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**An Integrated Assessment approach to linking
biophysical modelling and economic valuation tools**

Marit Kragt, Jeff Bennett and Tony Jakeman

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About the authors

Marit Kragt is a PhD Student at the Crawford School of Economics and Government,
Australian National University, Canberra ACT 0200, AUSTRALIA

Jeff Bennett is a Professor at the Crawford School of Economics and Government at
the Australian National University.

Tony Jakeman is a Professor at the Fenner School of Environment and Society at the
Australian National University.

E-mail: marit.kragt@anu.edu.au

Crawford School of Economics and Government
THE AUSTRALIAN NATIONAL UNIVERSITY

http://www.crawford.anu.edu.au

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Abstract

Natural resource management (NRM) typically involves complex decision problems that affect a wide variety of stakeholder values. Efficient NRM that achieves the greatest environmental, social and financial net benefits, necessitates assessments of the environmental impacts, costs and benefits of investments in an integrated manner. Integrated assessment (IA) provides an approach to incorporate the several dimensions of catchment NRM by considering multiple issues and knowledge from various disciplines and stakeholders. Despite the need for IA, there are few studies that integrate biophysical modelling tools with economic valuation.

In this paper, we demonstrate how economic non-market valuation tools can be used to support an IA of catchment NRM changes. We develop a Bayesian Network model that integrates a process-based water quality model, ecological assessments of native riparian vegetation, estimates of management costs and non- market (intangible) values of changes in riparian vegetation. The modelling approach illustrates how information from different sources can be integrated in one framework to evaluate the environmental and economic impacts of NRM actions, as well as the uncertainties associated with the estimated welfare effects. The estimation of marginal social costs and benefits enables a Cost-Benefit Analysis of alternative management intervention, providing more economic rationality to NRM decisions.

Keywords: Bayesian Networks; Bio-economic modelling; Catchment Management; Cost-Benefit Analysis; Environmental values; Integrated Assessment and Modelling; Non-market valuation; Riparian Vegetation

1. Introduction

Natural resource management (NRM) typically involves complex decision problems that involve a variety of issues and evolve in a dynamic social context (Ritchey, 2004; Letcher and Giupponi, 2005). There may be a range of perspectives among stakeholders about the values at stake, varying from environmental and ecological issues to social and economic concerns. It is increasingly acknowledged that catchment NRM requires integrated approaches to address all the potential economic, social and environmental impacts of policy decisions (Letcher and Giupponi, 2005). An integrated assessment (IA) approach to catchment NRM aims to integrate and share scientific and stakeholder knowledge drawn from multiple disciplinary backgrounds, in order to evaluate a decision problem from different perspectives and provide support for its solution (TIAS, 2009). Different tools, methods and procedures are needed to inform the different phases of the assessment process, for example biophysical modelling tools, participatory methods and cost-effectiveness analysis (De Ridder et al., 2007).

Integrated catchment management calls for targeted investments to achieve the greatest environmental, social and financial net benefits (NWI, 2004). If IA is to support the development of efficient catchment NRM, all the marginal social costs and benefits associated with the impacts of alternative NRM actions need to be assessed. However, despite the policy interest and identified need for IA, there are few studies that integrate environmental impact assessments with economic analysis of marginal costs and benefits in a robust framework to guide NRM decisions (Kirkpatrick and Lee, 1999; Croke et al., 2007).

Economics valuation tools can improve the estimates of marginal social costs and benefits of NRM changes. Non-market values are expressed in monetary terms, allowing for a direct comparison of the trade-offs between different environmental impacts. The decision framework for economic valuation is based on cost-benefit analysis (CBA). CBA can support economically rational decision making by systematically assessing and comparing the marginal social costs and benefits of catchment NRM actions. The decision rule is that if the benefits of a policy change exceed its costs by a larger amount than any other management alternative, then the proposed policy should be adopted. Traditionally, CBA has focused on financial analysis and the scientific underpinning of CBA has often been poor (Brouwer et al., 2003: 35). The limited integration of biophysical modelling into traditional CBA studies reduces their flexibility to assist in the formulation and assessment of efficient policies.

In this paper, we demonstrate how economic valuation tools can be integrated with predictions of biophysical changes in one modelling framework. An IA approach underlies the development of an integrated Bayesian Network (BN) model of NRM changes in the George catchment, Tasmania. We show how the model can be used to support a CBA of

catchment management decisions. In the next section, the analytical framework that underlies this study is described. It is shown were biophysical and economic tools and techniques can be used to inform the IA process, and how IA can be combined with CBA to support economically efficient NRM decisions. The various tools that were used to predict impacts of NRM actions on catchment water quality, native riparian vegetation and non-market environmental values are briefly described in Section 3. The model development process and the techniques used to integrate information about multiple systems in the BN model are described in Section 4. The results are illustrated by a model scenario in Section 5. A final section concludes.

2. Analytical framework

The dynamic nature and multiple dimensions of catchment NRM problems require integrated assessment (IA) approaches to help inform and design targeted policies that, in theory, achieve the greatest net social benefit. In order to evaluate the net benefits of alternative policy investments in a CBA decision framework, all the marginal costs and benefits associated with a management change need to be estimated. Environmental changes and financial costs and benefits of NRM changes may be relatively easy to estimate. However, changes in catchment environments will also impact non-market values that people derive from ecosystem goods and services (Hanley and Barbier, 2009: 40). Predicting the changes in these non-market costs and benefits requires the use of non-market valuation techniques. Although there are challenges involved in estimating non-market values (Hanley and Barbier, 2009: 55-61, 67-70 and 91-93), not accounting for non-market values of environmental impacts may lead to a misallocation of resources and less efficient decision making (Bennett, 2005).

We propose the use of an IA approach to assess the changes in environmental[1] and socio-economic systems resulting from catchment NRM changes. IA provides a flexible and multidisciplinary approach to identifying and predicting the impacts on multiple systems. The iterative nature of the IA approach to policy assessments recognises that catchment systems continuously evolve, changing the context of the system and leading to the emergence of new issues and values (Ritchey, 2004).

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[1] In this paper, the term 'environmental' refer to natural systems and impacts on biophysical indicators.

IA phases

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1. Understanding the context        ⟹    Describing the system variables and interactions,
   of the issue                            analysing the institutional and policy context,
                                           identifying the stakeholders involved as well as the
                                           system's spatial and temporal boundaries

2. Identifying                      ⟹    Characterising the (policy) scenarios to be
   policy changes                          considered -which may include controllable and
                                           uncontrollable factors- and specifying the indicators
                                           used to assess impacts.

