LANDSCAPE LOGIC
LINKING LAND AND WATER MANAGEMENT TO RESOURCE CONDITION TARGETS

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Developing a water-quality model for the George catchment, Tasmania

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Cover: Erosion near Binalong Road.

LANDSCAPE LOGIC is a research hub under the Commonwealth Environmental Research Facilities scheme, managed by the Department of Environment, Water Heritage and the Arts. It is a partnership between:

- **six regional organisations** – the North Central, North East & Goulburn–Broken Catchment Management Authorities in Victoria and the North, South and Cradle Coast Natural Resource Management organisations in Tasmania;
- **five research institutions** – University of Tasmania, Australian National University, RMIT University, Charles Sturt University and CSIRO; and
- **state land management agencies in Tasmania and Victoria** – the Tasmanian Department of Primary Industries & Water, Forestry Tasmania and the Victorian Department of Sustainability & Environment.

The purpose of Landscape Logic is to work in partnership with regional natural resource managers to develop decision-making approaches that improve the effectiveness of environmental management.

Landscape Logic aims to:

1. Develop better ways to organise existing knowledge and assumptions about links between land and water management and environmental outcomes.
2. Improve our understanding of the links between land management and environmental outcomes through historical studies of private and public investment into water quality and native vegetation condition.

Developing a water-quality model for the George catchment, Tasmania

By Marit E. Kragt and Lachlan T.H. Newham

Summary

In order to make informed decisions, catchment managers require information about the likely impacts of management changes on catchment water quality. The Landscape Logic project, was set up to provide information by investigating how land use can impact river flows and water quality, and how water quality changes in turn affect riverine and estuarine aquatic ecosystems.

Over the past two years, a catchment-scale water quality model has been developed for the George catchment, Tasmania. The model development took place under the Landscape Logic Knowledge Integration Theme. The CatchMODS modelling framework was used to identify (i) the likely sources of sediment and nutrients in the George catchment and (ii) options to manage sediment and nutrient loadings to the George catchment rivers and the Georges Bay estuary. This report describes the hydrologic, sediment and nutrient export modules that are included in the George catchment model, and the data sources that were used in the model's development. The George catchment model includes the likely impacts of a range of land-use changes and riparian management interventions, and can readily be extended to include climatic and land management changes.

The modelling suggested that the North and South George sub-catchments in the west of the catchment are the major sources of sediment and nutrient loads to the George River, primarily through hill-slope erosion, while the Upper and Lower George sub-catchments are significant sources of nutrients through stream-bank erosion. Consequently, management actions that reduce or trap hill-slope erosion in the western parts of the catchment and riparian zone management that reduces stream-bank erosion in the middle of the catchment are the most likely strategies to reduce nutrient and sediment loadings to Georges Bay.

This research is supported by the Environmental Economics Research Hub and Landscape Logic, both of which are funded through the Australian Government's Commonwealth Environmental Research Facility program, managed by the Department of Environment, Water, Heritage and the Arts.

Chapples Bend in the Georges River.

Contents

Introduction

To maintain and improve the productivity and health of natural resources, catchment management needs to be based on accurate scientific information. The Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIWE) is committed to using detailed information on the condition of land and water resources and understanding how these resources are linked as a basis for catchment management decisions (DPIW, 2007). Information about how catchment management practices impact river flows and water quality is fundamental in establishing effective catchment management policies and practices and providing performance indicators to assess the effectiveness of environmental programs.

To aid informed decision-making, the Landscape Logic project aims to develop evidence-based tools that enable an assessment of the links between land management actions and river health conditions. The present report is part of a larger research project that aims to demonstrate how different processes associated with catchment management actions can be integrated into a decision-making framework. The outcomes of the study will enable decision makers to analyse the tradeoffs between the costs and benefits associated with changes in catchment management and environmental conditions. In this report, the results of two years of research on predicting changes in sediment and nutrient loadings to the streams and estuary of the George catchment, Tasmania, are described.

Section 1 outlines the various approaches to water quality modelling, describing how physical processes and spatial and temporal variability can be represented. Section 2 provides an overview of different approaches to predicting sediment and nutrient loads in Australian catchments including the CatchMODS framework that was used for this study. Descriptions of the CatchMODS structure, algorithms and input data for the George catchment model are provided in Sections 3 and 4. Section 5 describes the modelling platform, while Section 6 presents the results of the model calibration and shows examples of predicted sediment and nutrient changes in the George catchment under different management scenarios. A discussion of the modelling process and the George catchment framework is presented in Section 7.

Fending on Groom River at Goshen.

Model classifications

Hydrological models are biophysical models that aim to predict the impacts of environmental change and human intervention on changes in water quantity and/or quality in physical and/or chemical terms. Models may focus on surface water or ground-water and are classified based on the way they represent spatial or temporal variability (Singh, 1995).

A classification system based on the way a model represents spatial scales distinguishes between lumped and distributed models. In lumped models, a catchment is considered as a single functional unit, with variables and parameters representing average values for the entire catchment. Distributed models take spatial variability into account by considering catchment processes in multiple, geographically distributed areas within a catchment. In semi-distributed models, spatial units with the same characteristics (for example, land use or vegetation) are lumped within larger sub-units (for example, sub-catchments or hydrological response units), without regard for the explicit location of each unit.

Models may operate at different temporal scales. Models may be continuous time or event-based; they might focus on daily changes or on longer (e.g. monthly or annual) averages. This temporal classification of models is dictated by the interval of computation. The shorter the time interval of the model components, the smaller the temporal scale of the overall model (Singh, 1995).

A distinction between deterministic models can also be made based on a model's description of biophysical processes. The treatment of biophysical processes can be empirical, conceptual or physically based. Empirical models, often called 'black box' models, typically involve mathematical equations based on observed input and output data. Empirical models are often based in statistics without an explicit description of the underlying processes responsible for the observed changes (Refsgaard, 1996: 19). Conceptual models use verbal descriptions, equations, governing relationships or 'natural laws' that purport to describe biophysical processes. Although based in empirical observations, conceptual models use simplified descriptions to 'conceptualise' variability in catchment characteristics (Refsgaard, 2007: 10). Physically-based models are often detailed models containing equations that provide comprehensive descriptions of the biophysical processes involved in catchment hydrology.

Georges River downstream water intake at Reids Road.

Water-quality models

Australia has a unique hydrological setting that has strongly influenced the development of water-quality models built for Australian catchments (Croke and Jakeman, 2001). For example, there is a high spatial and temporal variability in rainfall, with areas that experience long periods of drought as well as widespread flooding events. Demand for water resources is concentrated in the populated coastal areas where demand is increasingly exceeding supply. The impacts of large storage dams and groundwater usage extend from lowering water tables and dryland salinity to impacts on ecosystem from reduced river flows.

There is relatively little data available about biophysical processes in Australia compared to Europe or America. Information on erosion, soil properties or spatially referenced land use and ecosystem data is relatively sparse, complicating the development of water-quality models in Australia. Because of these specific characteristics of Australian catchments, the discussion of water-quality models in this section is restricted to models that have been developed or applied in Australian catchments.[1]

WaterCAST/E2

WaterCAST (Water and Contaminant Analysis and Simulation Tool, formerly E2) is an empirical model developed as part of the Cooperative Research Centre for Catchment Hydrology (CRCCH) Catchment Modelling Toolkit. WaterCAST is part of a whole-of-catchment modelling framework that incorporates a range of sub-models. This provides a flexible approach that allows the model to vary with the modelling objectives. The basic spatial units in the WaterCAST tool are 'Functional Units' (FUs). FUs are identified as areas of a catchment with similar water quality processes or land use. Within each FU, different models may be assigned. For example, different models of rainfall runoff, nutrient generation and filtering may be used within each FU (Argent *et al*, 2005).

Spatial variability is represented by defining sub-catchments, which can each contain a number of FUs. The loads from each FU within a sub-catchment are lumped to form sub-catchment loads, which are then routed downstream through a node-link structure (Kandel and Argent, 2005). Nodes may represent sub-catchment outlets, stream confluences, or other places of interest, like stream gauges or dam walls. Links may represent river reaches, dams, or floodplains. Within each link, the flow of water and constituents can be modified through routing, storage, decay, enrichment, sources and sinks.

The WaterCAST tools can run at a range of temporal resolutions, depending on the choice of sub-models. Input requirements are specified for the component models and methods selected in setting up an WaterCAST scenario. WaterCAST can simulate the effects of a range of scenarios on outputs such as nutrient loadings, sedimentation and water yield. The framework has been applied in many Australian studies, ranging from assessing the impacts of bushfires on water quality (Feikema *et al*, 2005) to developing a decision support system for water quality improvements in Port Phillip Bay (Argent *et al*, 2007); and supporting water quality improvement plans and management activities in Queensland (Waters and Webb, 2007).

Considerable modelling experience and knowledge is needed to develop and use this model framework to have confidence in its outputs. Employing a selection of sub-models requires the user to be familiar with the detail, applicability and data requirements of each of the component models and with the challenges of linking multiple component models.

The model is limited to water quality and river flows. It currently does not incorporate economic variables or eco-hydrological response in streams, lakes or estuaries. The use of generation rates for each FU generally provides reasonable predictions of average long-term constituent loads but the model predictions may not be reliable for large events or for more detailed analyses at fine time scales (Kandel and Argent, 2005).

SedNet

The SedNet (Sediment River Network) model was developed in 2003 by CSIRO Land and Water as part of the National Land and Water Resources Audit. SedNet is a conceptual, lumped, semi-distributed model that identifies patterns in erosion rates, sedimentation and nutrient fluxes on a regional catchment scale (areas of 3,000 to 1,000,000km^2) (Prosser *et al*, 2001a; Wilkinson *et al*, 2004).

SedNet defines a stream network as a series of links (Figure 1), and can be used to construct sediment and nutrient budgets for each link. Information on material transport processes, soil mapping, vegetation cover, geology and climate are used to estimate sediment and nutrient supply from various sources. This information is combined with measurements of river flows to calculate: the mean annual suspended sediment output from each river link;

1 A useful European review of hydrological models used to predict water quality changes is given in Arheimer and Olsson (2002).

the depth of sediment accumulated on the river bed in historical times; the relative supply of sediment from sheet wash, gully and bank erosion processes; the mean annual export of sediment to the coast; and the contribution of each sub-catchment to that export (Prosser *et al*, 2001c). The nutrient budget module of SedNet is known as ANNEX (Annual Network Nutrient Export). ANNEX is used to predict mean annual loads of phosphorus and nitrogen in each link of the river system (including particulates, organic and inorganic forms of dissolved nutrients) (Wilkinson *et al*, 2004).

SedNet has been used to identify the relative importance of different processes that supply sediment and nutrients to rivers in catchments throughout Australia (and Kinsey-Henderson *et al*, 2003; see, for example, Dougall *et al*, 2005). However, the model offers the user little flexibility in modifying the underlying algorithms. SedNet is also constrained by its requirements to estimate erosion from observed averages over longer time periods, providing insufficient consideration of contemporary erosion rates.

CMSS

The Catchment Management Support System (CMSS) was first used in the 1990s and has since been further developed by CSIRO (Reed *et al*, 1999). It is a simple lumped-catchment model developed to analyse the likely impacts of land-use changes on the total phosphorus and total nitrogen loads delivered to rivers (Davis and Farley, 1997).

CMSS predicts average annual nutrient loads based on the nutrient generation rates for different land uses. The finest spatial scale is the 'Mapping Unit', which represents a disaggregation of land use per sub-catchment. Nutrient loads are calculated as the summation of generation rates per unit area and the total area of each land-use in the catchment. The model has been applied in the Mount Lofty Ranges in South Australia (Davis and Farley, 1997), the Hawkesbury-Nepean Basin in New South Wales (Baginska *et al*, 2003) and the Dawson River Basin in Queensland (Joo *et al*, 2000). CMSS is a simple catchment-scale empirical model for water-quality assessment. Being based on generation rates, it does not model processes such as rainfall runoff or infiltration empirically (Letcher *et al*, 2002).

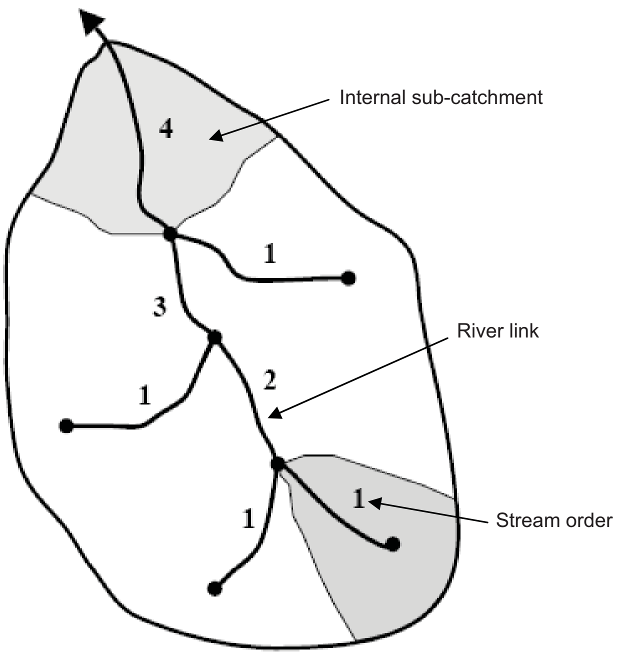


Figure 1. Elements of the SedNet model (Source: Wilkinson et al, 2004)

SWAT

The Soil and Water Assessment Tool (SWAT) was originally developed by the US Department of Agriculture in 1993 (Gassman *et al*, 2007) but has been modified and extended in several Australian applications (Watson *et al*, 2003; Sun and Cornish, 2005; Watson *et al*, 2005; Githui *et al*, 2009). SWAT is designed to predict the effect of catchment management decisions on water, sediment, nutrient and pesticide yields.

The model is physically-based and runs continuous simulations with daily updating of water balance, plant growth, nutrients and pesticide concentrations. Spatial variability is accounted for by dividing catchments into sub-catchments which are further subdivided into hydrologic response units (HRUs). HRUs consist of homogeneous land use, management, and soil characteristics. SWAT is increasingly being used in Australian catchments. For example, Sun and Cornish (2005) used SWAT to estimate recharge in the headwaters of the Liverpool Plains in New South Wales, and Watson *et al* (2005) adapted SWAT to simulate the conditions of eucalyptus and pine plantations common to Australia.

Although SWAT has been shown to provide reasonable predictions of pollutant loadings, the model is data-intensive and hence complex. The multitude of parameters requires the availability of monitoring data and a high degree of modelling expertise.

CatchMODS

The Catchment Scale Management of Diffuse Sources (CatchMODS) framework is a spatially semi-distributed catchment modelling approach that simulates the effects of different catchment management actions on pollutant loadings to surface waters. CatchMODS aims to identify the critical diffuse sources of erosion, suspended sediments and nutrients, including the appropriate management interventions to address these loads. The framework further allows an assessment of point-source pollution, such as dairy effluent, to be included in the model (see, for example, Newham, 2002; Newham *et al*, 2008; and Norton *et al*, 2008). Note that pollution from point-sources was not included in the CatchMODS model for the George catchment.

