rare native animals and plant species will be in one of the four states (<40, 40-60, 60-70 and >70) is conditional on the states of water quality, land use, native riparian vegetation and habitat connectivity. Current catchment land use is 2 percent urban, 15 percent agriculture, 5 percent forestry plantation, 45 percent native production forest and 33 percent native vegetation under conservation. Uncertainty about the state of the water quality node is shown by a 40 percent probability of being moderate or pristine and a 20 percent probability of being poor.

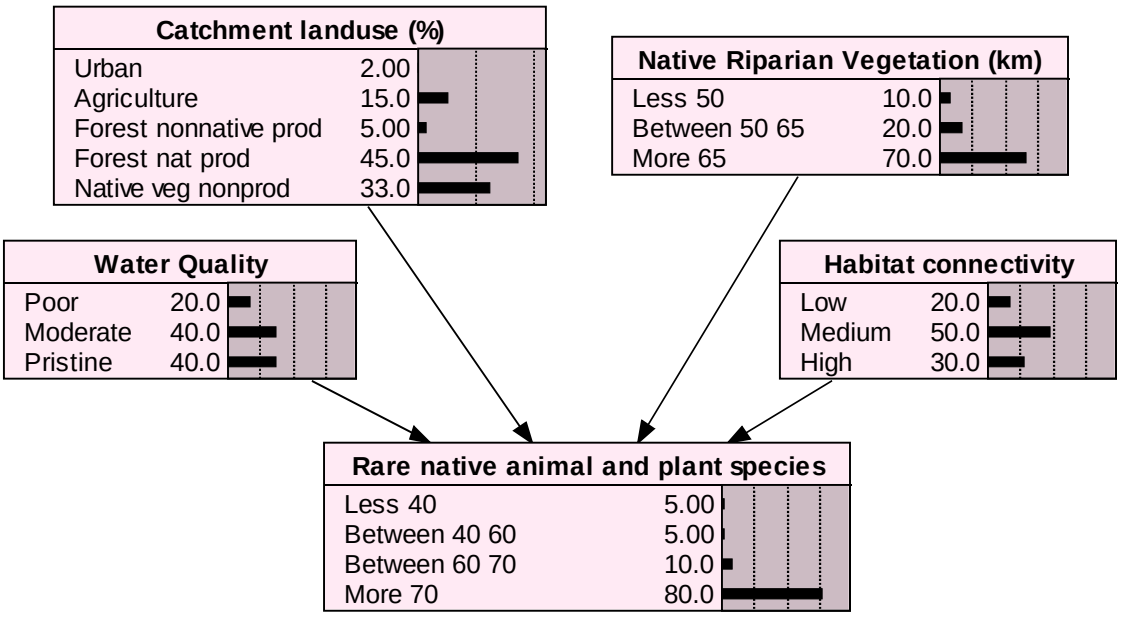


Figure 8 Species sub-model in the George catchment Bayesian Network

Inputs from monitoring data and CatchMODS Monte Carlo simulations are required to refine the probability distribution of the water quality node. The current length of healthy native riparian vegetation is more than 65 km and habitat connectivity is most likely to be medium. Using the observations from the Natural Values Atlas (DPIW, 2008), the number of species is most likely to be more than 70 species. To account for the uncertainty in this number of observations, small probabilities were also assigned to the number of species being in one of the other states. More accurate predictions and refining probability distributions are ongoing, involving a combination of water quality modelling and expert review[11].

6.3 The economics network

The various levels of the attributes presented in the CE survey were based on the minimum and maximum levels predicted in the ecological modelling, and included the current level observed (see Table 4). An intermediate level between the current observation and the 'worst case' scenario was also included as an attribute level. For the purpose of the valuation study, the level of the riparian vegetation attribute was described to respondents as the length in km of native riverside vegetation, so the percentage of healthy vegetation in the George catchment riparian zone was converted into kilometres rather than percentages. Note that the survey questionnaire described both measurement units in the choice sets[12].

Table 4 States of the nodes in the BN and levels of the attributes in CE survey

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

* Observed levels in bold

[11] Results are expected by mid 2009

[12] One split sample did not include a percentage description of attribute levels to examine respondents' choice behaviour to different ways of describing attributes.