3. Predicting                       ⟹    Assessing the impacts of a change in the system
   environmental impacts                   context on a range of biophysical indicators (using,
                                           e.g., biophysical modelling tools)

4. Predicting socio-                ⟹    Estimating the economic value impacts of
   economic impacts                        management and environmental changes on human
                                           welfare (using, e.g., economic valuation tools)

5. Policy                           ⟹    Evaluate the impacts of alternative policy actions on
   evaluation                              the system under consideration (using, e.g. cost-
                                           benefit analysis as a decision making framework)
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Figure 1 Analytical steps in an IA process to policy analysis

The set of tools and techniques that is used to carry out an IA should be adapted to the requirements of the issue under consideration (Lee, 2006). Different tools can be used to inform different stages of the assessment process (De Ridder et al., 2007). For example, participatory techniques may be useful to *gain an understanding* about the existing economic, environmental and social context of the issue. Conceptual influence diagrams may be used to *describe* the multiple system variables and their interrelationships. The *identification* of alternative policy strategies can be aided by surveys, focus group discussions or other tools such as General Morphological Analysis (Ritchey, 2004). A *prediction* of environmental or socio-economic changes can be based on biophysical models or economic valuation tools. *Evaluating* the likely outcomes of alternative policies requires the use of decision support tools such as cost-benefit or cost-effectiveness analysis (Ward, 2009).

The research context

Defining the research context requires an understanding about the system variables that are related to the issue under consideration and the interrelationships between them (Jakeman et al., 2006). This entails a description of the biophysical drivers and processes, as well as an analysis of institutions, the affected population, the spatial scales and time periods involved. One major feature of IA is the identification of interest groups and a recognition of different

stakeholder concerns. Stakeholders may include different scientific disciplines, model developers, natural resource managers, and/or local landholders, who will typically have different (and sometimes conflicting) ideas about the issues at stake. An iterative IA approach that involves multiple stakeholders can strengthen a shared understanding about the issue under consideration.

Policy changes

The aim of the second phase is to identify the alternative future policy actions that may be undertaken to address the issues identified in the first step (De Ridder et al., 2007). IA recognises that catchment NRM problems are often not well-defined. A wide range of management scenarios may need to be considered, and these scenarios may need to be amended or refined as the assessment proceeds (Lee, 2006). It is important that the policy scenarios match the (scientific, political and socio-economic) context of the system and are relevant to the stakeholders involved. A characterisation of multiple policy scenarios enables a comparison of the impacts of alternative courses of actions. One of the courses of action should include an analysis of a status quo scenario: the future effects of 'doing nothing' (Dobes, 2009: 48). This establishes the baseline, against which the impacts of alternative policies are assessed.

Environmental impacts

All the potential impacts of the alternative policy actions specified in phase two need to be assessed. This includes an analysis of impacts on bio-physical processes. Science-based modelling tools are useful to represent the interactions between management actions and environmental systems, and to predict the changes in a range of (biophysical) indicators that are impacted by NRM changes. An important feature of IA in this phase is an analysis of the risks and uncertainties in modelling inputs, structure and model predictions (Jakeman and Letcher, 2003).

Socio-economic impacts

An economic valuation of all the relevant impacts of NRM actions is required to allow an assessment of the costs and benefits of alternative policy scenarios. IA modelling studies often focus on natural systems, with a sparse representation of socio-economic costs and benefits (Ward, 2009). Economic tools are needed to estimate the impacts of NRM changes on socio-economic values in monetary terms. The use of money as an indicator of changes allows for a direct analysis of the trade-offs between different systems (such as water quality and biodiversity).[2] All the market and non-market impacts of a policy change are valued over

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[2] Note that an assessment of physical impacts remains an essential prerequisite to environmental valuation

the time period of the project, and discounted into present value terms (Dobes, 2009; Hanley and Barbier, 2009).

Policy evaluation

An IA of catchment NRM implies an analysis of changes in multiple systems and output indicators. This approach reflects different stakeholder perspectives and shows the complexity of the interactions between natural and human systems. However, the use of multiple indicators in the assessment means that impacts are measured in disparate units, which does not allow for a comparison of impacts in a meaningful way (Brouwer et al., 2003: 32). Cost-benefit analysis provides a decision making framework to consistently compare NRM impacts by measuring all impacts in identical (monetary) units. This enables an analysis of the trade-offs between the marginal costs and benefits of alternative policy proposals and can aid decision makes to evaluate the economic efficiency of management changes.

3. Tools

In the research described in this paper, multiple tools are used to inform different phases of the IA process. The principal research objective is to demonstrate how IA can be used to integrate environmental modelling predictions with economic information on the non-market costs and benefits of catchment management changes. The IA process and integration of tools are demonstrated by developing an integrated model for a case study of the George catchment in Tasmania. Knowledge uncertainties about environmental system processes and human-environment interactions are explicitly considered in the modelling approach, allowing an analysis of the risks associated with catchment NRM changes. Acknowledging the diversity of perspectives about catchment management issues, this study engages multiple academic disciplines along with public and other stakeholder representatives.

The first phases of the project were aimed at gaining an understanding of the George catchment system. A complete assessment of all the processes and interactions between variables was not feasible, if possible at all, within the time frame of this study. Subsequent phases therefore narrowed down to assessing changes in ecosystem indicators that were considered to affect human welfare.

Water quality modelling

A physically based, semi-distributed catchment model was developed for the George catchment to predict the impacts of different management actions on river flows, sediment delivery and nutrient loads, calculated as steady-state averages (Kragt and Newham, 2009). The model was based on the Catchment Scale Management of Diffuse Sources framework (CatchMODS - Newham et al., 2004). CatchMODS requires a relatively small number of