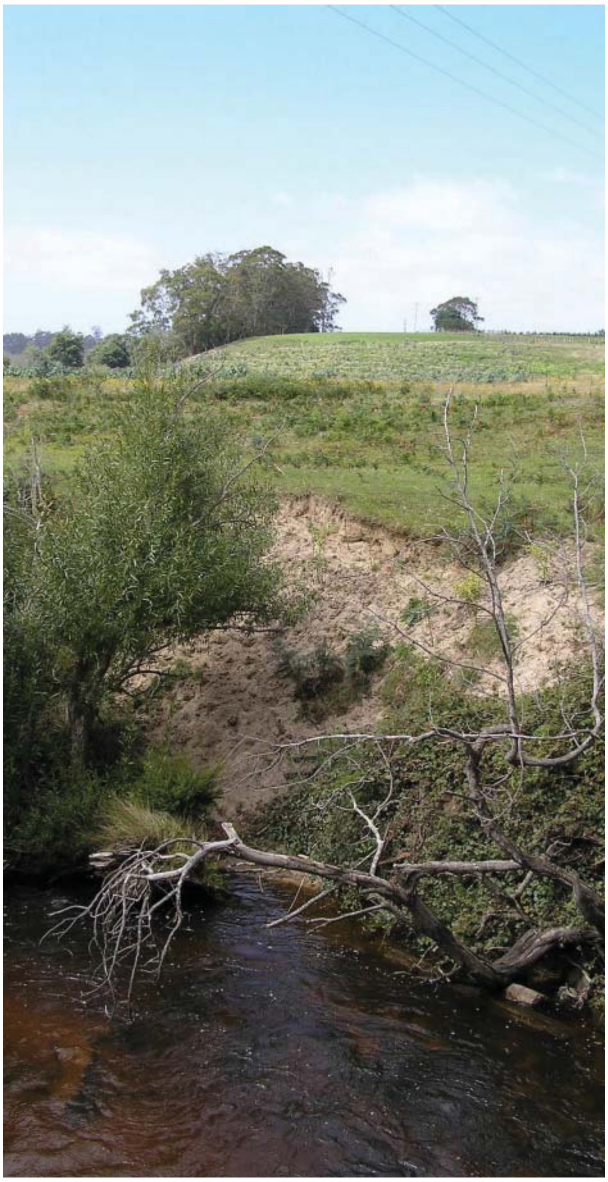
The framework is based on a series of linked river reaches and associated sub-catchment areas (similar to Figure 1). The modelling is lumped at the stream reach and sub-catchment units. The topology of the stream network enables tracking the downstream movement of pollutants (Newham *et al*, 2004). Physically-based sub-models simulate the hydrological processes and export of sediment and nutrients. Sources of other types of pollution can also be included in the framework. These models are linked to additional models of pollutant trapping and/or decay and a simple economic cost component to predict annual average sediment and nutrient loads, water flows and management costs. Lumping estimates at a sub-catchment scale leads to a coarser representation of spatial variability but increases the ease of scenario construction.

CatchMODS is built in the object-oriented modelling environment ICMS (Reed *et al*, 1999). Scenarios that can be considered within the framework include land-use changes, gully-zone engineering works, riparian-zone revegetation, climate variability and reducing point source pollution. Additional sub-models can be added to the framework's structure to allow assessments of other pollution sources or management actions. A more detailed description of the CatchMODS framework is provided in Section 4.

Selecting a model for the George catchment

Many models have been developed to predict changes in water quality in Australian catchments. However, few models have been used to simulate end-of-catchment sediment or nutrient loadings in Tasmania. Catchment water-quality modelling for Tasmania must hence build on available knowledge from mainland Australia. For the purpose of this study, a comprehensive, physically-based model was needed that could (i) be used on a sub-catchment scale and (ii) could be used to identify both point and non-point sources of pollution.

Consequently the CatchMODS framework was selected for use in the George catchment. Like SedNet, CatchMODS allows an assessment of sediment delivery and nutrient fluxes from various sources. The framework can incorporate various sub-models to simulate the effects of different management interventions. Whereas the WaterCAST and CMSS models use coefficient-based nutrient generation rates, CatchMODS allows for a representation of the physical processes involved. The framework is spatially explicit, providing information on nutrient and sediment loadings on a sub-catchment scale and can track their routing along a stream network. The model already incorporates a simple economic component which can be easily built on to compare the costs and benefits of different catchment management interventions. Further reasons for choosing CatchMODS are the relatively small number of parameters it has already been developed and successfully tested in other parts of Australia, and the expertise available at the Australian National University in developing and applying the model.



Bank erosion on Georges River at Priory

The CatchMODS framework

The CatchMODS modelling framework is designed to simulate current conditions and the effects of alternative management actions on the quality of receiving waters at catchment scales (Newham et al, 2004). CatchMODS is based on a node-link structure where loadings from upstream sub-catchments provide inputs to the downstream reaches. The framework can integrate a range of hydrologic, erosion and economic sub-models (Figure 2). The hydrological component of the model operates on a daily time step with outputs presented as steady-state annual averages.

Stream reach and catchment data input is coded using Arc/Info GIS mapping software (ESRI, 2006). The spatial disaggregation into stream reaches and sub-catchment units is based on area thresholds that can be set by the user. These area thresholds define the modelled reach extent and topology of the stream network. It is also used to determine the associated sub-catchment areas. Details on the representation of spatial variability in the model and network topology are provided in Newham (2002).

Hydrologic sub-model

The hydrologic sub-model used to predict surface and sub-surface discharge is based on the IHACRES rainfall runoff model (Jakeman et al, 1990; Jakeman and Hornberger, 1993; Croke and Jakeman, 2004). IHACRES is a conceptual parameter model, with parameters reflecting the integral, lumped properties of the sub-catchment under consideration. IHACRES models hydrologic response separated into two modules: (1) a non-linear loss module where effective rainfall from precipitation and temperature time-series data are converted into effective rainfall, evaporation, recharge and catchment moisture deficit and (2) a linear module which converts effective rainfall to modelled stream-flow (Figure 3).

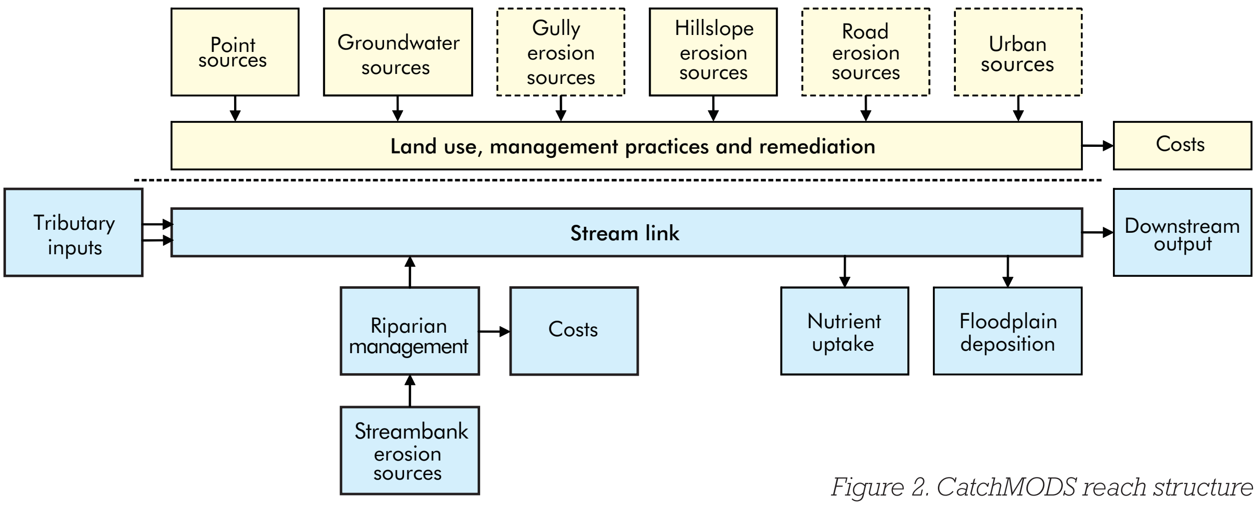


Figure 2. CatchMODS reach structure

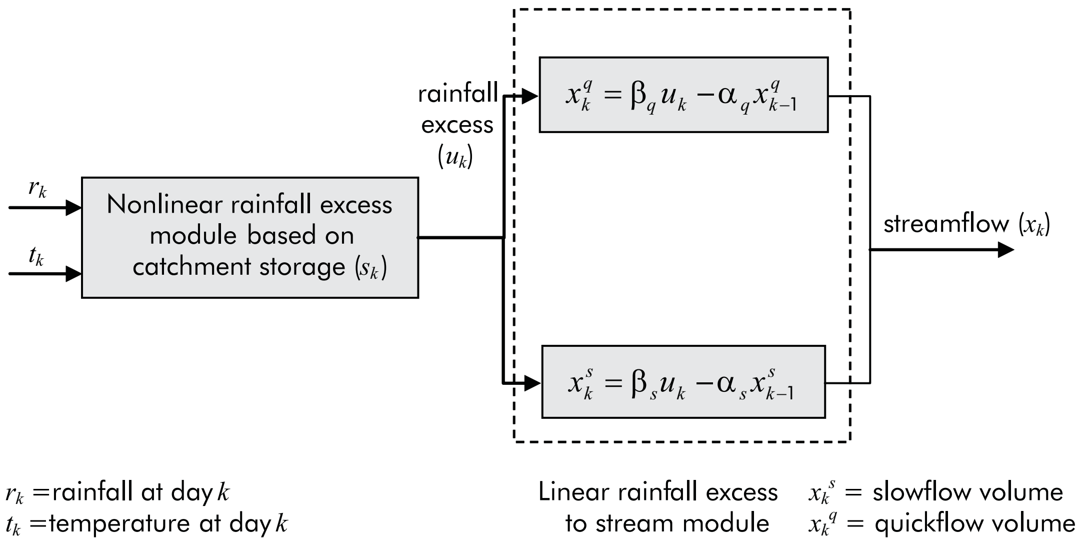


Figure 3. IHACRES model (source: Jakeman and Hornberger, 1993)

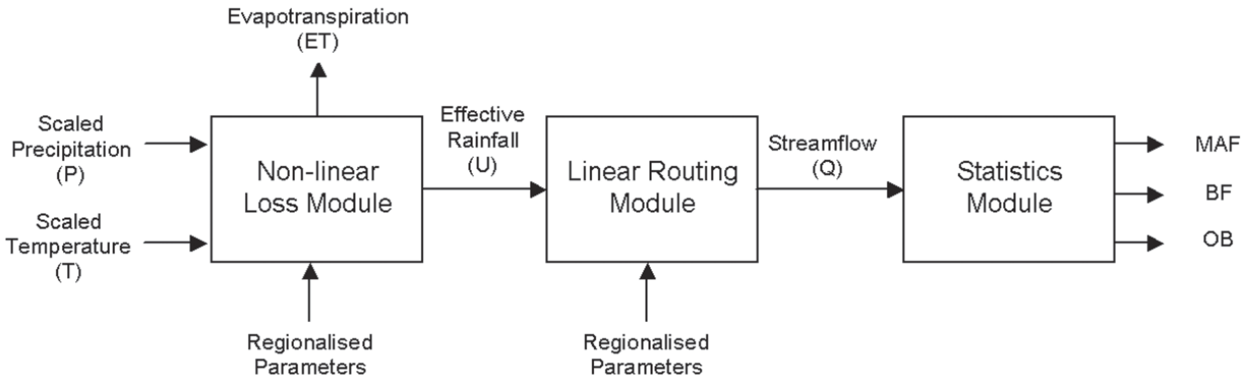


Figure 4. Structure of the hydrologic sub-model in CatchMODS

IHACRES is applied at a daily time-step with temperature and rainfall inputs linearly scaled according to sub-catchment mean rainfall and mean elevation, respectively (Newham et al, 2008). The modelled daily discharge from the IHACRES model is used to estimate steady state (average annual) flow-related statistics for each sub-catchment, including base-flow, quick-flow, mean annual flow (MAF), bankfull discharge (BF) and median overbank flow (OB) (Figure 4). These statistics provide the basis for further water-quality modelling in CatchMODS.

The mean annual flow for a sub-catchment i ($Q_{MAF,i}$) is estimated as the sum of all recorded daily flows divided by the number of days of record. Local base-flow and quick-flow volumes $Q_{BF\_loc,i}$ and $Q_{QF\_loc,i}$ are calculated for each sub-catchment i using a simple flow filter:

$$Q_{F\_loc,i} = Q_{F,i} - \sum_{UP} Q_{F,up} \qquad (1)$$

where QF,i is the quick-flow or base-flow from sub-catchment i (mL/day); and ∑QF,up is the sum of the upstream flow inputs (mL/day). Scenarios of the impact of climate changes can be implemented by substituting the climate (rainfall and temperature) inputs to the model. The effect of changes in the climate inputs cascade through the modelling framework via the flow-related statistics that are generated for each sub-catchment (Newham et al, 2008).

Sediment sub-model

The sediment sub-model in CatchMODS is based on SedNet (Prosser et al, 2001c; Wilkinson et al, 2004). The hydrologic inputs to the sub-model are provided by daily flow data generated by the IHACRES rainfall runoff model. Sediment delivery is estimated from hill-slope, gully and stream-bank erosion sources. A road erosion model and point source sediment inputs can also be included (Newham et al, 2008).

The focus of the sediment sub-model in CatchMODS is on the estimation of mean annual suspended sediment (SS) exports. This reflects the relative importance of SS over bedload as a source and transport medium for many water pollutants (Newham et al, 2008). SS is defined as the less than 63μm diameter sized particle fraction.

Hill-slope erosion

Hill-slope erosion is estimated using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al, 1997):

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad (2)$$

where A is soil erosion (tonnes/ha), R is rainfall erosivity, K is soil erodibility, LS is the length of slope, C is a cropping factor and P is a factor accounting for differences in erosion between land management practises. The application of the RUSLE in CatchMODS is lumped at the sub-catchment scale.

The rainfall, soil erodibility and length and slope factors (RKSL) are combined and multiplied on a cell-by-cell basis. For each sub-catchment i, the mean value of these combined factors is calculated:

$$\overline{RKLS_i} = \sum_k R_k K_k LS_k / c \qquad (3)$$

where $\overline{RKLS_i}$ is the mean value of the combined R, K and LS factors for sub-catchment i and c is the number of cells k in the sub-catchment. $\overline{RKLS_i}$ is assumed to be constant over time. Due to a lack in spatial data of contour cultivation and bank systems, the land practice factor (P) is set to 1. Hence, considerations of the effects of changes in land *practices* are not included in the model. The impacts of alternative land use scenarios are simulated through changes in the vegetation cropping factor C. This cropping factor is calculated on a sub-catchment scale as:

$$\overline{C_i} = \sum_j C_j \cdot A_{j,i} / A_i \qquad (4)$$

where $\overline{C_i}$ is the average cropping factor in sub-catchment i, $C_{,j}$ is the cropping factor associated with land use j, $A_{j,i}$ is the area of land use j in sub-catchment i and A_i is the area of sub-catchment i.