The next step is to integrate estimates of individual WTP for attribute changes from the base alternative in the BN nodes for seagrass area, riparian vegetation or rare native species. These value estimates need to be a function of the likelihood that the variable is in a certain state, and the 95% confidence intervals of the WTP estimates obtained from the CE modelling. In this approach, the defined uncertainty[13] in the economic estimates are combined with the uncertainty of observing a certain attribute level. There currently exist no detailed, prescriptive guidelines as to how conduct an assessment of accumulated model uncertainties (Brouwer and De Blois, 2008). Ongoing work is aimed at formulating an approach to perform structural uncertainty analyses in the model

7 Discussion and lessons learned

A number of challenges that apply to interdisciplinary research and the development of integrated hydro-economic model applications were revealed in this study. One integral feature in developing the model was frequent communication between various academic disciplines and non-academic participants, such as NRM bodies and community members. The study required scientists to think beyond disciplinary boundaries. The use of different languages between natural science and economics (e.g. 'asset' versus 'attribute', or 'node' versus 'variable') and sometimes limited understanding of other disciplines posed a challenge for model developers.

Scientists needed to reach agreement about the level of model complexity. From a modelling perspective, model parsimony was desirable. Hydrological modellers, ecologists and economists all had their own idea of how detailed the model should be. Where ecologists wanted to capture the complete system processes, the level of detail needed to be limited in the valuation study. Developing a conceptual model with the most *relevant* variables was a lengthy and iterative process.

Discussions between scientists also involved the compatibility of the output variables provided and input data required by the different sub-models. The spatial and temporal dimensions of the various sub-models as well as the variables and their units of measurement needed to be the same. The selection of variables and the definition of their levels based on sound scientific predictions proved a considerable challenge that should not be underestimated (Brookshire et al., 2007). The variables needed to be relevant to all stakeholders, including scientists, economists, decision makers and CE survey respondents. These variables needed to be described in a way that matched 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. An important question from a CE perspective was how to accurately present the scientific results in ways that were comprehensible to respondents.

[13] *Defined* uncertainty allows an analysis of the risk associated with uncertain WTP estimates.

Bayesian network modelling provides a suitable approach to integrating economic valuation and biophysical modelling. The graphical representation of a BN clearly displays the links between different system components. This facilitated discussions of the conceptual model structures with scientists and decision makers. Advantages of using BNs to model environmental systems further included the ability to incorporate data from different sources and the comprehensive representation of system uncertainty in the form of probability distributions (Uusitalo, 2007). It should be noted, however, that defining the probability distributions can be a lengthy and difficult process. A considerable benefit of using the CE approach to environmental valuation lies in its ability to enable an estimation of marginal values for multiple attributes. Results from the CE study can readily be linked to the output nodes of the BN, through a matching of attribute levels and states.

8 Conclusion and further steps

Catchment decision makers are facing a wide range of management issues that involve complex environmental and socio-economic systems. Biophysical modelling tools have been developed to support decision making by representing and predicting changes in the hydrological and ecological systems. To effectively support catchment management, such tools needs to be integrated with economic techniques. Integrated catchment models that are based on sound scientific foundations, and include a representation of hydrological, ecological and socio-economic systems, are more likely to provide decision makers with the appropriate information to enable an assessment of multiple values.

There are currently few catchment models that integrate sophisticated natural science models and non-market economic valuation studies. This research addresses this knowledge gap by developing a integrated model that combines science-based biophysical modelling and non-market valuation in one framework, for a case study of the George catchment, Tasmania. A Bayesian Network modelling approach was used to accommodate different source data and to represent the uncertainty in the available information. Biophysical models were combined with a non-market valuation study to enable an assessment of the impacts of alternative catchment management actions. Choice experiments were used to assess the economic values Tasmanians hold for different environmental attributes in the George catchment. The use of choice experiments enabled a valuation of changes in several distinct attributes on a stepwise scale, making it a suitable valuation approach to be linked to the Bayesian Network attribute 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.

Defining the relationships between variables involved iterative rounds of expert consultation and great efforts were made to collect as much appropriate information in the time frame of this study. However, the availability of scientific information about biophysical and socioeconomic processes in Tasmanian catchments is sparse. Obtaining detailed, quantitative information about the environmental

attributes was limited by available scientific knowledge. Knowledge uncertainty was represented in the BN through a coarse discretisation of states and by defining wide probability distributions in the output nodes. Further discussions with natural scientists are carried out to refine the probability distributions in the model.