parameters and has already been developed and successfully tested in other parts of Australia (Newham et al., 2004; Drewry et al., 2005; Vigiak et al., 2009). The framework integrates a range of process-based hydrologic, erosion and economic sub-models to simulate the effects of different management interventions on various sources of pollution (Figure 2). Scenarios that were considered in the George catchment application include land-use changes, stream-bank remediation actions and riparian-zone revegetation (Kragt and Newham, 2009).
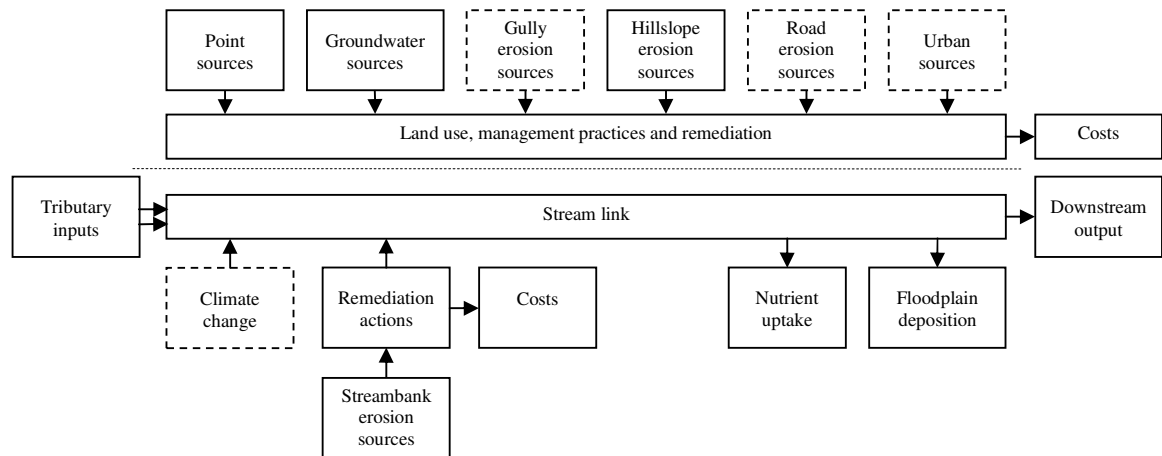
Figure 2 CatchMODS framework (Adapted from Newham et al., 2004)

Choice Experiments

Information about the non-market value impacts of changed catchment NRM was elicited using choice experiment (CE) techniques. CEs use a survey in which respondents are presented with a series of choice questions describing the outcomes of alternative hypothetical policy scenarios (Bennett and Blamey, 2001; Hensher et al., 2005). The outcomes are described in terms of different levels of a monetary attribute (costs) and several non-marketed attributes. Respondents are asked to choose their preferred option in each choice question. This allows an analysis 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. The CE technique is especially useful in cases where management decisions are expected to affect an array of attributes and where policy makers are interested in the trade-offs between attributes (Bennett and Blamey, 2001).

For the present study, a CE survey was developed using a combination of literature review, biophysical modelling, interviews with science experts and regional natural resource managers and feedback from focus group discussions (Kragt and Bennett, 2008). An example choice question is shown in Figure 3. The survey was administered in various regions in Tasmania 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 <u>only ones</u> 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 3 Example choice question in the George catchment CE (Source: Kragt and Bennett, 2009b)

Bayesian Networks

A major challenge in this study was the integration of knowledge from different sources about changes in catchment systems. A process-based model provided predictions of water quality changes, literature values and expert judgements were used to assess changes in ecosystem variables, and CE survey data provided information about non-market value impacts. These different data sources needed to be combined into a logically consistent modelling framework. A further challenge was the representation of knowledge uncertainty about biophysical and socio-economic systems and the interactions between them. A modelling technique that can incorporate different data sources and represent uncertainties are Bayesian Networks (BNs - Pearl, 1988). In this research, BN modelling techniques are used to predict changes in native riparian vegetation and to link the information about multiple catchment systems in a single integrated model for decision support.

BNs (sometimes called belief networks) are probabilistic graphical models, consisting of a directed acyclic graph of variables (called 'nodes'). The values each variable can assume are classified into discrete, mutually exclusive, 'states'. These states can be defined in quantitative levels (e.g. <50, 50-150, 150-300 and >300mg/L) or as qualitative categories (e.g. 'decrease', 'no change', and 'decrease'), enabling the use of different data sources, including expert opinion when observational data is not available (Pearl, 1988). The propagation of information between variables is described by conditional probability tables. Unlike most integrated modelling approaches, BNs thus use probabilistic, rather than deterministic, expressions to describe the relationships between variables (Borsuk et al., 2004).

BNs are widely used for knowledge representation and reasoning under uncertainty in NRM and have been applied to different catchment issues (see, for example, Bromley et al., 2005; McCann et al., 2006; Castelletti and Soncini-Sessa, 2007). There are, however, few BN

applications that focus on economic impacts of environmental changes. We found only one BN publication that has incorporated non-market costs and benefits of catchment management changes (Barton et al., 2008). In that study, financial costs of nutrient abatement measures and impacts of changed land management practices on lake water quality in the Morsa catchment, Norway were analysed. The integration of the expected abatement costs and environmental impacts enabled a cost-effectiveness ranking of abatement measures. The non-market benefits of improved water quality on recreation were also evaluated, using results from a 1994 contingent valuation survey. Combining the economic valuation of water quality benefits to abatement costs allowed a cost-benefit analysis of alternative management actions in the catchment. The study showed that accounting uncertainty through a BN modelling approach could conflict with the outcomes of deterministic cost-effectiveness or cost-benefit analyses. However, the economic data collected in Barton et al. (Barton et al., 2008) was not specifically designed to match the biophysical modelling predictions. Synchronous model development could have improved the integration of biophysical and economic knowledge.

4. The George catchment model

The IA study described in this paper demonstrates the integration of environmental modelling predictions with economic information in a BN model of catchment management in Tasmania. A multidisciplinary process involving researchers from various disciplines was used to select a study area that was suitable for both the biophysical modelling and the economic research. The George catchment, in North-Eastern Tasmania, was chosen as a suitable study area because scientific monitoring data were available for catchment hydrology, water quality and ecosystem conditions and because the catchment has significant socio-economic values through its environmental assets, recreational values and aquaculture production in the estuary. Land use in the catchment is dominated by native vegetation, native forestry, forest plantations and agriculture. Although the catchment environment is currently in good condition (Davies et al., 2005), there are significant concerns that land use changes are affecting catchment ecosystem conditions (Sprod, 2003; BOD, 2007).

In the first phase of the IA process, a conceptual influence diagram was developed to define the scale and scope of the system under consideration. Natural scientists, policy makers and community stakeholders were involved in the conceptual model development[3], to ensure that

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[3] The consultation process involved three workshops with Tasmanian scientist between November 2007 and September 2008, 31 structured interviews with experts on river health, threatened species, bird ecology, forestry management, riparian vegetation, estuary ecology and local natural resource

the considered variables and links between variables matched the scientific and policy context of the system. The geographical scale of the system was based on the contours of the George catchment, delineated using digital elevation models. A projection of changes in the next twenty years was considered an appropriate time frame from both a biophysical and socio-economic modelling perspective. The model development was an iterative process, aimed at identifying a parsimonious model that would represent the interactions between catchment management actions and environmental variables that impact human welfare (Kragt and Bennett, 2009a; Kragt et al., 2009). The conceptual model for the George catchment (Appendix 1) incorporated three main ecosystem indicators (used as attributes in the CE survey): native riparian vegetation, number of rare native species and the area of seagrass in the estuary. Local management changes that impact these ecosystem attributes are: (i) Stream-bank engineering works; (ii) Riparian zone management through limiting stock access to rivers and establishing buffer zones; (iii) Changed catchment land use; and (iv) Vegetation management through weed removal. 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 CE study.