Hill-slope erosion H for each sub-catchment i can now be calculated as:

$$H_i = \overline{RKLS_i} \times \overline{C_i} \times SDR \times e_{rip\_h} L_{rip} \quad (5)$$

where *SDR* is a sediment delivery ratio, required to scale the hill-slope erosion via the RUSLE to the sediment yield in the stream network. SDR takes a value between 0 and 1 and is included to account for the deposition of sediment between the site of erosion and the stream network. The sediment delivery ratio is constant across the sub-catchments.

A distinction is made between vegetated and non-vegetated areas, with runoff from vegetated areas significantly smaller than the runoff from zones without vegetation. Hill-slope erosion is trapped in the riparian zone through factor $e_{ri\_hp}L_{rip}$ where e_{rip_h} is the effectiveness of the riparian zone in trapping hill-slope erosion and L_{rip} is the length of total stream with vegetated riparian buffer zones. It is assumed that forested areas (conservation, production forest and plantations) have fully vegetated riparian zones.

Gully erosion

Annual sediment yields from gully erosion are calculated for each sub-catchment. The sediment mass derived from gully erosion is estimated as the product of the physical volume of gully erosion and the bulk density of the eroded sediment. Severity of gully erosion is reflected by the physical dimensions of gullies in a catchment, with different types of gullies producing different amounts of sediment. The estimated gully erosion *G* (tonnes/year) for each sub-catchment is:

$$G_i = \sum_s L_{s,i} \cdot 2r_s \cdot d_s \cdot \rho \quad (6)$$

where $L_{s,i}$ is the length of gullies of severity class *s* in sub-catchment *i*, *rs* is the rate of annual average sidewall erosion in gullies of severity class *s*, *ds* is the average depth of gullies of severity class *s* and ρ is the mean bulk density of eroded sediments. Management actions such as revegetation or engineering works are simulated to reduce the length of eroding gullies in the model and can therefore reduce gully erosion inputs.

In Tasmania, moderate levels of gully erosion are found in areas south of Launceston, the Southern Midlands and east of Hobart near Buckland (SoER Tasmania, 2003). There are only minor occurrences of gully erosion in the George catchment. For that reason, gully erosion is not modelled in CatchMODS for the George catchment.

Stream-bank erosion

Sub-catchment stream-bank erosion Si is a function of flow, stream-bank dimensions and the length of actively eroding sites. The total stream-bank erosion sediment load is estimated using the algorithm of Prosser et al (2001b):

$$S_i = a \cdot Q^b_{bankfull} \cdot h \cdot \rho \cdot (L_{act,i} - e_{eng} L_{eng,i} - e_{rip\_s} L_{rip,i}) \quad (7)$$

where factor $a \cdot Q^b_{bankfull}$ acts to estimate the lateral erosion rate, *a* is a constant and *b* is an empirical parameter that is between zero and one to account for declining per unit sediment yield (Prosser *et al*, 2001b). $Q_{bankfull}$ is the bank-full stream-flow volume (mL/day), *h* is stream-bank height (*m*) and ρ is the mean bulk density of eroded sediments. The total length of active bank erosion along the stream length is $L_{act,i}$.

Management actions to reduce stream-bank erosion include engineering works over stream length $L_{eng,i}$ and riparian revegetation over stream length $L_{rip,i}$. The effectiveness of these management actions in reducing stream-bank erosion is captured by effectiveness coefficients e_{eng} and e_{rip_s} that can be set by the user.

Sediment routing

The total sediment concentration in a reach $X_{inr,i}$ is equal to the sum of all hills-lope, gully and stream-bank erosion from sub-catchment *i* plus the upstream sediment inputs X_{up}:

$$X_{inr,i} = Hi + \omega_g G_i + \omega_s S_i + X_{up} \quad (8)$$

where ω_g and ω_s are included to account for the proportion of suspended sediment in eroded gully and stream-bank erosion material respectively. Deposition of sediment is modelled in CatchMODS by including a floodplain area A_f in which sediment particles settle with velocity ν. Sediment routing to the downstream reach X_{outr} is therefore a function of total suspended sediments, flows and floodplain deposition, as estimated by:

$$X_{outr,i} = X_{inr,i} - \left[\frac{Q_{OB,i}}{Q_{MAF,i}} \cdot X_{inr,i} \left\{ 1 - \exp\left(\frac{-\nu \cdot A_f}{Q_{OB,i}} \right) \right\} \right] \quad (9)$$

Nutrient sub-models

The phosphorus and nitrogen sub-models in CatchMODS have similar structures. They are based on observed relationships between suspended sediment, nutrient concentrations and stream characteristics. Total nutrient (TNi) exports from sub-catchment i are calculated as the sum of both particulate and dissolved fractions.

Particulate nutrient input

Particulate nutrient inputs PNi (t/yr) are calculated as:

$$PN_i = SS\_prop_i \cdot (\sum_j \varepsilon \cdot H_{ij} \cdot C_j + S_i \cdot C_s + G_i \cdot C_g) \quad (10)$$

where *SS_propi* is the proportion of suspended sediment load that is routed through the model, H_{ij}, S_i, G_i are estimated annual hill-slope, stream-bank and gully erosion in sub-catchment *i*; and C_j, C_s, and C_g are soil nutrient concentrations (g/g) for land use *j*, stream-banks and gullies respectively; ε is a dimensionless nutrient enrichment factor, introduced to represent the effects of preferential erosion and delivery of finer soil particles that have higher nutrient concentrations. This ε-factor is generic across all sub-catchments and land uses in the absence of knowledge for each land use and soil combination (Newham et al, 2008).

Dissolved nutrient input

Dissolved nutrient inputs DNi from sub-catchment i are estimated as

$$DN_i = (bf\_conc \cdot Q_{BF,local,i} + qf\_conc \cdot Q_{BF,locali})/1000 + P_i \quad (11)$$

where *bf_conc* and *qf_conc* are the dissolved nutrient concentrations associated with the base-flow and quick-flow (mg/l); $Q_{BF\_loc,i}$ is the local base-flow volume (ML); $Q_{QF\_loc,i}$ is the local quick-flow volume (ML); and Pi is the nutrient input from point sources like intensive dairy farming or sewage treatment plants in sub-catchment *i*. The total dissolved nutrient concentration in a reach *DN*inr is equal to the sum of the nutrient inputs from the sub-catchment DN_i and upstream inputs DN_{up}.

Nutrient routing

Attenuation of dissolved nutrients through a reach is modelled in the nutrient routing module by scaling the total dissolved nutrient output from a stream reach by an empirically determined parameter *z*. Routing of dissolved nutrients to the downstream reach DN_{outr} is estimated as:

$$DN_{outr} = DN_{inr} \exp(-z \cdot L_{r,i} \cdot \overline{W}_{r,i} / Q_{MAF,i}) \quad (12)$$

where *z* is an attenuation scaling factor, $L_{r,i}$ is the reach length in sub-catchment *i*; $\overline{W}$ is the average width of the stream in sub-catchment *i*, and $Q_{MAF,i}$ is the mean annual flow. The attenuation of dissolved nutrients increases with higher nutrient concentrations, low flows, and for larger stream reaches (Newham et al, 2008).

Economics sub-model

The economic component of CatchMODS is based on estimating three types of costs: fixed, maintenance and land use-related.

Fixed costs FC_w are those one-off costs which are incurred when remediation works *w* are implemented. These include riparian and/or gully zone revegetation (km), stream-bank engineering works (km) or abatement of point sources. Maintenance costs MC_w are the yearly costs required to keep riparian and gully zone remediation works effective as control measures. The land use-related costs LUC_j represent the change in gross margins associated with the conversion of one land use type to another. The costs are calculated as in equations 13 to 15:

$$LUC_j = \Delta Area_j \, returns_j \quad (13)$$

$$FC_w = works \cdot \$/km \quad (14)$$

$$MC_w = works \cdot \$/km/year \quad (15)$$

The total costs of changes in land use and land management are simply the sum of fixed, maintenance and land use related costs. The ongoing maintenance costs are calculated as the yearly costs; no discount factor has been included to permit the user to define their own discount factor and number of years to write off investments.

George water quality model parameterisation

The CatchMODS framework described in the previous section was used to develop a sediment and nutrient model for the George Catchment in Tasmania. The 557km² George catchment is located on the north-east coast of Tasmania, Australia (Figure 5). The catchment and its estuary have significant socio-economic significance through their production, recreation and non-market values. Although the catchment environment has been rated as being in good condition (Walker et al, 2006), there is concern that dairy runoff, forestry operations and urban pollution are affecting water quality in the George catchment (NRM North, 2008) and there are general concerns about degradation of the catchment environment (Lliff, 2002; Break O'Day Council, 2007). Local natural resource management actions designed to improve water quality include limiting stock access to rivers, on-farm retention of dairy effluent, improving wastewater treatment and revegetation of riparian buffer zones. The model development process, including the collection of data and parameterisation, is described here.

Figure 5 Location of the George catchment

Sub-catchment delineation

The George catchment boundaries were constructed using the 25m digital elevation model (DEM) for Tasmania (3rd ed). The TasDEM was processed in Arc/Info GIS (ESRI, 2006) to remove spurious sinks in the model. This ensures that surface flows run into the streams and estuary. The Georges Bay was defined as the catchment endpoint, with elevation set to zero. All existing sinks in the DEM were then filled to match the nearest value in neighbouring grids using the fill function in Arc/Info GIS.

Following this, the catchment boundary was delineated using a cell-by-cell grid search of all streams flowing into the Georges Bay. Sub-catchments were delineated using an area threshold of 30km². Setting the area threshold at 30km² has been shown to result in sub-catchment areas that are small enough to be

Figure 6. George catchment and sub-catchment delineation

homogenous for the modelling of sediment and nutrient loadings but are large enough to be recognisable management units (Newham et al, 2008). Using this approach, fifteen sub-catchments were identified for the George catchment. A sixteenth sub-catchment was defined as the Georges Bay estuary drainage area rather than as a river reach sub-catchment (Figure 6)

Climate data inputs

Information on daily maximum temperatures for 1957–2006 was obtained from the Bureau of Meteorology for gauges at the St Helens Post Office and St Helens Aerodrome. The average maximum temperature at these gauges over the fifty-year monitoring period was 18.4 degrees Celsius (Table 1). Sub-catchment temperatures were calculated by using a 0.007 degree correction for each metre difference in mean sub-catchment elevation with the temperature gauge (at 9.6m).

Daily rainfall data was available from seven raingauges in the George catchment (Figure 7). The observations at the St Helens Post Office (gauge 92033) were used to calculate average daily rainfall $\overline{R}_k$ in the catchment. Missing observations were filled with rescaled data from the nearest gauges with observations for that date.

Table 1. Rainfall and temperature observations in St Helens (Source: Australian Bureau of Meteorology)

	Temperature (daily max in ºC, 1957–2006)	Rainfall (mm/day, 1957–2006)
Min	2.0	0.0
25th percentile	15.1	0.0
Mean	18.41	2.2
Median	17.9	0.0
75th percentile	21.1	1.2
Max	39.8	190.4
# days in record	16,914	18,017

The mean annual rainfall $\overline{r}_i$ for each sub-catchment was calculated using a scaling factor based on the average annual rainfall in that sub-catchment (BOM, 2007). Four annual average rainfall zones were derived from the Bureau of Meteorology: at 700, 900, 1100 and 1400mm/year (Figure 7 and Figure 10). Mean annual rainfall in sub-catchment i was then calculated as:

$$\overline{r}_i = \sum (Area_{iz} \cdot r_z) \qquad (16)$$

where $Area_{iz}$ is the proportional area of the sub-catchment in rainfall zone z and r_z is the average

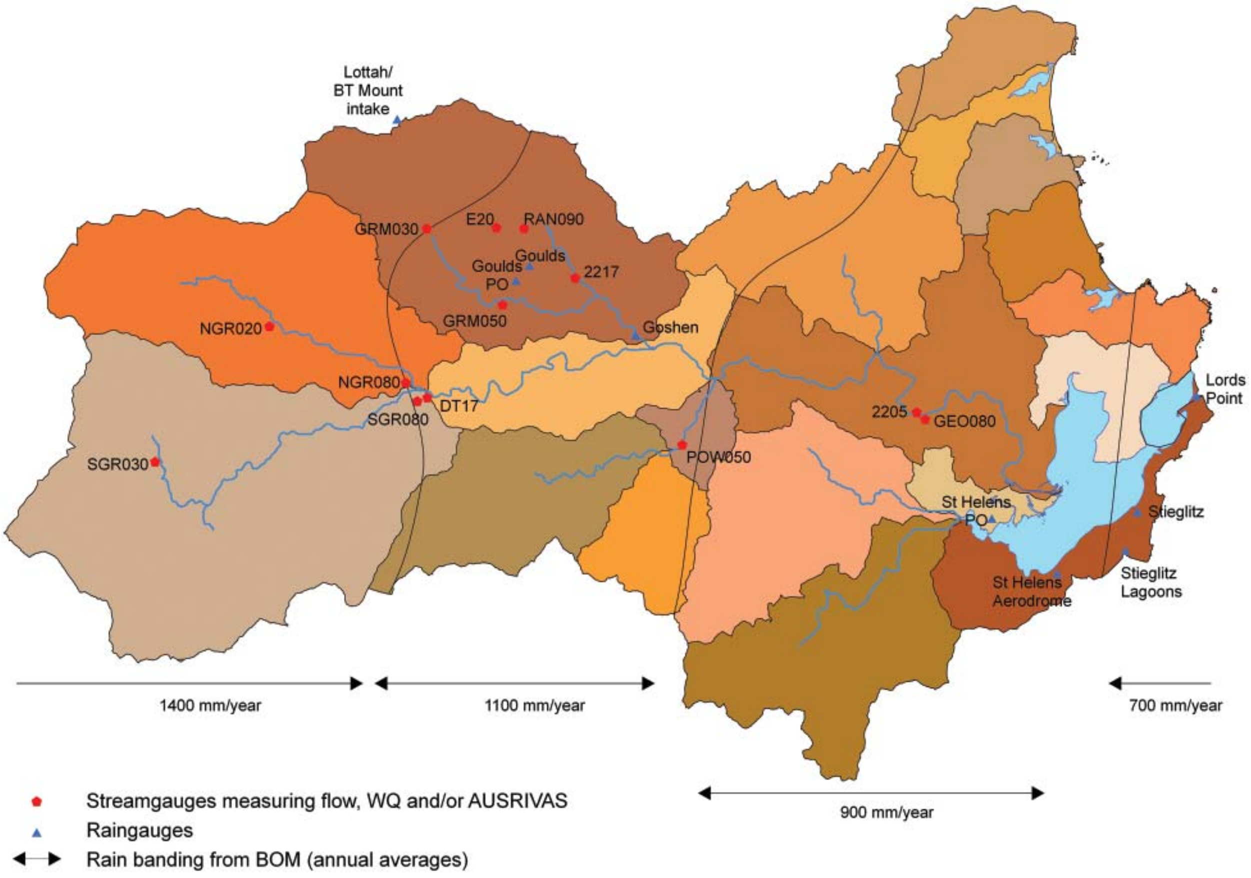


Figure 7. Gauge locations in the George catchment

Table 2. Mean annual rainfall (mm) and elevation (m) of George sub-catchments

Sub-catchment ID	Sub-catchment name	Mean annual rainfall (mm)	Mean elevation (m)
1	Ransom River	1204.7	337
2	Groom River	1232.2	348
3	Ransom-Groom	1100.0	310
4	Forester	970.5	336
5	Mid George River	1097.8	400
6	Lower George River	901.8	360
7	North George River	1378.9	487
8	Upper George River	1187.9	446
9	George River Floodplains	900.0	320
10	Powers Rivulet	1091.8	249
11	South George River	1399.8	526
12	St Columba Falls	1400.0	621
13	Golden Fleece Rivulet	900.1	106
14	Mount Albert	1399.7	579
15	Constable Creek	900.0	165
16	Georges Bay	858.8	44

annual rainfall (mm) in zone *z*. The results in Table 2 show that the average rainfall in the elevated western parts of the catchment is higher than coastal precipitation.