The study described in this paper has not been completed. Work is on-going to validate and refine the models, through comparison with observational data and additional rounds of expert reviews. Prior validation of the water quality and ecological modelling is essential to enable analyses of the effects of alternative management scenarios in the Bayesian Network. It should be acknowledged that improved quantity and quality of environmental data is needed to improve the representation of the interactions between natural systems and their subsequent impacts on social and economic systems. In particular, monitoring data and advanced modelling of ecological systems is required to achieve a more sophisticated representation of the biophysical features underlying changes in socio-economic systems.

Important further steps in the models' development include sensitivity analyses to assess which variables contribute most to environmental changes, and which variables have the largest impact on subsequent value estimates. Additional analyses are also required to identify the variables that contribute most to the model's uncertainty. It is important to assess the propagation of uncertainty in the linkages between models, and the sensitivity of the outcomes to the discretisation of states. Such sensitivity and uncertainty analyses are needed to aid evaluation of the integrated model and to identify weaknesses in the BN. Further research is being undertaken to formulate a structured and systematic approach to performing uncertainty analyses in the integrated network.

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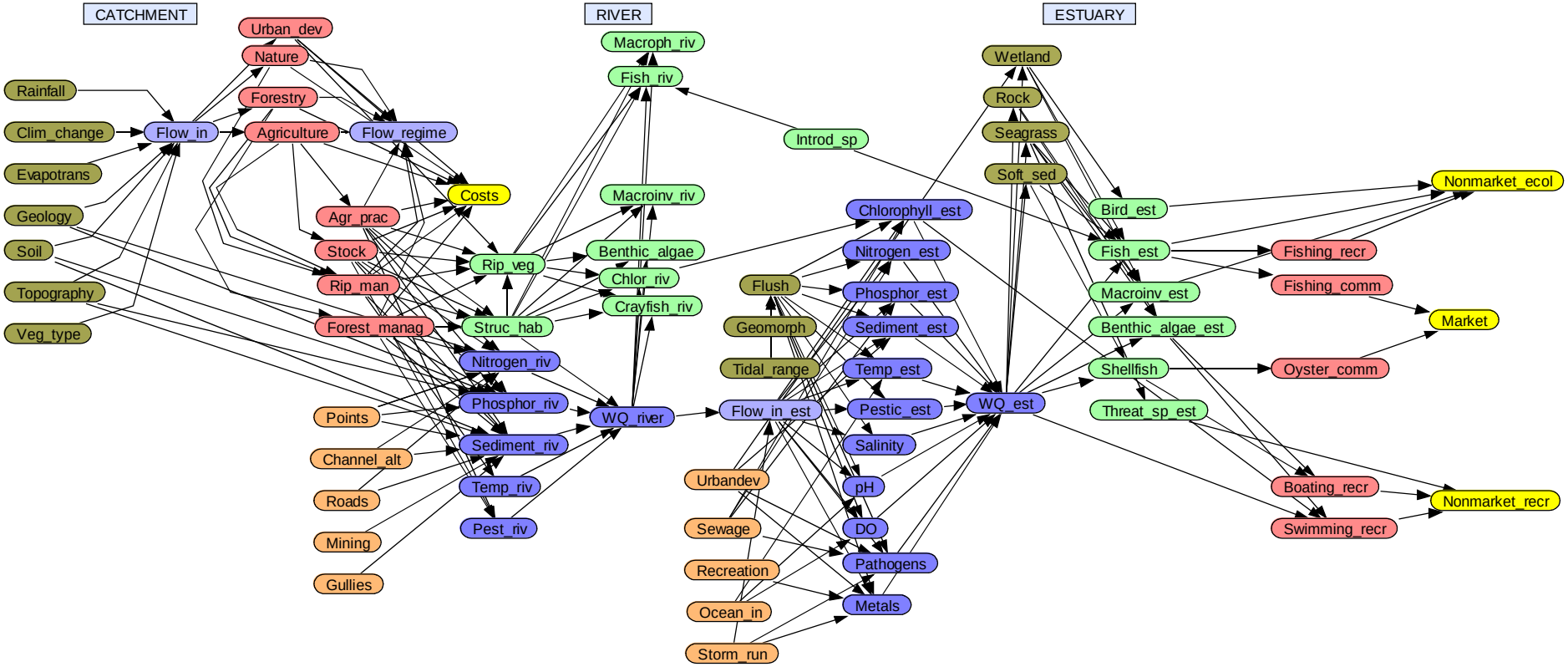
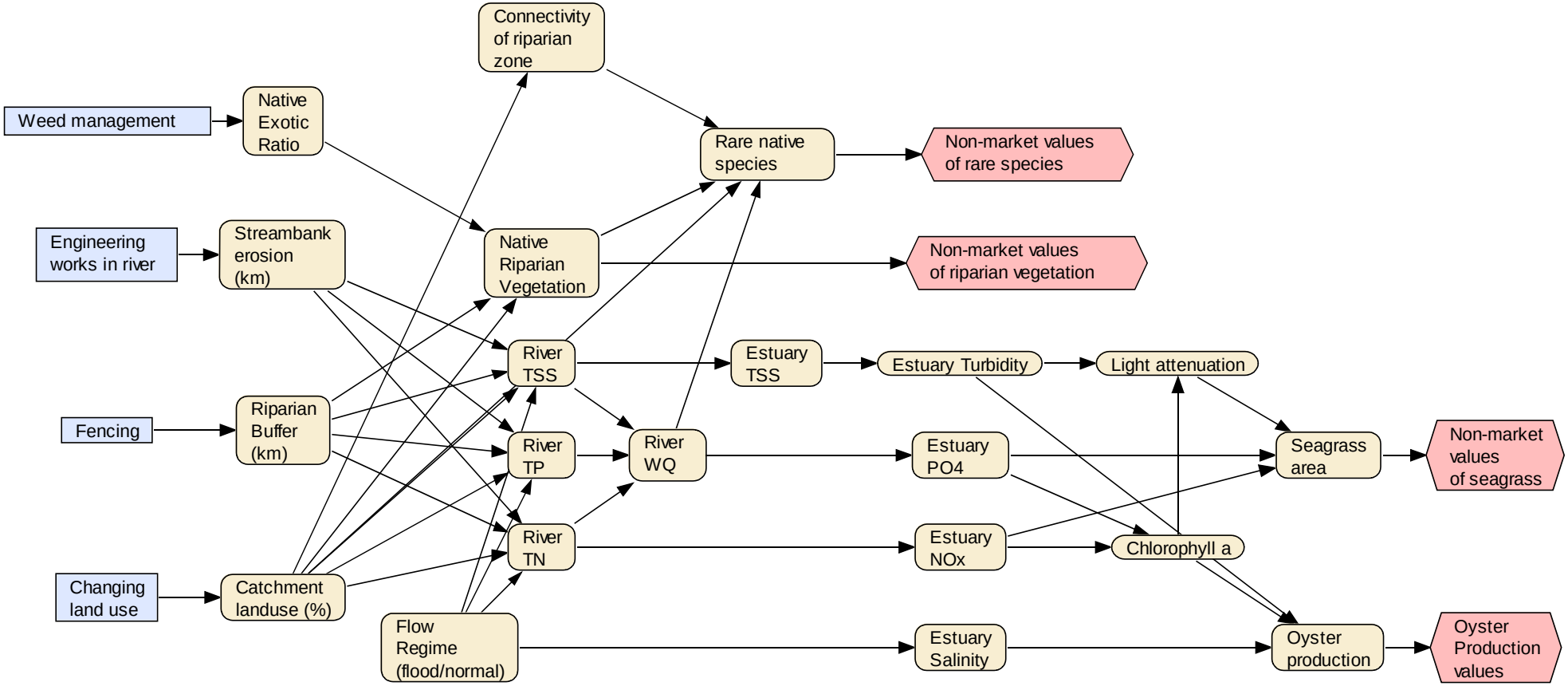
Appendix 1 First conceptual BN framework for the George catchment



Appendix 2 Integrated BN model for the George catchment



Appendix 3 Seagrass and riparian vegetation sub-models in the George catchment BN