There was not enough information about changes in all the variables included in the conceptual model (Appendix 1) to develop a fully functioning Bayesian Network (BN) for the whole George catchment system. To adequately populate the conditional probability tables for all variables, one needs to know the probability that a certain state is observed at *every possible combination* of the input variables. Within the time frame of this study, it was not feasible to collect data about all the variables in the conceptual model and specify the relationships between them as probability distributions. Research efforts therefore focused on a sub-section of the conceptual model. A BN was developed that integrates the costs of management actions (stream-bank engineering, establishing riparian buffer zones, changing catchment land use and weed management) with predictions of river water quality (flows and total suspended sediment, phosphorus and nitrogen loads), native riparian vegetation length and non-market values (Figure 4). Each of the model variables is described in more detail in Appendix 2. The different techniques used to predict the levels of the variables and the ways in which they were integrated into one BN model are described below.

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managers and eight focus group discussions with members of the public in Hobart, St Helens and Launceston in February and August 2008.
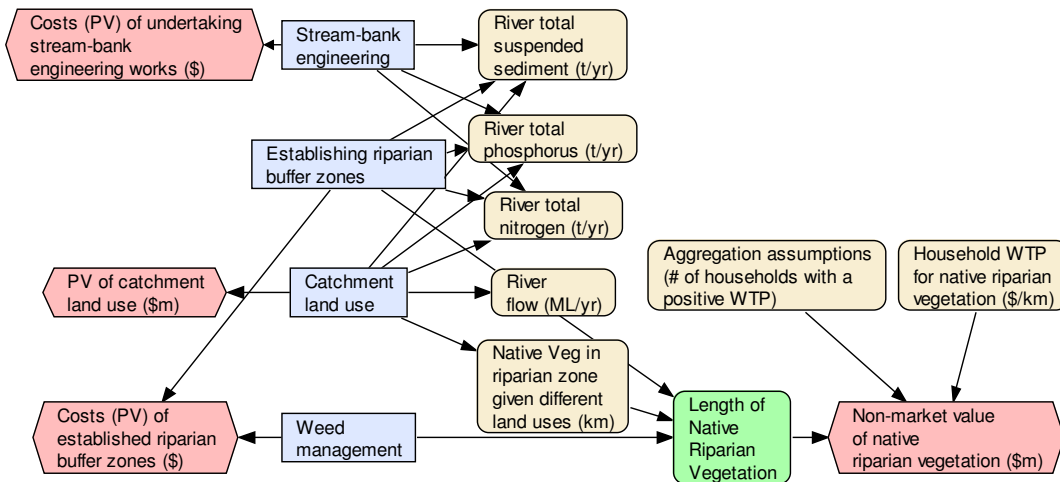
Figure 4 Integrated model for predicting water quality changes, impacts on native riparian vegetation, and changes in economic costs and benefits in the George catchment

Predicting management costs

The main focus of this research was the integration of environmental modelling and non-market valuation. However, in order to demonstrate how the integrated assessment and modelling approach can be used in a CBA, the direct costs associated with implementing and maintaining management actions were included in the model. Assumptions about the costs of NRM in the George catchment were based on literature values (Appendix 3). The impacts of land use changes were represented as the change in aggregate present values (PVs) of different land use scenarios in the George catchment. The costs of establishing riparian buffer zones and stream-bank engineering works were calculated as the PV of the summed one-off implementation costs and discounted maintenance costs over a twenty year period. A discount rate of three percent was used in the PV calculation. It is worth noting here that the BN could be extended with a 'discount rate' node to show how alternative discount rates would impact the predicted management costs.

Notwithstanding efforts to obtain accurate information, the knowledge about management costs in the George catchment remains limited. Uncertainties arise from, for example, knowledge gaps about the returns to land use, the types of materials used and the labour time involved in implementation and maintenance. These uncertainties are represented in the BN model by estimating a *range* of costs, rather than a single value (Appendix 3). Given the limited number of data-sources and the high levels of uncertainty in knowledge, the predicted costs should be seen as an illustration rather than reliable estimates for a CBA.

Predicting water quality changes

The process-based George-CatchMODS water quality model was used to predict the impacts of management changes on steady state average mean annual river flow (MAF in '000

ML/year) and steady state average loadings of total suspended sediment (TSS in tonnes/year), total phosphorus (TP in tonnes/year) and total nitrogen (TN in tonnes/year) to the George catchment streams and estuary. Monte Carlo simulations of the George-CatchMODS model were run that combined different scenarios of land use changes with varying lengths of stream-bank engineering works and riparian buffer. The results from the Monte Carlo simulations were used to define the conditional probability distributions for the water quality variables. Uncertainties in the predictions arise from uncertainty in the model parameters and were specified as an uncertainty bound around the deterministic predictions from the George-CatchMODS model.

Predicting impacts on native riparian vegetation

The impacts of NRM actions on native riparian vegetation were predicted based on information collected through literature reviews and expert interviews (Kragt and Bennett, 2008).[4] The most important management actions assumed to impact native riparian vegetation in the George catchment are land use changes, establishing riparian buffer zones[5] and weed management in the catchment (Figure 4). An intermediate node ('Native Veg in riparian zone given different land uses') was included to measure the length of native vegetation in the riparian zone under different land use scenarios. Assumptions about the proportion of the riparian zone that is likely to be vegetated under each land use, and the 'naturalness' of that vegetated riparian zone were based on Tasmanian digital vegetation mapping (DPIW, 2005a; DPIW, 2005b) and expert review (Table 1).