Land use

Land use data for the George catchment were sourced from digital mapping by the Bureau of Rural Science (BRS, 2003). These data were compared to aerial photography and TasVeg mapping (DPIW, 2005) to represent current land use in the catchment (Figure 8). From the BRS mapping, six land uses categories were identified for the purpose of water quality modelling (Table 3). The proportion of each land use by sub-catchment are presented in Table 4.

Table 3. Land use in the George catchment

Land-use category	BRS code	Description	George catchment mapping (%)
Conservation and natural environments (conservation)	1.1	Nature conservation	28.4
	1.2	Managed resource protection	0.9
	1.3	Remnant native cover	8
Production from native forests (prod_forest)	2.2	Production forestry	42.4
Production from forestry plantations (plant_forest)	3.1	Plantation forestry	4.5
Production from dryland agriculture (grazing)	2.1	Grazing natural vegetation	0.9
	3.2	Grazing modified pastures	12.5
Production from irrigated agriculture (irrigation)	4.1	Irrigated modified pastures	1
Intensive uses (urban)	5.1	Residential	1
	5.2	Services	0.1
	5.3	Transport and communication	0.1

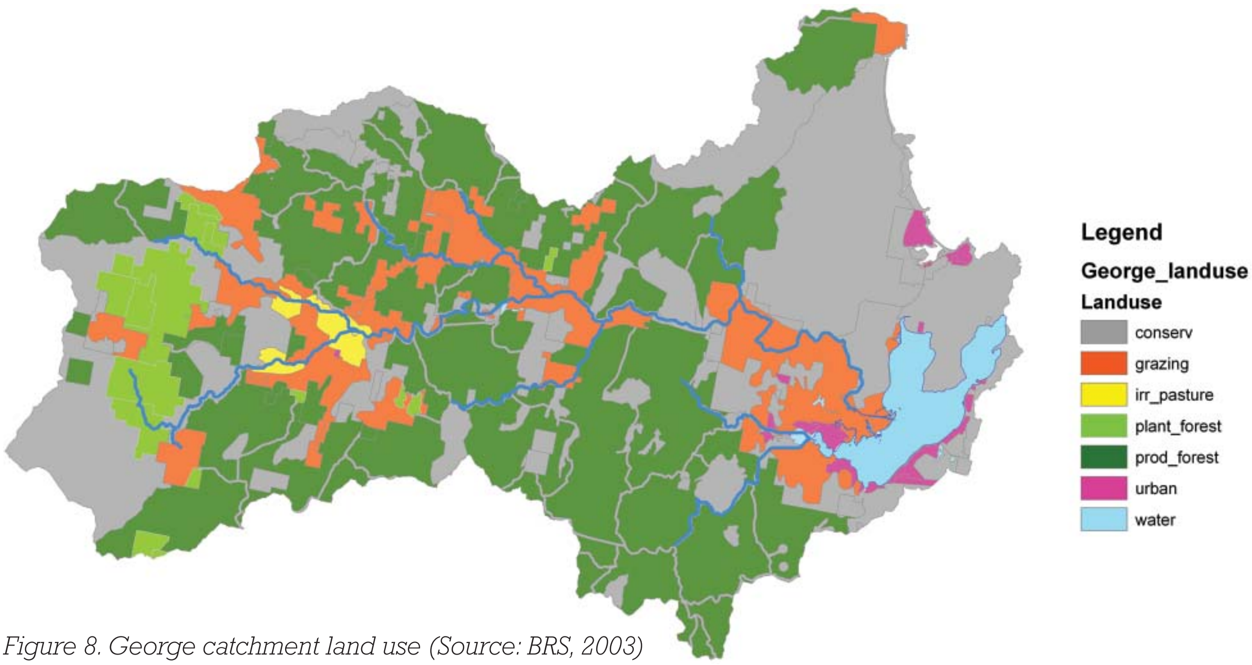


Figure 8. George catchment land use (Source: BRS, 2003)

Table 4. Proportional land use in George sub-catchments

Sub-catchment	Conservation	Grazing	Irrigation	Urban	Prod_forest	Plant_forest	Other
Ransom River	22.7%	15.3%	0.0%	0.0%	61.6%	0.0%	0.4%
Groom river	24.4%	21.6%	0.0%	0.0%	53.7%	0.0%	0.3%
Ransom-Groom	13.2%	21.7%	0.0%	0.0%	60.2%	3.3%	1.5%
Forester	40.0%	4.3%	0.0%	0.0%	55.4%	0.0%	0.3%
Mid George River	26.2%	50.9%	0.0%	0.0%	22.3%	0.0%	0.5%
Lower George River	41.8%	15.0%	0.0%	0.0%	42.4%	0.0%	0.8%
North George River	25.4%	18.8%	3.9%	0.0%	35.5%	16.1%	0.3%
Upper George River	26.8%	18.5%	3.5%	0.0%	49.7%	0.0%	1.4%
George River Floodplains	68.0%	31.4%	0.0%	0.0%	0.0%	0.0%	0.6%
Powers Rivulet	21.3%	8.1%	0.0%	0.0%	69.0%	1.2%	0.4%
South George River	24.9%	16.1%	6.6%	0.2%	46.7%	5.6%	0.0%
St Columbia Falls	59.6%	5.7%	0.0%	0.0%	6.1%	28.3%	0.3%
Golden Fleece Rivulet	24.8%	5.4%	0.0%	0.9%	68.5%	0.0%	0.4%
Mount Albert	15.1%	13.0%	0.0%	0.0%	62.1%	9.3%	0.4%
Constable Creek	18.5%	3.7%	0.0%	0.1%	76.9%	0.0%	0.8%
Georges Bay	60.5%	23.8%	0.0%	10.9%	3.7%	0.0%	1.1%

Each land use has a different rate of soil loss, therefore changing catchment land use will result in different rates of erosion and sediment and nutrient loads to the George catchment streams.

The land-use mapping generally provided an accurate picture of existing land uses in the George catchment. However, feedback from local stakeholders suggested that recent changes may have occurred in the areas under production and plantation forestry. The 2003 mapping used for the development of a George catchment water-quality model was visually compared with the most recent aerial photography. This showed that there had been a slight increase in the area under plantation forestry, particularly in the northern sections of the Ransom-Groom sub-catchment and the southern parts of Powers Rivulet sub-catchment (Figure 9). However, the differences were small and the 2003 land-use mapping was considered appropriate for the purpose of the model development. Scenarios of increased plantation areas can be run in the model to predict changes in nutrient and sediment loadings to the George Bay (see Section 7.4.1).

Hill-slope erosion

The Revised Universal Soil Loss Equation (RUSLE; Renard et al, 1997) is used in CatchMODS to estimate hill-slope erosion (Section 4.2.1). The effects of land-use changes are simulated through changes in the cropping factor. Other factors that needed to be estimated for the George catchment include the soil erodibility, rainfall erosivity and the length

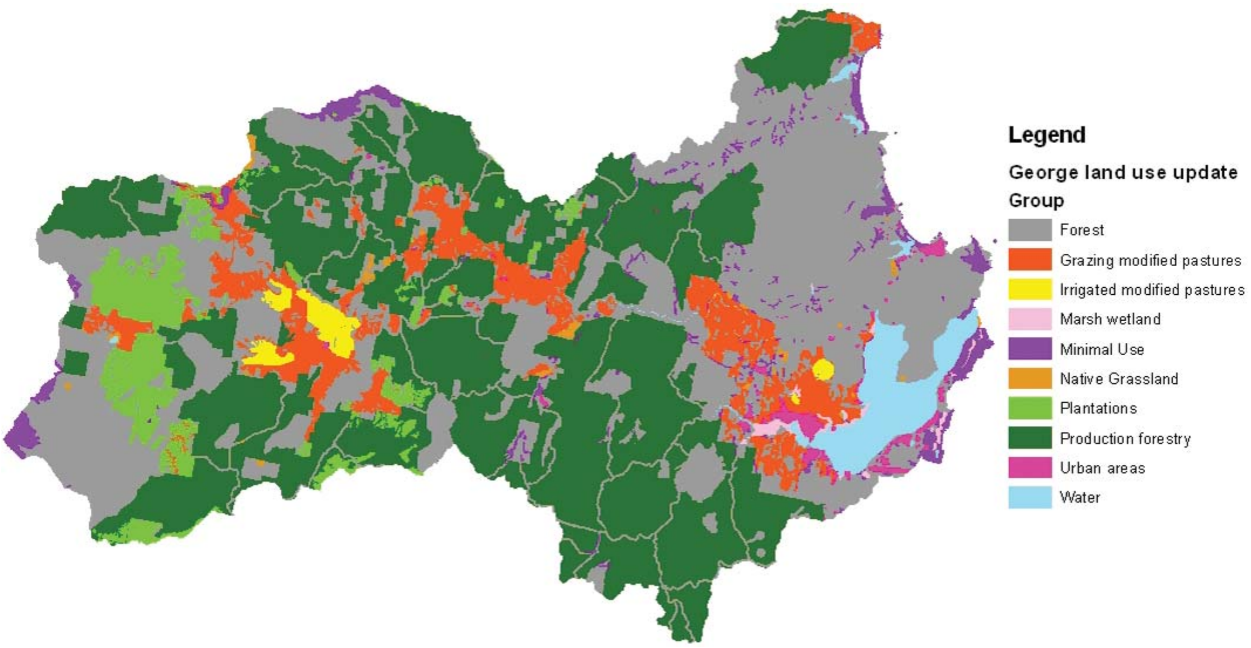


Figure 9. George catchment land use – updated (Source: Shane Broad, 2008)

of the slope. The sediment delivery ratio (*SDR*) was modelled at 0.05 to account for the average deposition of sediment between the site of erosion and the stream network. The SDR can be used as a calibration parameter should higher quality data become available for the catchment (see Section 7.1).

Cropping factor

The C-factor in the RUSLE measures the combined effect of all the interrelated cover and crop management variables. It is defined as the ratio of soil loss from land maintained under specified conditions to the corresponding loss from continuous tilled bare fallow (Rosewell, 1993). Rosewell (1997) suggests using digital vegetation maps with information on vegetation types and canopy cover to estimate the cropping factors in the RUSLE. Since such data was unavailable for the George catchment, C-factors were estimated using assumptions for each of the land-use categories following the procedure outlined in Rosewell (1993, pages 23–25 and Appendix D):

- a C-factor of 0.01 was used for grazing lands, assuming a long-term average groundcover of 85%
- irrigated pastures were assumed to have a slightly higher C-factor than grazing lands of 0.015, and
- the C-factor for forestry plantations depends on the plantation's rotation rate.

Experts from the Forest Practices Board Tasmania suggested using a twenty-year rotation rate for plantation forest. C-factors were assumed for every month of the forestry rotation, starting with a virtually bare disturbed forest soil in the first month after harvesting to a 90% cover of shrub and weeds over the subsequent twelve-month period. It was assumed that the status of an undisturbed forest would be achieved by year four, with canopy and ground cover similar to the natural state after year 10 (Table 5). The C-factors for each period are detailed in Table 5. These assumptions lead to an average weighted annual C-factor for plantation forests of 0.0069.

Table 5. Forestry C-factors

Period	Month 1–3	Month 4–6	Month 6–12	Year 2–3	Year 4–10	Year 10–20/80
C-factor	0.24	0.14	0.02	0.01	0.001	0.0005

Native forestry production was suggested to have a longer rotation period of 80 years. The same process of using a weighted annual C-factor (Rosewell, 1993; 51) was used to estimate a C-factor for production forests of 0.002.

The area covered by undergrowth in conservation environments was assumed to be between 75 and 100%. The C-factor suggested by Rosewell then lies between 0.001 and 0.0001. A value of 0.0005 was used in the RUSLE for all conservation areas in the George catchment.

The C-factor for urban areas is determined by the effectiveness of vegetation in providing ground cover and resistance to overland flow to reduce erosion. It was assumed that urban areas had an average grassy ground cover and a C-factor of 0.02 was used.

Soil erodibility

Soil erodibility (the K-factor in the RUSLE) is a measure of the resistance of the soil to sheet and rill erosion, expressed in $t{\cdot}ha{\cdot}h$ / $ha{\cdot}MJ{\cdot}mm$. The value of K will always be greater than zero and generally less than 0.1. Usually, a soil type becomes more erodible (a higher K-factor) with an increase in silt content (Rosewell, 1993).

Information on K-factors was unavailable for Tasmania in digital form and was estimated. This estimation required information on soil properties in the George catchment in terms of permeability, soil structure, nutrient concentrations etc. The only GIS data on Tasmanian soils that is currently available is limited to information on land systems. Using a description of each of these land systems (Pinkard, 1980) and the 'Australian Soil and Land Survey Field Handbook' (McDonald and Isbell, 1998), the approximate clay, sand and silt content of the soils for each land system in the George catchment could be estimated.