Table 1 Modelling assumptions about the percentage of native vegetation in the riparian zone under different land uses

Land use	% of total riparian zone likely to be vegetated	% of native vegetation
Native vegetation non-production	100	80
Native production forest	90	70
Forestry plantations	80	30
Grazing pastures	0	-
Irrigated agriculture	0	-
Urban areas	0	-

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[4] The review included regional, State and National documents about the impacts of catchment management on native vegetation conditions, and previously developed models of vegetation changes in river catchments. Structured interviews were conducted with Tasmanian experts on river health and riparian vegetation.
[5] Note that establishment of riparian buffer does not change catchment land use in our model

The 'Length of Native Riparian Vegetation' variable in Figure 4 measures the total length of rivers in the George catchment with healthy native vegetation along both sides of the river. The intermediate node 'Native Veg given land use' was assumed to contribute directly to the total Length of Native Riparian Vegetation in the George catchment. The base case assumption was that agricultural and urban areas did not have any vegetation in their riparian zones, but that the establishment of riparian buffers and weed management could increase this. The 'nativeness' of the newly established riparian buffers depend on the type of vegetation that is planted and the extent of weed management in the riparian zone (Daley, 2008). It was assumed different weed management scenarios would result in different proportions of native vegetation in the established riparian buffer:

- 'low' weed management → 15 percent of healthy native vegetation in the established riparian buffer zones;
- 'medium' weed management → 50 percent of healthy native vegetation in the established riparian buffer zones;
- 'high' weed management → 85 percent of healthy native vegetation in the established riparian buffer zones.

These assumptions mean that if, for example, six km of riparian buffer is established with 'medium' weed management, the contribution to the total Length of Native Riparian Vegetation in the George catchment is three km (in addition to the native vegetation in the riparian zone under the given land use scenario). Uncertainty in the assumptions was accounted for by imposing a 95% uncertainty bound on the calculated values.

The riparian vegetation model was used to predict the length of native riparian vegetation in the George catchment under a 'best case' and 'worst case' scenario. The predictions ranged from 40km (the 'worst case' scenario) to 81km (the 'best case' scenario) and were used as attribute levels in the CE survey (Kragt and Bennett, 2009b).

Estimating non-market values

The non-market values of the native riparian vegetation in the George catchment were estimated based on results from the CE study. CE results indicated that Tasmanian households are, on average, willing to pay (WTP) 3.57$ for every km increase in native riparian vegetation (Kragt and Bennett, 2009b). Note that the point of reference (the 'status quo scenario) presented in the CE survey was the 'worst case' scenario of 40km of native riparian vegetation in the George catchment and that the WTP results are valid within the range of presented scenarios (i.e. 40-81km). The CE results also provided information about the uncertainty range in the WTP distribution, with an estimated standard deviation of 0.532.

Household WTP estimates are expressed as *marginal* values. This means that the CE data provides information about the non-market value of a *change* in the length of riparian vegetation. Individual household WTP was aggregated over the total numbers of households in the 'relevant' population to calculate the total non-market values of changed native riparian vegetation condition in the George catchment. What constitutes the 'relevant' population and which proportion of this population has a positive WTP is subject to debate (Morrison, 2000). To reflect this aggregation issue, an additional variable 'Aggregation assumptions' was included in the BN. This variable represents three alternative assumptions for aggregating the household WTP estimates:

- Only the survey respondents have a positive WTP = 832 households;
- 64 percent[6] of all households at the sample locations has a positive WTP = 35,799 households;
- 64 percent of all Tasmanian households have a positive WTP = 116,418 households (ABS, 2006a).

5. Results

Different tools and data sources were used to define the conditional probability distributions that link the various components of the catchment system in one BN model (Figure 4). A process-based water quality model was integrated with a probabilistic model of native riparian vegetation length through a matching of management scenarios. These biophysical models predict the environmental conditions in the George catchment, given a certain management input. Note that CBA of NRM actions are based on analyses of *marginal* changes, which requires predictions of *changes* in environmental conditions that result from implementing new management actions. In the integrated model, this was achieved by using the predictions from the biophysical models in a before and after the management change (Figure 5).The costs of changed management were predicted based on literature values. Predictions of changes in the length of native riparian vegetation were integrated with data from a choice experiment (CE) study to provide information about the non-market benefits of changed native riparian vegetation conditions.

The integrated model can be used to assess the impacts of NRM actions on a range of indicators, including water quality parameters, native riparian vegetation condition and non-market environmental values. Including the management costs of NRM actions as well as non-market benefits allows a cost-benefit analysis (CBA) to determine which management

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[6] The average survey response rate was 64 percent (Kragt and Bennett, 2009b)

investments deliver the greatest net returns to society. Using a BN modelling approach accounts for knowledge uncertainty in the input data and allows an analysis of the *probability* that one of the output indicators is in a certain state, given the management interventions.

Policy evaluation

To illustrate how the model enables an integrated impact assessment of different scenarios, results of an example scenario are presented in Figure 5. In this scenario, land use in the George catchment is as currently observed, and no stream-bank engineering works are undertaken. The top part of the figure illustrates the predicted environmental conditions before implementing a management change. For example, the model predicts a 73.3 percent probability that total suspended sediment loads are between 6900 and 8000 tonnes/year. The bottom part of Figure 5 illustrates the impacts of establishing between six and twelve km of additional riparian buffers combined with 'medium' weed management actions. Total suspended sediment loads are now predicted to be between 6100 and 6900 tonnes/year. The direct costs of establishing new riparian buffers are approximately $149,000 (Figure 5). Uncertainty in the predicted costs is represented in the model by predicting a 92.3 percent probability that costs are somewhere between $100,000 and $200,000. If no changes are made to land use or stream-bank engineering, establishing an additional six to twelve km of riparian buffers with 'medium' weed management is most likely to increase the length of native riparian vegetation in the George catchment from between 45 and 67km ('before') to between 67 and 78km ('after'). Note that uncertainty in the model still leads to a 32.4 percent probability that the length of native riparian vegetation will remain between 45 and 67km.

If we assume that 64 percent of the population at the sample locations has a positive WTP for riparian vegetation changes, there is a 32.4 percent probability that the total non-market value of the change in native riparian vegetation is between two and five million dollars. However, uncertainty in the predicted length of native riparian vegetation and uncertainty in household WTP results in a predicted probability of 24.3 percent that the total non-market values are between one and two million dollars, and even a 21.9 percent probability that there is no change in non-market values at all. Hence, although the length of native riparian vegetation is likely to increase as a result of establishing riparian buffer zones in the George catchment, there remains a probability that the benefits will not outweigh the costs.

Sensitivity analysis

Sensitivity analyses were also conducted, to assess which variables have the largest influence on reducing the uncertainty in predicted length of native riparian vegetation and total non-market values. These analyses revealed that, in our model, establishing new riparian buffer zones, land use changes and the assumptions on native vegetation under different land uses

have the largest impact on uncertainty in the predicted total Length of Native Riparian Vegetation in the George catchment. The predicted Length of Native Riparian Vegetation, establishing riparian buffers and land use changes have the largest impact on uncertainty in the predicted total non-market values.

MANAGEMENT AND ENVIRONMENTAL CONDITIONS - BEFORE

Stream-bank engineering (0 km)

Total Suspended Sediment (t/yr)	
4500 to 5500	6.67
5500 to 6100	6.67
6100 to 6900	6.67
6900 to 8000	73.3
8000 to 12300	6.67
7290 ± 1100	

TN (t/yr) TP (t/yr)

Catchment land use (current land use scenario)

Flow (ML/yr)

Establishing riparian buffer (km)	
none	100
0 to 6 km	0
6 to 12 km	0
> 12km	0
0 ± 0	

Native Vegetation in the riparian zone given land use (km)

COSTS

Costs (PV) of undertaking additional stream-bank engineering ('000$)

BENEFITS

Weed management	
Low	100
Medium	0
High	0
0.15	

Length of Native Rip Veg (km)	
<45 km	2.00
45-67 km	88.5
67-78 km	9.50
>78 km	0
57.2 ± 8.3	

Aggregation assumptions (# of hholds)	
Only sampled hh	0
RR at sample locations	100
RR at all TAS	0
35799	

PV of changed catchment land use ($m)

Total non-market value of change in Nat...	
no value change	21.9
0-0.5 $m	7.97
0.5-1 $m	11.8
1-2 $m	24.3
2-5 $m	32.4
5-10 $m	1.24
10-20 $m	0.40
20-45 $m	0 +
>45$m	0
-13.6 ± 35	

MANAGEMENT AND ENVIRONMENTAL CONDITIONS - AFTER

Costs (PV) of establishing additional ripa...	
no costs	1.54
0-40 ('000$)	1.54
40-100 ('000$)	1.54
100-200 ('000$)	92.3
200-500 ('000$)	1.54
500-2500 ('000$)	1.54
149 ± 270	

Stream-bank engineering (0 km)

Total Suspended Sediment (t/yr)	
4500 to 5500	4.00
5500 to 6100	4.00
6100 to 6900	84.0
6900 to 8000	4.00
8000 to 12300	4.00
6600 ± 890	

TN (t/yr) TP (t/yr)

Catchment land use (current land use scenario)

Flow (ML/yr)

Establishing riparian buffer (km)	
none	0
0 to 6 km	0
6 to 12 km	100
> 12km	0
9 ± 1.7	

Native Vegetation in the riparian zone given land use (km)

Household WTP ($) for changes in NatRi...	
0 to 2	0.16
2 to 3	13.9
3 to 4	64.8
4 to 5	20.7
5 to 6	0.37
6 to 10	0 +
3.57 ± 0.67	

Weed management	
Low	0
Medium	100
High	0
0.5	

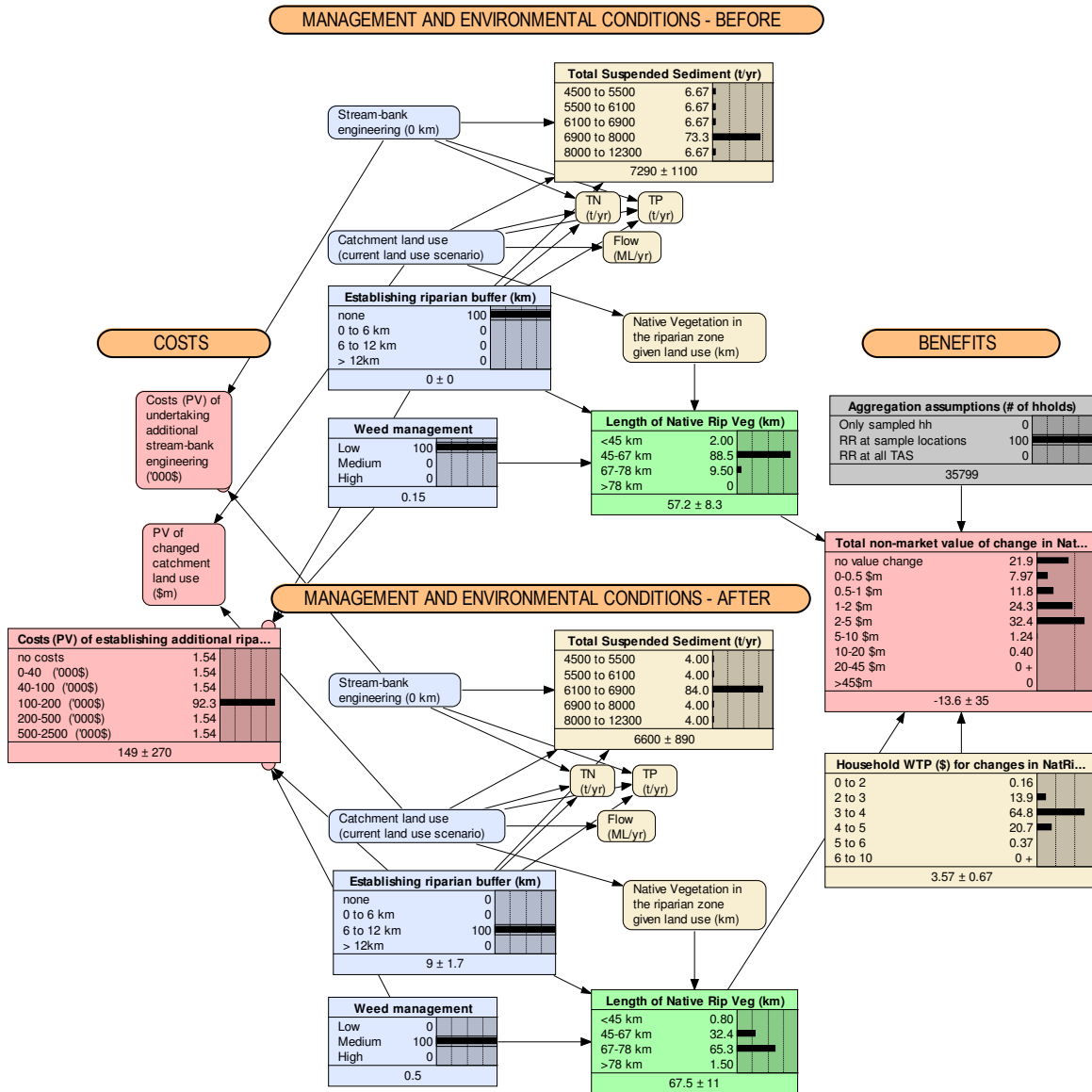| Length of Native Rip Veg (km)	
<45 km	0.80
45-67 km	32.4
67-78 km	65.3
>78 km	1.50
67.5 ± 11	