Permeability (ranging from 'rapid = 1 to 'very slow' = 6) was also given by Pinkard (1980) for each land system. Soil structure (varying from 'very fine granular' = 1 to 'blocky, platy, massive = 4) was estimated from the soil description. Following Rosewell (1993), organic matter content was assumed to be 2%. K-factors were then estimated using the soil erodibility nomograph (Foster et al, 1981). For soils containing up to 68% silt plus very fine sand, the nomograph solves the equation (Rosewell and Loch, 2002):

$$K=2.766\mathrm{x}10^{-7}\mathrm{x}M^{1.14}(12-OM)+4.28\mathrm{x}10^{-3}(SS-2)+3.28\mathrm{x}10^{-3}(PP-3) \quad (17)$$

where M is (% silt plus % very find sand) (100 minus % clay), OM is organic matter content (%), SS is soil structure code and PP is profile permeability class. The calculated K-values were compared to values suggested by Rosewell for different soil types (1993: page 13) and data from the Australian Soil Atlas. An average of the three was used as the K-factor for each land-system in the George CatchMODS model (Table 6).

Table 6. Estimated K-factors and soil erodibility for the George catchment land systems

Land system name	CatchMODS K–factors	Erodibility
Avenue River	0.023	moderate
Barrow	0.029	moderate
Barrow Hills	0.030	moderate-high
Binalong Bay	0.011	low
Dianas Basin	0.020	low-moderate
Diddleum Plains	0.032	high
George River	0.031	high
Lulworth	0.013	low
Mathinna Plains	0.023	moderate
Mount William	0.032	high
Poimena	0.032	high
Retreat	0.030	moderate-high
St Columba Falls	0.031	high
Weldborough Pass	0.031	high
West Scottsdale	0.032	high

Rainfall erosivity

Rainfall erosivity (R) is a measure of the ability of rainfall to cause erosion (Rosewell, 1993). The R factor is measured in $MJ \cdot mm \, / \, ha \cdot h \cdot y$ and can be calculated using equation:

$$R = 164.74 \cdot (1.1177^{Is} \cdot (Is)0.6444 \qquad (18)$$

where Is is the two-year, six-hour log-Pearson type III Rainfall intensity (mm/h). Because long-term rainfall intensity data is unavailable across the George catchment, another approach was used to estimate R factors. Yu and Rosewell (1996) found a relationship between mean annual precipitation in south-eastern Australia and the R-factor of:

$$R = 0.0438 \cdot P^{1.61} \qquad (19)$$

where P is the average annual precipitation (mm). This relationship was used to estimate an R for each of the George sub-catchments. The rainfall zoning statistics from the Bureau of Meteorology (BOM, 2007) were used to calculate four R-values of 1668, 2499, 3452 and 5090 for the George catchment (Figure 10). The R-factor for each sub-catchment was then calculated as a weighted sum of the sub-catchment area in each rainfall zone and the associated R-value.

Slope length and steepness

The slope length (L) and steepness (S) factors are measures of the effect of slope length and slope steepness on sheet and rill erosion (Rosewell, 1997). For the CatchMODS framework in the George catchment, the slope length and steepness were estimated from the high resolution Tasmanian 25m digital elevation model (3rd ed) and calculated within the Arc/Info GIS software (ESRI, 2006) using the 'slope' function of Arc/Info as:

$$LS = \left(\frac{A_s}{22.13}\right)^{0.56} \times \left(\frac{\sin\beta}{0.0896}\right)^{1.22} \qquad (20)$$

where As is the upstream contributing area and β is the slope angle in degrees (Rosewell, 1997).

Buffer effectiveness

In the George catchment model, it was assumed that riparian zones in areas with native vegetation or forestry are fully vegetated. The length of stream sides available for riparian revegetation actions therefore equals the total stream length in sub-catchment i with adjacent land uses 'grazing', 'irrigation' or 'urban'. The model user can define the percentage of stream length in the non-forested areas of the George catchment that is vegetated.

The proportion of hill-slope erosion that is captured by the vegetation in the riparian zone is set to e_{rip_h}. (Equation 5). In the George catchment model, this factor is set to 0.45 but model users can readily change these assumptions in the model.

Stream-bank erosion

Stream-bank erosion S_i is modelled as a function of empirical parameters, stream bank height and the length of actively eroding sites. Stream bank height was assumed to average 2.5 metres. A further assumption was made on the location of stream-bank erosion sites. The total length of actively eroding sites in the George catchment was assessed using the information in various George Rivercare Plans (Rattray, 2001; Lliff, 2002 and; Sprod, 2003). This information was used to map the existing sites of stream-bank erosion (Table 7). It was

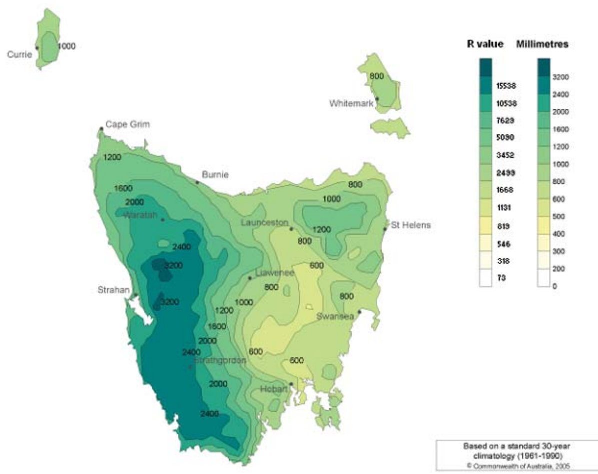


Figure 10. Average annual rainfall (mm) and R-values for Tasmania (Source: Australian Government Bureau of Meteorology)

assumed that stream-bank erosion occurs predominantly in non-forested areas, therefore stream-bank erosion remediation actions reduce erosion in the non-forested areas first.

Management activities available to reduce the length of eroding streams are riparian revegetation and stream-bank engineering works (Figure 11). Direct stream engineering works are more effective in reducing stream-bank erosion than revegetation of the riparian buffer zone. This difference was captured by setting e_{eng} to 0.95 and e_{rip_s} to 0.75 in the model. The model user can specify different effectiveness coefficients for engineering and riparian revegetation if desired. In the CatchMODS model for the George catchment, direct stream-bank erosion works takes priority over riparian revegetation, so that 'double-counting' of remediation works is avoided. This is modelled by first reducing the length of actively eroding sites $L_{act,i}$ through engineering works $L_{eng,i}$ and then addressing remaining stream-bank erosion through riparian buffering $L_{rip,i}$. The length of actively eroding sites $L_{act,i}$ that is not addressed by stream-bank erosion remediation actions is assumed to contribute to hill-slope erosion and is available for riparian revegetation works (Section 5.4.5).

Nutrient loading

The nutrient sub-models in CatchMODS are based on observed relationships between suspended sediment, nutrient concentrations and stream characteristics. The suspended sediment loads $S_{i,j}$ are calculated for each sub-catchment i and land use j in the sediment sub-model. As no active gully erosion was modelled for the George catchment, the factor $\omega_g G_i$ (Equation 8) was excluded. In the absence of catchment-specific knowledge, the nutrient enrichment factors ε were set to 4.5 and 1.5 for the nitrogen and phosphorus models respectively.

Table 7. Sub-catchment stream length and length of actively eroding sites with stream-bank erosion (m) in the George catchment.

Sub-catchment	Total stream length (m)	Length of stream-bank erosion sites (m)
Ransom River	3,782	900
Groom river	9,094	1,100
Ransom-Groom	3,374	2,300
Forester	4,926	none mapped
Mid George River	2,889	none mapped
Lower George River	7,873	1,400
North George River	11,620	1,400
Upper George River	12,281	1,200
George River Floodplains	11,904	300
Powers Rivulet	9,865	none mapped
South George River	10,738	1,900
St Columbia Falls	4,363	none mapped
Golden Fleece Rivulet	7,425	none mapped
Mount Albert	1,220	none mapped
Constable Creek	9,912	none mapped
Georges Bay	–	none mapped

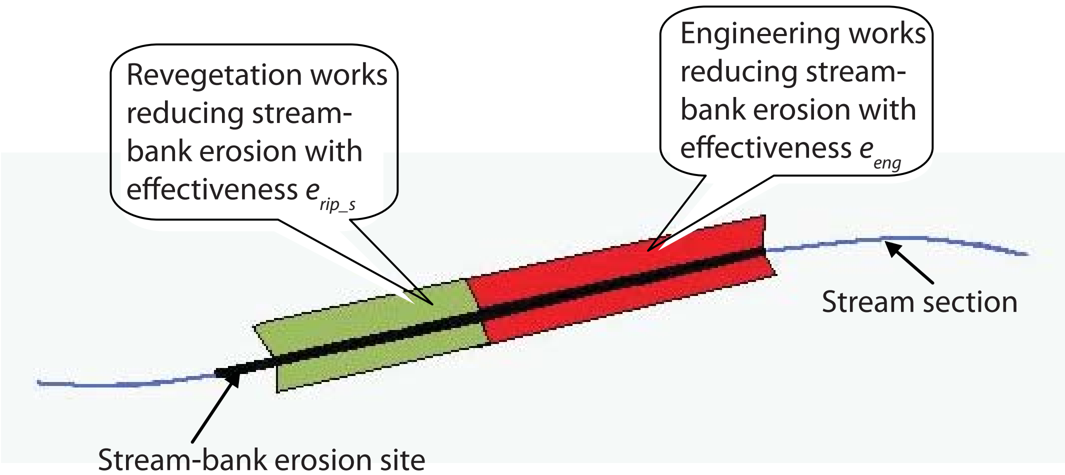


Figure 11. Management of stream-bank erosion

Further information was required about surface soil nutrient concentration (g/g) for each land use in the catchment. Because no data was available for soil properties in the George catchment, soil sampling was undertaken at different locations in the catchment. An attempt was made to sample across different sub-catchments, land uses and land systems (Figure 12). These samples were analysed to estimate the median total phosphorus (TP) and total nitrogen (TN) concentrations in the George catchment soils (Table 8).

Table 8. Soil nutrient concentrations (g/g) in the George catchment

Land use	TN	TP
Grazing	0.0030	0.00057
Irrigation	0.0056	0.00095
Plantation forest	0.0023	0.00027
Native forest production	0.0033	0.00029
Conservation	0.0043	0.00030
Urban	0.0026	0.00015
Bulk stream bank	0.005	0.00060

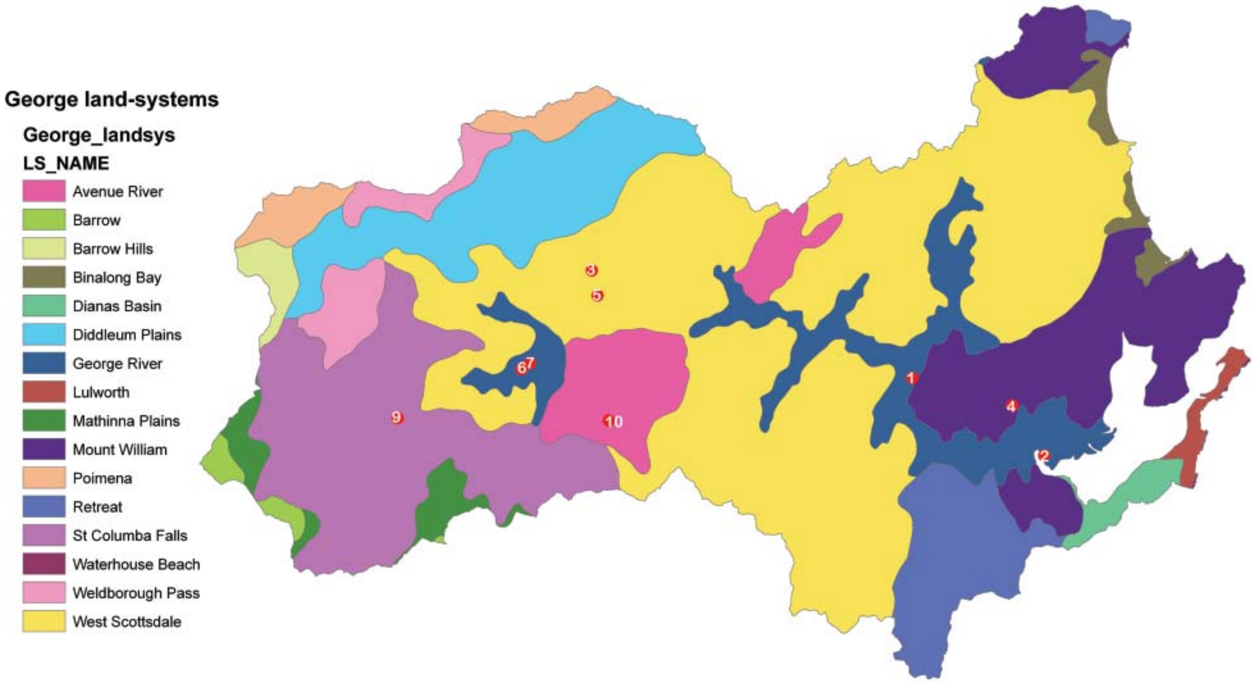


Figure 12. Soil sampling sites in the George catchment by land system (land systems from Pinkard, 1980 #782)

Modelling platform

CatchMODS operates using two modelling platforms (Newham et al, 2004). Arc/Info GIS software (ESRI, 2006) is used for spatial data processing. GIS data sets are used to identify catchment topology, physical data about streams, rainfall distribution, land use and soil properties. The use of GIS software enables spatial disaggregation of the catchment in terms of topography and widely available land use mapping. The use of publicly available data sets facilitates application of the model to other catchments for which up-to-date digital maps are available.

CatchMODS is built in the object-oriented Interactive Component Modelling System (ICMS – Reed et al, 1999). ICMS is a PC-based product developed to support the rapid building, integration, and deployment of models (Cuddy et al, 2002). The ICMS can incorporate a combination of models and data. The interactions between models are managed within the ICMS, using a graphical tree-structure to visualise available models, objects and data (Figure 13) (Argent et al, 2006).

The ICMS retains the underlying structure of the models, using a simple graphical user interface system to present the information. Multiple, user-customised 'views' can be build within ICMS to extract the relevant data for different model users. These views separate the interface and data, providing easy access to model results for a wide range of non-technical users (Cuddy et al, 2002). Ideally, a custom view is constructed through a stakeholder-driven process, to offer the functionality required by the model users (Argent et al, 2006). For the George catchment model, consultations with local natural resource managers provided stakeholder inputs to the modelling process. The ICMS allows for ongoing development of the model, as it can readily add extensions of the framework.