Figure 5 Scenario analysis of establishing between 6-12 km new riparian buffers with 'medium' weed management in the George catchment, assuming that 65 percent of the population at the sample locations have a positive WTP and keeping land use and stream-bank engineering constant

6. Discussion and conclusion

The research described in this paper aimed to assess the impacts of catchment NRM actions in the George catchment, Tasmania, on biophysical and economic systems in an integrated manner. IA provided a useful approach to integrate the multiple dimensions of catchment NRM, by considering a range of issues and knowledge from different stakeholders. Various academic disciplines, policy makers and community stakeholders were engaged in the model development. The iterative consultation process provided valuable inputs to account for multiple stakeholder perspectives in the final integrated model. Probabilistic modelling techniques were used to integrate results from deterministic models, expert interviews and survey data into a Bayesian Network (BN) model of management costs, river water quality, native riparian vegetation and non-market values.

A major focus of this research was the integration of non-market valuation with scientific predictions of environmental changes. The integrated, iterative process to developing the biophysical models and the economic non-market valuation survey tailored the information exchange between separate model components and ensured that the outputs of the different tools were compatible with each other. A conceptual BN model was developed that demonstrates the integration of environmental modelling with economic information about the costs and benefits of NRM actions. Including these costs and benefits in the modelling framework allows for a cost-benefit analysis of alternative NRM investment strategies, providing policy makers with a tool to assess the net social benefits of their decisions. Contrary to traditional CBA studies, the integrated model accounts for uncertainties in the relationships between NRM actions, environmental impacts and economic consequences in a probabilistic way. The wide probability distributions in the scenario predictions show the large uncertainties in predicted costs and benefits. The explicit recognition of these probabilities enables an assessment of the risks associated with implementing new management actions.

Some challenges related to using a BN modelling approach should also be mentioned here. The stakeholders involved in the model development process found it difficult to express their knowledge about relationships between variables as probability distributions. Another limitation of BN models lies in its use of discrete states, rather than continuous probability distributions. Information losses arise from discretisation of probability distributions, which may affect modelling outcomes.

The model development was based on limited information about management costs and ecosystem changes in the George catchment. This means that model predictions of the net welfare impacts should not be considered as reliable inputs into a CBA. Results from the

sensitivity analysis indicated that future research should focus on the impacts of riparian buffers or land use on native vegetation in the riparian zone to reduce the uncertainty in the model predictions. It is also recommended that the estimated management costs undergo further peer review to improve the accuracy of predictions.

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Appendix 1 - Conceptual model for the George catchment, incorporating four management actions (stream-bank engineering, creating riparian buffer zones, land use changes and weed management) and three environmental attributes (seagrass, rare native species and native riparian vegetation)
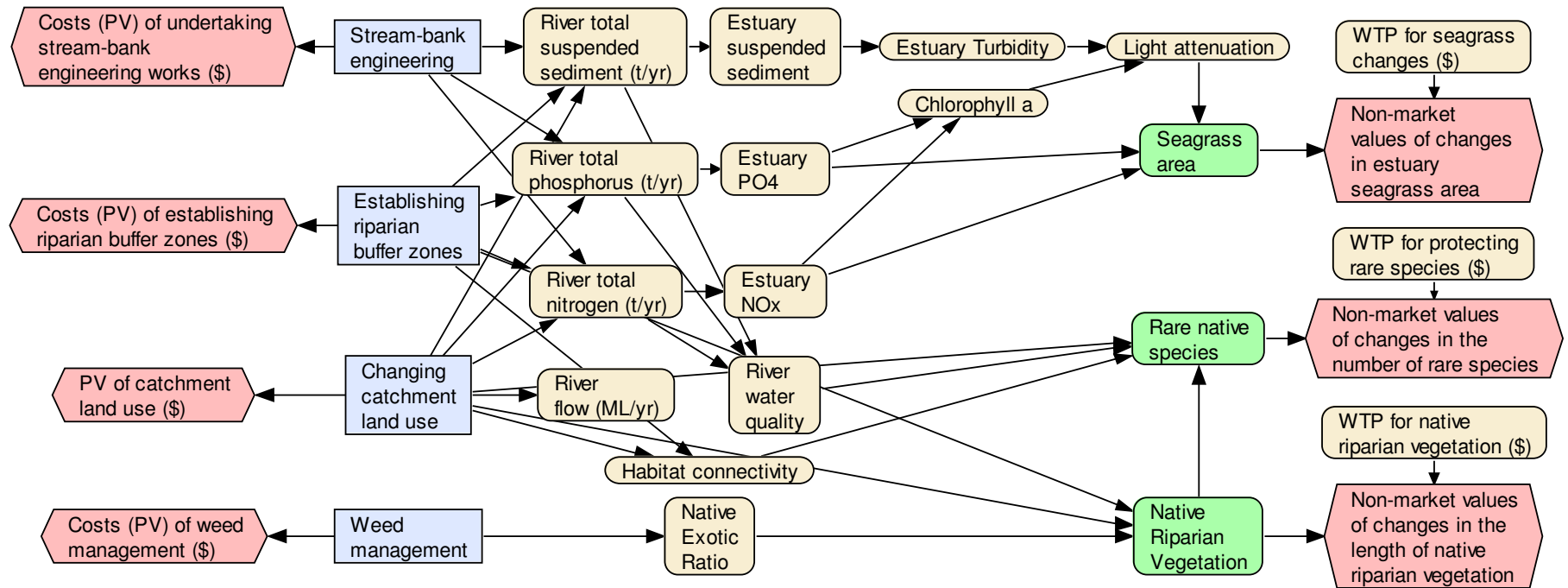
Appendix 2 Variables in the integrated model for the George catchment model