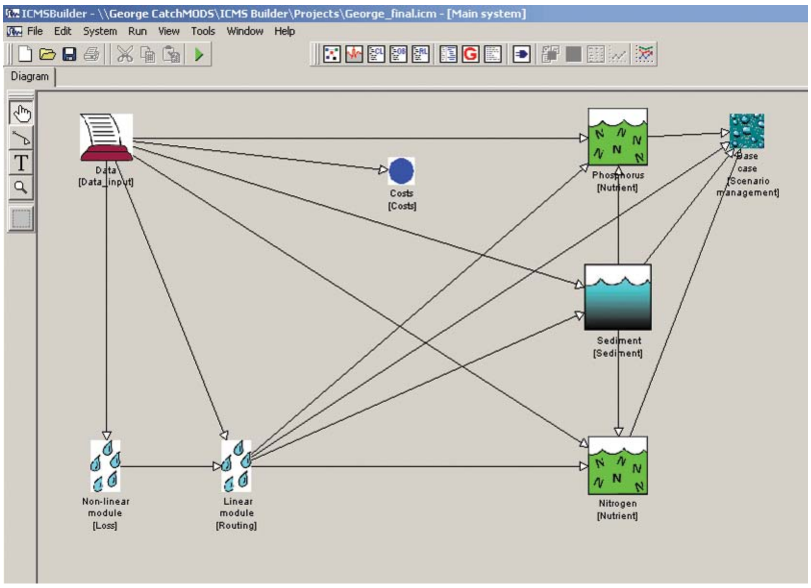


Figure 13. Graphical structure of the George catchment CatchMODS model

Model evaluation and results

Model validation traditionally consists of evaluating the results from the model simulations on datasets other than those used in constructing the model (Letcher et al, 2006). However, comprehensive testing of the entire George catchment water quality model against observed data was not feasible because of the limited monitoring data available in the George catchment. Following Letcher et al (2006) the model evaluation process involved a range of separate components. The evaluation process included a testing and calibration of the hydrological model component in the next section, validation of sediment and nutrient model outputs through comparisons against observed data in Section 7.2 and a subsequent sensitivity analysis of outputs to changes in model parameters. The validity of the George catchment model was further evaluated through an assessment of the model's ability to differentiate between different catchment management options (Section 7.4).

Calibration

Because flow observations were only available from April 1968 to September 1990, the George CatchMODS rainfall runoff model IHACRES was calibrated using a subset of data points from the total climate dataset. Continuous flow data came from the George River stream gauge at St Helens (station 2205; Figure 7). A summary of the data used for IHACRES calibration is provided in Table 9. The model was applied to the whole dataset for validation. The final model performance statistics over the total dataset and the parameters used are summarised in Table 10.

Table 10. IHACRES calibration and model parameters

Model fit		IHACRES parameters	
Relative bias (mm)	1.98	Flow threshold	260
R2	0.58	Stress threshold_forested areas	0.65
Log(R2)	0.55	Stress threshold_ non_forested areas	0.25
Monthly R2	0.69	Evaporation coeff	0.186
Modelled runoff	0.35	Slow-flow time constant	71
		Quick-flow time constant	1.31
		Prop volume slow-flow	0.49
		Prop volume quick-flow	0.51

Table 9. Rainfall runoff calibration data (station 2205)

	Precipitation (mm/day)	Stream-flow (ML/day)	Temperature (daily max °C)
minimum	0.00	25.78	2.00
1st quartile	0.00	185.41	15.50
median	0.00	332.27	18.30
mean	3.60	535.33	18.46
3rd quartile	2.02	574.96	21.00
maximum	215.08	30,134.3	39.80
# observations	8,207	7,024	7,375

Monthly nutrient monitoring data were available for the Ransom River at Sweets Hill (station 2217) from November 2003 to December 2008 and for the George River at the St Helens water intake (station 2205) from November 2004 to December 2008. A summary of the nutrient data is provided in

Table 11. Observed and nutrient concentrations (mg/l) in the George catchment rivers

Station		Nitrite	Nitrate	Ammonia	TN	Dissolved PO4	TP
Georges River at St Helens water intake	Min	0.000	0.067	0.003	0.26	0.000	0.009
	25th perc	0.002	0.159	0.01	0.382	0.004	0.016
	Mean	0.003	0.212	0.017	0.517	0.005	0.030
	Median	0.002	0.199	0.015	0.440	0.005	0.020
	75th perc	0.003	0.265	0.021	0.523	0.006	0.024
	Max	0.006	0.539	0.059	3.10	0.013	0.451
	# samples	29	50	51	51	49	51
Ransom River at Sweets Hill	Min	0.000	0.005	0.002	0.204	0.000	0.005
	25th perc	0.002	0.136	0.008	0.350	0.003	0.009
	Mean	0.002	0.176	0.013	0.407	0.003	0.013
	Median	0.002	0.174	0.011	0.403	0.003	0.012
	75th perc	0.003	0.212	0.015	0.437	0.004	0.015
	Max	0.003	0.373	0.115	0.960	0.007	0.065
	# samples	16	62	63	63	52	62

Table 12. Calibrated sediment and nutrient model parameters

Model	Parameter	Value	Data source
Sediment	Mean sediment bulk density (t/m3)	1.5	Prosser et al (2001a, page 7)
	Stream-bank erosion constant	0.003	Calibrated value
	Stream-bank erosion exponent	0.4	Calibrated value
	Mean stream-bank height (m)	2.5	Observed value
	Sediment delivery ratio	0.05	Prosser et al (2001a, page 28)
	Suspended sediment settling velocity (m/s)	1 · 10–06	Prosser et al(2001a, page 28)
	Proportion of suspended sediment	0.5	Wilkinson et al (2004)
	Trapping effectiveness of riparian zone	0.45	Calibrated value
Nitrogen	Nutrient enrichment factor	4.5	Calibrated value
	Base-flow N conc (mg/L)	0.169	Weighted average
	Quick-flow N conc (mg/L)	0.282	Weighted average
	N attenuation scaling factor	0.4	Calibrated value
Phosphorus	Nutrient enrichment factor	1.5	Calibrated value
	Base-flow P conc (mg/L)	0.0039	Weighted average
	Quick-flow P conc (mg/L)	0.0058	Weighted average
	P attenuation scaling factor	0.4	Calibrated value

Table 11. Unfortunately, sampling data for suspended sediment were not available for the George catchment so no values are available for comparison.

The calibrated sediment and nutrient model parameters were based on available monitoring data and literature values (Table 12). Weighted averages of the 25th and 75th percentiles of dissolved nitrogen and phosphorus concentrations observed at both stations were used as the base-flow and quick-flow nutrient concentrations in CatchMODS.

Steady-state outcomes

The model was run over a 49–year period to estimate steady-state averages of flow, sediment and

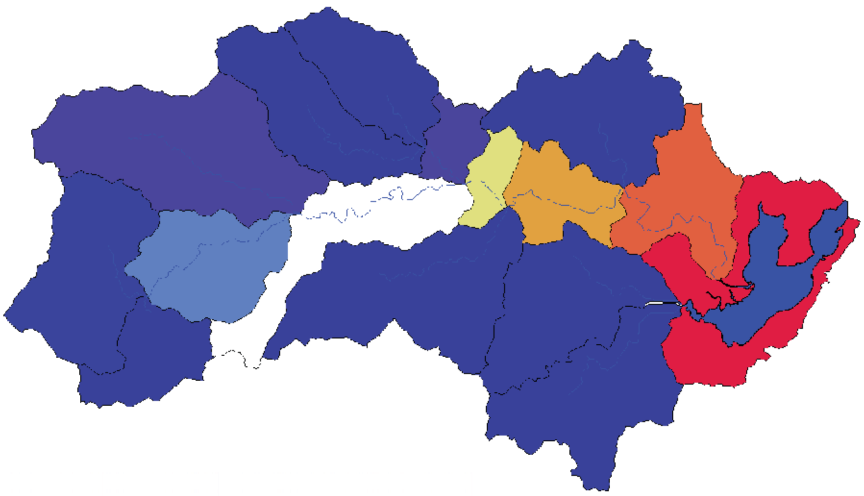


Figure 14. Predicted mean annual flows (ML) under George catchment base case scenario (blue and white indicate sub-catchments with flows of less than 100,000 ML/yr and orange and red sub-catchments have flows greater than 100,000 ML/yr)

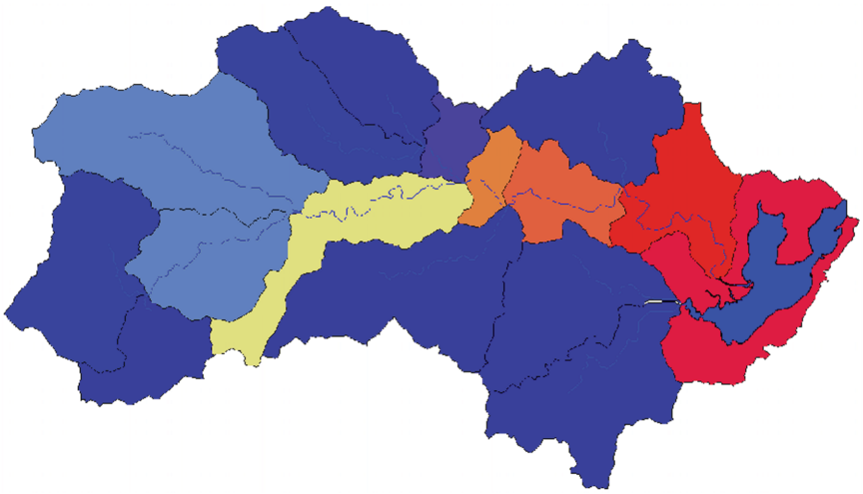


Figure 15. Predicted Total Nitrogen loads (t TN/yr) under George catchment base scenario (blue indicates sub-catchments with less than 55 t/yr TN, yellow indicates sub-catchments with between 55 and 70 t TN/yr, orange and red indicated sub-catchments with more than 70 t TN loads/year)

nutrient concentration in the George catchment rivers and to identify the most important sources of sediment and nutrients in the George catchment. Sub-catchments that supply a relative high proportion of loads compared to other sub-catchments would represent priority areas for management intervention (Newham et al, 2004).

The simulation results from the calibrated George catchment model are compared to the observed monitoring data and shown in Table 13. The observed mean annual flow (MAF) at the Ransom River stream gauge is 11,712 ML/yr, while the MAF in the George River St Helens stream gauge is 195,530 ML/yr. The MAF simulated in the George catchment model are slightly lower than the observed flows (Figure 14). In Figure 14, blue and white areas indicate sub-catchments with flows of less than 100,000 ML/yr, while orange and red sub-catchments have larger flows. Logically, MAF is maximised at the Georges Bay end-of-catchment outlet.

Monitoring data on total nutrient concentrations were averaged over the observed MAFs to calculate mean annual nutrient loadings. TN loadings are 4.77t/yr in the Ransom River and approximately 101 t/yr in the George River (Figure 15). The observed mean annual TP loadings are 0.16 t/yr in the Ransom and 5.8t/yr in the George River. The total nutrient concentrations from the model simulations are higher than the observed values in the Ransom River sub-catchment but it should be noted that the stream-gauge is located upstream of the sub-catchment outlet. Estimates of total nutrient loadings to the Georges Bay are in line with the observed nutrient concentrations at the George River stream-gauge (Table 13).

Table 13. George catchment model results

Sub-catchment outlet	Variable	Observed	Predicted
Ransom River at Sweets Hill	Mean annual flow (ML/yr)	11,712	10,391
	Suspended sediment (t/yr)	na	344
	Total Nitrogen (t/yr)	4.77	5.46
	Total Phosphorus (t/yr)	0.16	0.24
George River at St Helens	Mean annual flow (ML/yr)	195,530	191,209
	Suspended sediment (t/yr)	na	7,356
	Total Nitrogen (t/yr)	101	108
	Total Phosphorus (t/yr)	5.76	5.50

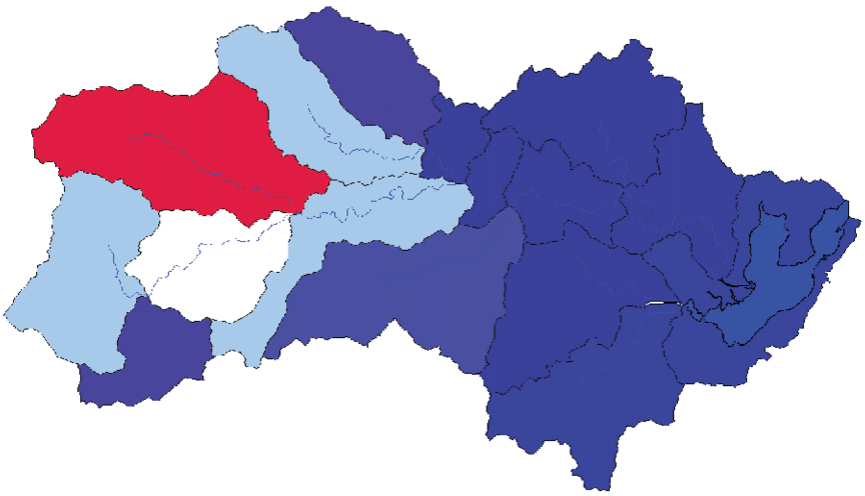
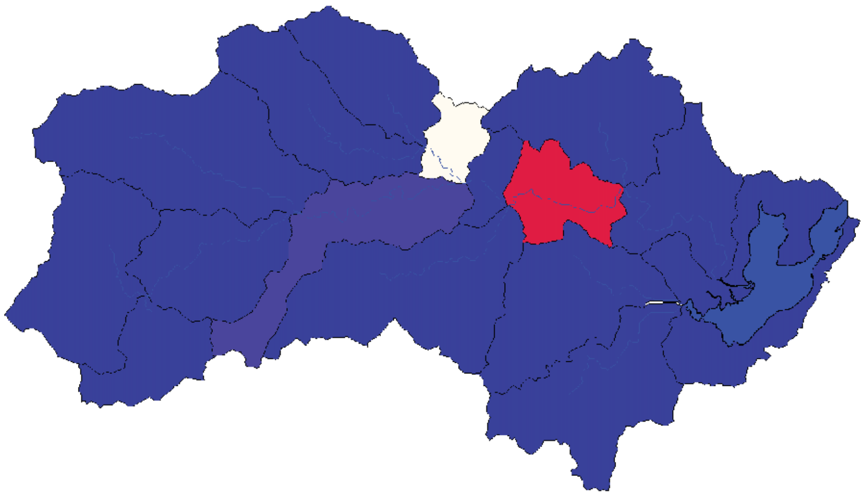


Figure 16. Predicted annual TSS loadings (t/yr) from hill-slope and stream-bank erosion under George catchment base case scenario (red indicates the major contributing sub-catchments)

Predicted sediment loads from hill-slope erosion (t/yr) (red indicates >1,500 t/yr, white and blue indicates <1,000 t/yr)



Predicted sediment loads from stream-bank erosion (t/yr) (red indicates >530 t/yr, white and blue indicates <500 t/yr)

The model runs show that hill-slope erosion is the most significant source of sediment and nutrients in the George catchment. The sub-catchments that contribute most to the sediment and nutrient loadings to Georges Bay are located in the west and middle of the catchment. The steep North and South George sub-catchments contribute predominantly through hill-slope erosion while the Upper and Lower George sub-catchments are major sources of stream-bank erosion (Figure 16). These sub-catchments have several major stream-bank erosion sites and high base flow volumes which means that less sediment deposition occurs within the sub-catchment, contributing a larger volume of sediment (and associated nutrients) being contributed to downstream reaches. The North, South, Upper and Mid George sub-catchments are the critical sources of nutrients (Figure 17). These sub-catchments all have a relatively high proportion of agriculture compared to the other sub-catchments (noting that there is still relatively little intensive agriculture in the George catchment compared to other catchments in Tasmania).