Variable	Description	States	Variable type	Data/information sources
Costs of undertaking stream-bank engineering works	Present value of the one-off implementation costs of stream-bank engineering works plus the discounted maintenance costs^	0, 0-50, 50-100, 100-150, 150-200, 200-400 ('000$)	Utility, continuous	Literature values (see Appendix 3)
PV of catchment land use changes	Total present value of land use changes in the George catchment	<-10, -10to-5. -5to-2, -2to0, 0, 0-2, 2-5, 5-10, >10 ($m)	Utility, continuous	Literature values (see Appendix 3)
Costs of established riparian buffer zones	Present value of the one-off implementation costs of establishing a riparian buffer zone plus the discounted maintenance costs associated with continuing weed management in the riparian buffer zone^	0, 0-40, 40-100, 100-200, 200-500, 500-2,500 ('000$)	Utility, continuous	Literature values (see Appendix 3)
Stream-bank engineering	Length of stream-bank engineering works undertaken in the George catchment to reduce stream-bank erosion	none, 0-3, 3-7, >7 (km)	Management action, continuous	Observed length of actively eroding sites from George Rivercare Plans (Sprod, 2003; Lliff, 2002).
Establishing riparian buffer zones	Length of riparian buffers established on agricultural and urban lands to reduce stream-bank erosion and trap sediment runoff from hill-slope erosion	none, 0-6, 6-12, >12 (km)	Management action, continuous	Modelling assumptions
Changing catchment land use	Changes in the total catchment area under alternative land uses (native vegetation non-production, native production forest, forestry plantations, grazing pastures, irrigated agriculture, urban area)	Current land use, loss native vegetation, expanding native vegetation, expanding production forest, expanding plantation forest, expanding agriculture, urbanisation (low, medium, high)	Management action, discrete	Modelling assumptions
Weed management	Weed control measures and planting native vegetation to improve the naturalness of the riparian zone	low, medium, high	Management action, discrete	Australian National Resource Atlas (NLWRA, 2000)

Variable	Description	States	Variable type	Data/information sources
River total suspended sediment (TSS)	Total Suspended Sediments loads into the Georges Bay at St. Helens under alternative management scenarios	4500-5500, 5500-6100, 6100-6900, 6900-8000, 8000-12300 (tonnes/year)	Nature, continuous	Modelled in CatchMODS water quality model
River total phosphorus (TP)	Total Phosphorus loads into the Georges Bay at St. Helens under alternative management scenarios	2.4-3.6, 3.6-4.1, 4.1-4.6, 4.6-5.7, 5.7-12 (tonnes/year)	Nature, continuous	Modelled in CatchMODS water quality model
River total nitrogen (TN)	Total Nitrogen loads into the Georges Bay at St. Helens under alternative management scenarios	66-80, 80-90, 90-100, 100-120, 120-220 (tonnes/year)	Nature, continuous	Modelled in CatchMODS water quality model
River flow	Total river flows into the Georges Bay at St. Helens under alternative land use scenarios	178-183, 183-188, 188-191, 191-203, 203-230 ('000 ML/year)	Nature, continuous	Modelled in CatchMODS water quality model
Native veg in riparian zone given different land uses	The total length of native vegetation in the riparian zone under alternative land use scenarios	<60, 60-65, 65-70, >70 (km)	Nature, continuous	Calculated in the model, based on assumptions of native vegetation
Length of Native Riparian Vegetation	The total length of native riparian vegetation given land use changes, creation of riparian buffers and weed management	<45, 45-67, 67-78, >78 (km) (equivalent to <40%, 40-60%, 60-70%, >70% of total catchment stream length)	Nature, continuous	Calculated in the model, based on assumptions of native vegetation from expert consultation
Aggregation assumptions	Assumptions on the total number of households in Tasmania with a positive marginal willingness-to-pay	Only sampled households (= 832), RR at sample locations (= 35,799), RR at all TAS (= 116,418)	Nature, discreet	Modelling assumptions based on choice experiment response rate and total number of households in Tasmania
Household WTP for change in native riparian vegetation	Household marginal willingness-to-pay for every additional km of native riparian vegetation, compared to the base case scenario (= 40km of native riparian vegetation left in the catchment)	<2, 2 to 3, 3 to 4, 4 to 5, 5 to 6, >6 ($)	Nature, continuous	Choice experiment survey results
Total non-market values of changes in native riparian vegetation	The total non-market value of increased length in native riparian vegetation in the George catchment, compared to the base case scenario	0, 0-0.5, 0.5-1, 1-2, 2-5, 5-10, 10-20, 20-45, >45 (m$)	Utility, continuous	Equation combining parent nodes 'WTP', 'Aggregation assumptions' and 'Native Riparian Vegetation'

^ Discounted at three percent over a twenty year period

Appendix 3 Assumptions on the costs of George catchment NRM actions

PV of alternative land uses ($/ha)[a]	Min	Max	Data sources
Native vegetation non-production[b]	0	0	-
Native production forest	156	260	(Freeman and Dumsday, 2003; FPA, 2007; ABARE, 2009)
Forestry plantations	612	1,740	(Freeman and Dumsday, 2003; ABARE, 2009)
Grazing pastures	-23	220	(NLWRA, 2000; ABS, 2006b)
Irrigated agriculture	491	546	(NLWRA, 2000; ABS, 2006b)
Urban areas	0	0	-
Stream-bank engineering			
Establishment ($/km)	4,000	10,380	(Lliff, 2002)
Maintenance ($/km/yr)	640	1,920	(Lliff, 2002)
PV of costs ($/km)[c]	13,167	37,882	
Riparian buffer zone			
Creating buffer– low weeding ($/km)[d]	1,900	9,600	(Sprod, 2003; Thorn, 2007)
Creating buffer– med weeding ($/km)[d]	7,900	15,600	(Sprod, 2003; Thorn, 2007)
Creating buffer– high weeding ($/km)[d]	25,900	36,600	(Sprod, 2003; Thorn, 2007)
Maintenance - low weeding ($/km/yr)	100	300	(Sprod, 2003)
Maintenance - med weeding ($/km/yr)	700	900	(Sprod, 2003)
Maintenance - high weeding ($/km/yr)	2,500	3,000	(Sprod, 2003)
PV of costs – low weeding ($/km)[c]	3,332	13,897	
PV of costs – medium weeding ($/km)[c]	17,927	28,491	
PV of costs – high weeding($/km)[c]	61,709	79,571	

[a] Present value of land use calculated as gross margins over a twenty year period; [b] No direct returns from native forests were included in the calculations. However, given that the George catchment is visited by >150,000 individuals each year (Tourism Tasmania, 2008) and the positive forest recreational values found in other studies (e.g. Dyack et al., 2007), the returns from native forest may be considerable; [c] Assuming a three percent discount rate and twenty year time period; [d] Assuming that creating riparian buffers incurs a one-off establishment costs for fencing, willow removal and provision of alternative watering points, with maintenance costs are based on the level of continuing weed management in the riparian buffer zone