The base scenario assumes that no management actions are undertaken to reduce sediment and nutrient loads to the George streams and estuary. CatchMODS can be used to investigate how changes in land use patterns, stream-bank engineering or riparian revegetation may reduce sediment and nutrient loads and where remediation actions should be focused. In the George catchment model, a hierarchical structure of management actions was employed. River bank engineering works are more efficient in reducing erosion than revegetation. Revegetation of riverbanks is first assumed to reduce stream-bank erosion. Additional riparian revegetation is assumed to trap hill-slope erosion only once all stream-bank erosion sites in a sub-catchment are addressed. In Section 7.4, two scenarios demonstrate how management changes may impact sediment and nutrient loadings in the George catchment.

Sensitivity analysis

An analysis of the changes in model results to variations in the model parameters was undertaken

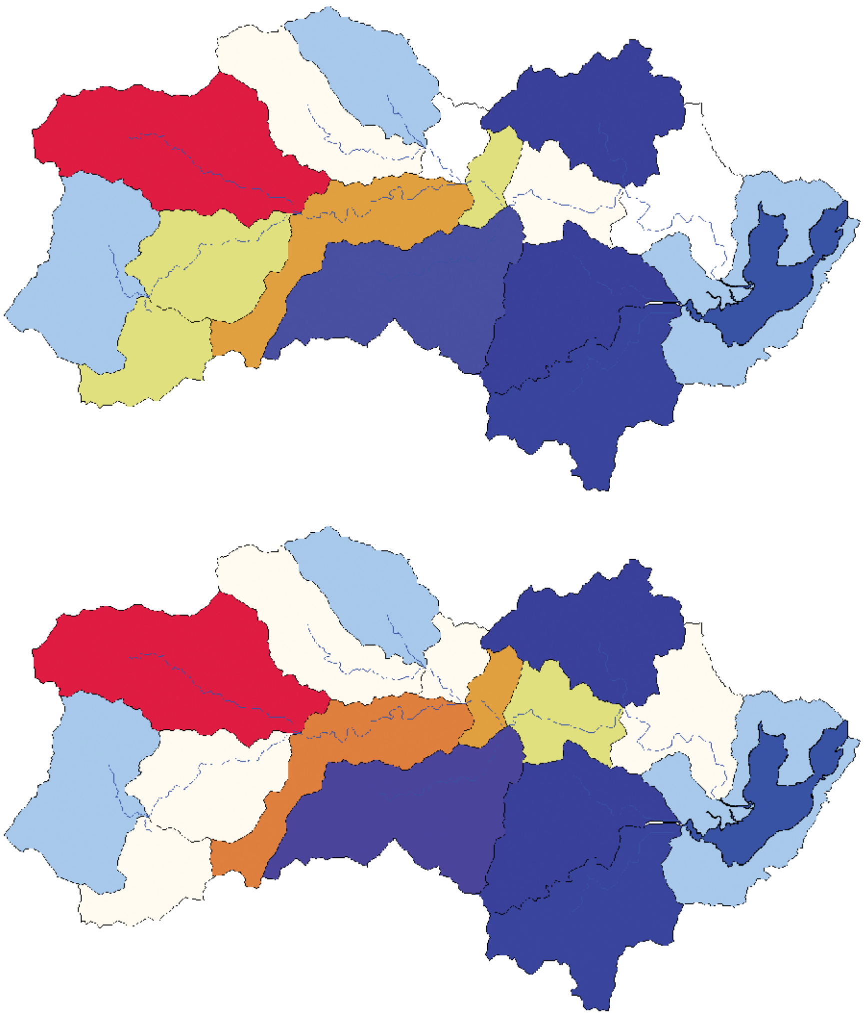


Figure 17. Predicted specific TN and TP yields (t/km/yr) under George catchment base case scenario

Predicted total nitrogen yields (t/km/yr)
(blue <0.2, white 0.2 – 0.3, yellow/orange 0.3 – 0.4 and red >0.4 t/km/yr)

Predicted total phosphorus yields
(blue and white <0.012, yellow/orange 0.012 – 0.022 and red >0.022 t/km/yr)

Table 14. Parameters base values and parameter bounds for sensitivity analysis

Model	Parameter	Base value	Lower bound	Upper bound
Sediment	Stream-bank erosion constant	0.003	0.001	0.01
	Stream-bank erosion exponent	0.4	0.2	0.6
	Sediment delivery ratio	0.05	0.01	0.1
	Suspended sediment settling velocity (m/s)	1 · 10–06	1 · 10–07	1 · 10–05
	Proportion of suspended sediment	0.5	0.3	0.7
	C-factors	varying per land use	–20%	+20%
Nitrogen	Nutrient enrichment factor	4.5	2	10
	Base-flow N conc (mg/L)	0.169	0.135	0.203
	Quick-flow N conc (mg/L)	0.282	0.226	0.338
	Soil nutrient concentrations (g/g)	varying per land use	–20%	+20%
	N attenuation scaling factor	0.4	0	1
Phosphorus	Nutrient enrichment factor	1.5	0.5	2.5
	Base-flow P conc (mg/L)	0.0039	0.0031	0.0047
	Quick-flow P conc (mg/L)	0.0058	0.0046	0.0070
	Soil nutrient concentrations (g/g)	varying per land use	–20%	+20%
	P attenuation scaling factor	0.4	0	1
Management effectiveness	Trapping effectiveness of riparian zone	0.45	0.27	0.63
	Effectiveness of engineering works on reducing stream-bank erosion	0.95	0.76	1.0
	Effectiveness of riparian revegetation on reducing stream-bank erosion	0.75	0.6	0.9

using parameter bounding techniques. Model parameters were systematically varied across a range of anticipated values derived from literature values and proportional changes in measured parameters (Table 14). Total suspended sediment, nitrogen and phosphorus loadings to the Georges Bay were used as output indicators in the analysis.

In the sediment model, the parameters that were varied one at a time were: the stream-bank erosion constant and exponent (a and b in Equation 7), the sediment delivery ratio (*SDR* in Equation 5), the settling velocity of suspended sediment (ν in Equation 9) and the proportion of suspended sediment in eroded stream-bank erosion material (ω_s in Equation 8). The c-factors (Section 5.4.1) were varied together, ranging from minus to plus 20% of the base values. Model parameters that were varied in the nutrient models were: nutrient enrichment ε (Equation 10), base-flow and quick-flow concentrations (Equation 11), soil nutrient concentrations (*C* in Equation 10) and the attenuation factor *z* (Equation 12). Enrichment and attenuation were varied one at a time, while base-flow and quick-flow were varied together (±20%) and soil nutrient concentrations were also varied together (±20%).

Management actions like revegetation and stream-bank engineering have the potential to reduce sediment loadings to streams but it is unknown how effective each of these actions is. Management effectiveness parameters were changed with ±40% for the effectiveness of the riparian buffer to trap hill-slope erosion (e_{rip_h}) and with ±20% for the effectiveness of riparian vegetation and engineering to reduce stream-bank erosion (e_{rip_s} and e_{eng}).

The impact of changing model parameters on the model output was analysed using a relative sensitivity (Sij) measure given by:

$$S_{ij} = \frac{(out_i - out_{i,0})}{out_{i,0}} \times \frac{par_{j,0}}{(par_j - par_{j,0})} \times 100 \quad (21)$$

where $out_{i,0}$ is the value of indicator i at the base value of parameter $j(par_{j,0})$ and out_i is the predicted output at a changed parameter value (par_j). If S_{ij} is positive, a change in the parameter value causes a change in sediment or nutrient loadings in the same direction. Where the relative sensitivity is less than 100%, a change in the parameter leads to a less than proportional change in the output value (Letcher et al, 2006). A representative subset of 5,000 datapoints (from October 1975 to June 1989) rather than the full 18,017 set of data were used to run the uncertainty analysis to increase model speed.

Results of the sediment model analyses are shown in Figure 18. It is shown that the relative sensitivity of sediment and nutrient loadings to changes in the bank erosion constant *a* are relatively low when the constant is between 0.001 and 0.005 but increases exponentially at higher values of *a*. The relative sensitivity of sediment and nutrient loadings to the bank erosion exponent increases considerably when

$b > 0.5$. Figure 18 shows a high sensitivity of the model output to the sediment delivery ratio, with a relative sensitivity of more than 90 when the SDR increases from 0.05 to 0.1. Model output is less sensitive to changes in the proportion of suspended sediment in eroded materials. Finally, as shown in Figure 18, the relative sensitivity of model outputs to changing all C-factors by ±20% is very low, at a maximum of 3.69 for TN loadings.

The results of varying the parameters in the nutrient models are presented in Table 15. It is evident from Table 15 that the relative sensitivity of predicted nitrogen loadings is larger than the responsiveness of phosphorus concentrations to changes in the model parameters. The negative results for changes in the attenuation factor indicate that the predicted nutrient loadings decrease when the attenuation factor increases and vice versa. Nutrient concentrations decline at a decreasing rate as the attenuation factor increases (Figure 19). The model shows low sensitivity to attenuation factors larger than approximately 0.4. The nutrient models are relatively sensitive to changes in the enrichment factor, with nutrient concentrations increasing linearly with the enrichment factors (Figure 20). The sensitivity to changes in flow and soil nutrient concentrations is very low in both the nitrogen and phosphorus models.

To illustrate the sensitivity of the model outputs to variations in the management effectiveness parameters, three management scenarios were run. In each scenario, changes were made to the length of riparian vegetation or engineering works in the George catchment, while keeping land use constant. In the first scenario, 50% of all non-forested stream-sides in each sub-catchment were assumed to be vegetated and e_{rip_hill} was varied with ±40%. In the second scenario, engineering works are undertaken at 50% of the mapped stream-bank erosion sites while e_{eng} is varied with ±20%. In the third scenario 50% of all mapped stream-bank erosion sites is revegetated and e_{rip_stream} is varied with ±20%. The impact of changing the management effectiveness parameters are measured as the relative change in output compared to the base scenario:

$$S_i = \frac{(out_i - out_{i,0})}{out_{i,0}} \times 100 \tag{22}$$

The relative changes in predicted nutrient and sediment loadings under each of these scenarios are displayed in Table 16. It is shown that changing the effectiveness of engineering works or riparian revegetation on reducing stream-bank erosion has very little impact on reducing total nutrient and sediment loadings to the Georges Bay. The impact of changes in the efficacy of riparian vegetation to trap hill-slope erosion is similar across indicators and greatest on total phosphorus output (nearly 6%, Table 16). These results are as expected, since hill-slope erosion is the dominant contributor to sediment and nutrient loadings in the George catchment (Section 7.2).

Table 15. Relative sensitivities of predicted TN and TP loadings to changes in nutrient model parameters

Parameter	Parameter change	Relative sensitivity TN	Relative sensitivity TP	Parameter	Parameter change	Relative sensitivity TN	Relative sensitivity TP
Attenuation factor	–100%	–29.79	–14.04	Enrichment factor	–60%	33.23	30.84
	–75%	–6.70	–3.16		–40%	14.77	13.71
	–50%	–1.40	–0.66		–20%	3.69	3.43
	–25%	–0.20	–0.09		0%	0.00	0.00
	0%	0.00	0.00		20%	3.69	3.43
	25%	–0.09	–0.04		40%	14.77	13.71
	50%	–0.28	–0.13		60%	33.23	30.84
	75%	–0.51	–0.24		80%	59.07	54.83
	100%	–0.77	–0.36		100%	92.29	85.67
	125%	–1.03	–0.49				
	150%	–1.30	–0.61				
	175%	–1.57	–0.74				
	200%	–1.84	–0.86				
Base-flow and quick-flow concentrations	–20%	0.11	0.05	Soil nutrient concentrations	–20%	3.89	3.88
	–15%	0.06	0.03		–15%	2.18	2.24
	–10%	0.03	0.01		–10%	0.97	1.02
	–5%	0.01	0.00		–5%	0.24	0.24
	0%	0.00	0.00		0%	0.00	0.00
	5%	0.01	0.00		5%	0.25	0.24
	10%	0.03	0.01		10%	0.97	1.03
	15%	0.06	0.03		15%	2.20	2.25
	20%	0.11	0.05		20%	3.89	3.88

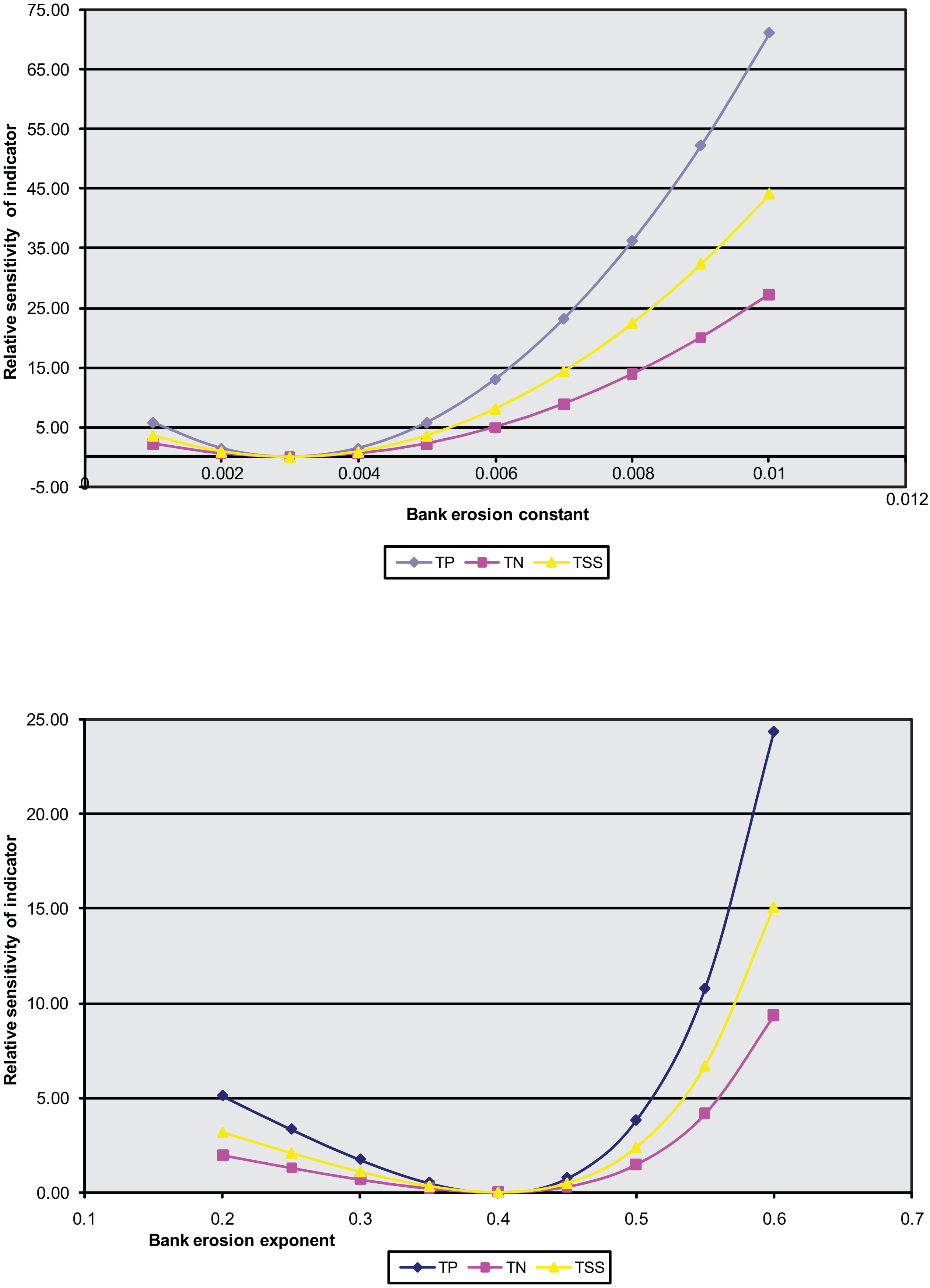
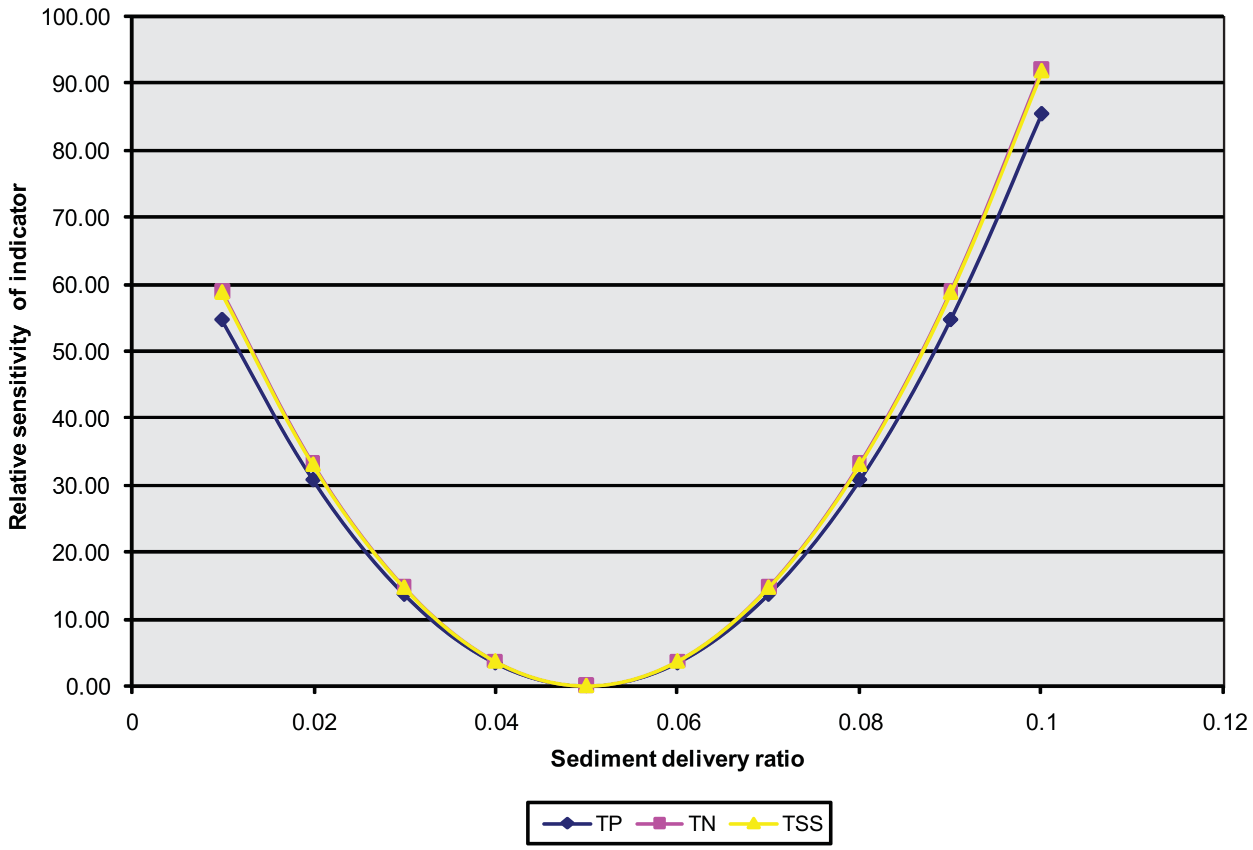
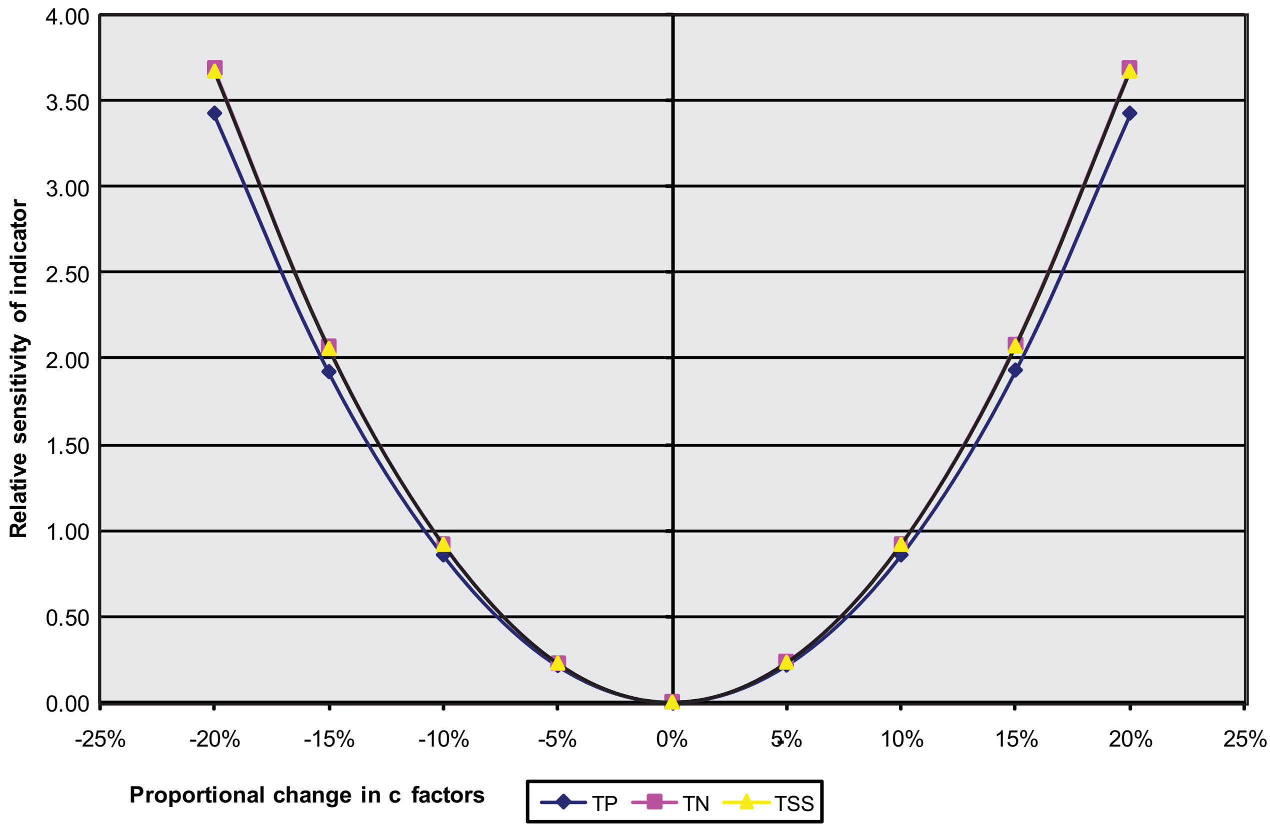


Figure 18. Changes in model output at different values of the sediment model parameters



100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
0.02
0.04
0.06
0.08
0.1
0.12
Relative sensitivity of indicator
Sediment delivery ratio
TP
TN
TSS



4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-25%
-20%
-15%
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0%
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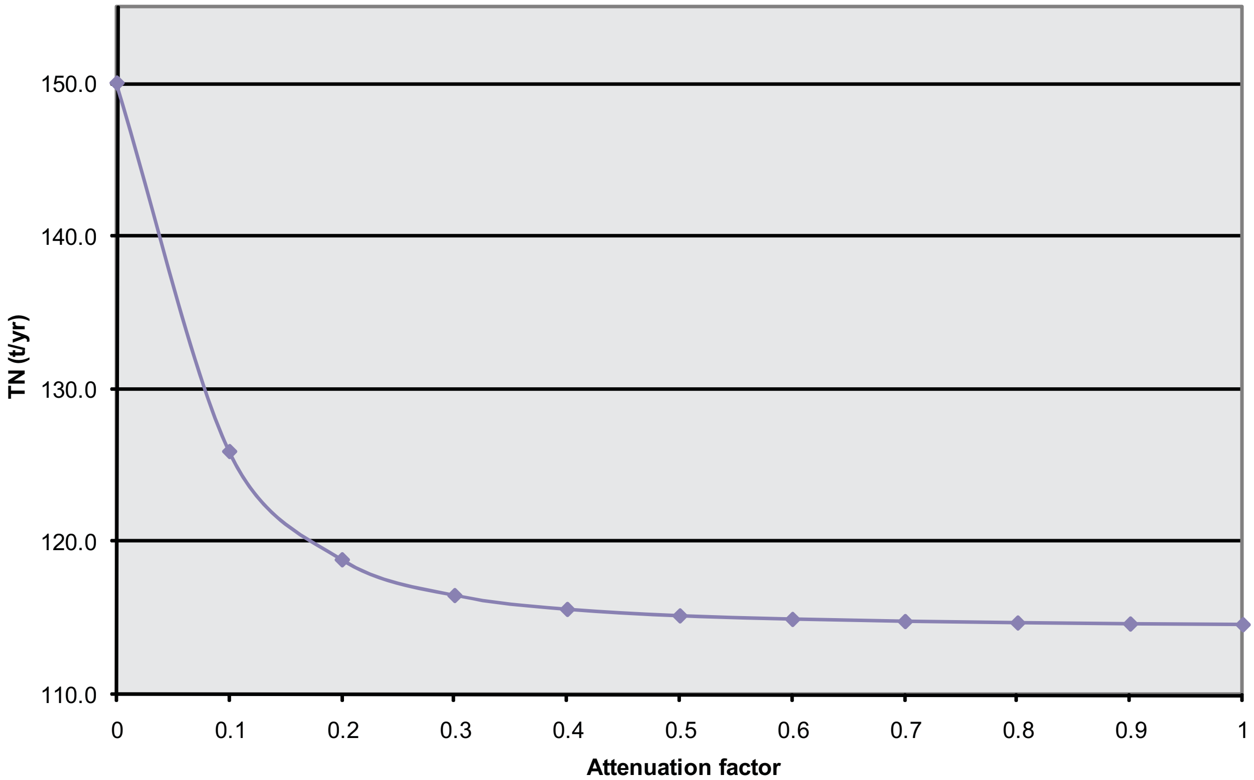
10%
15%
20%
25%
Relative sensitivity of indicator
Proportional change in c factors
TP
TN
TSS



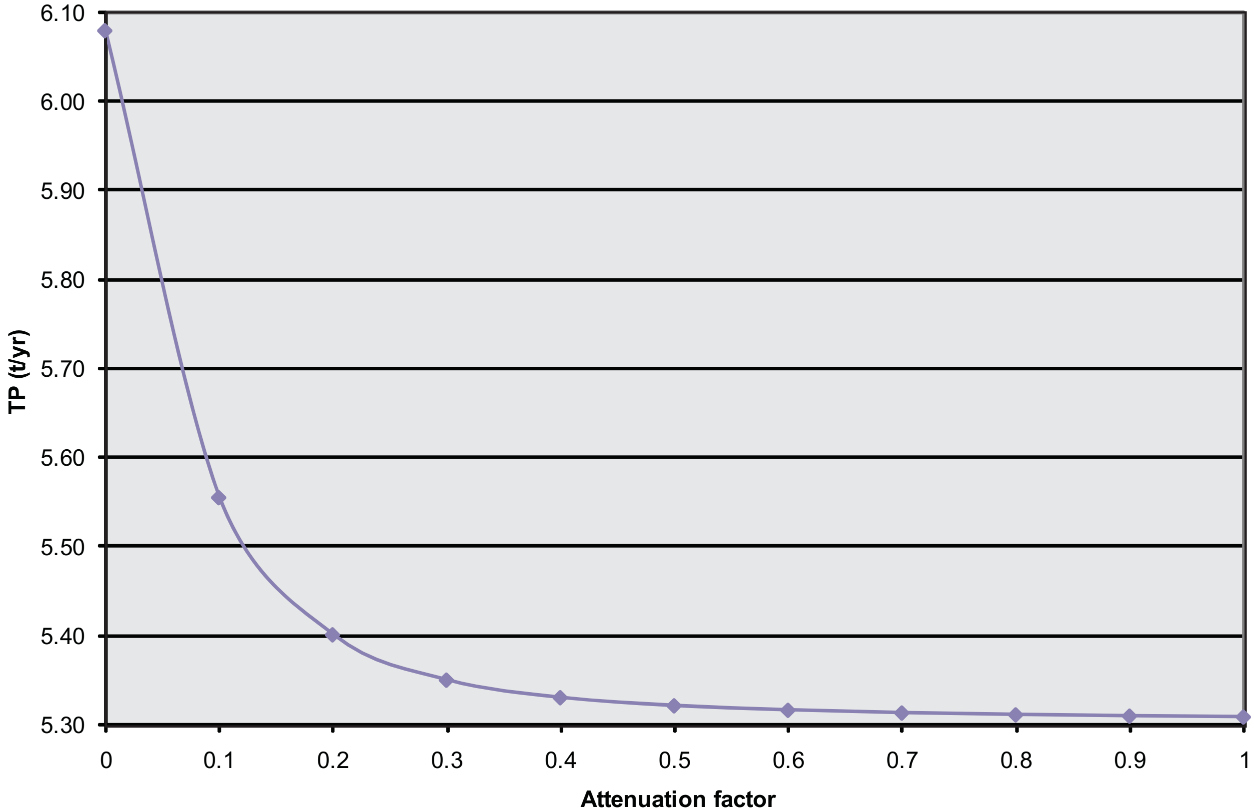
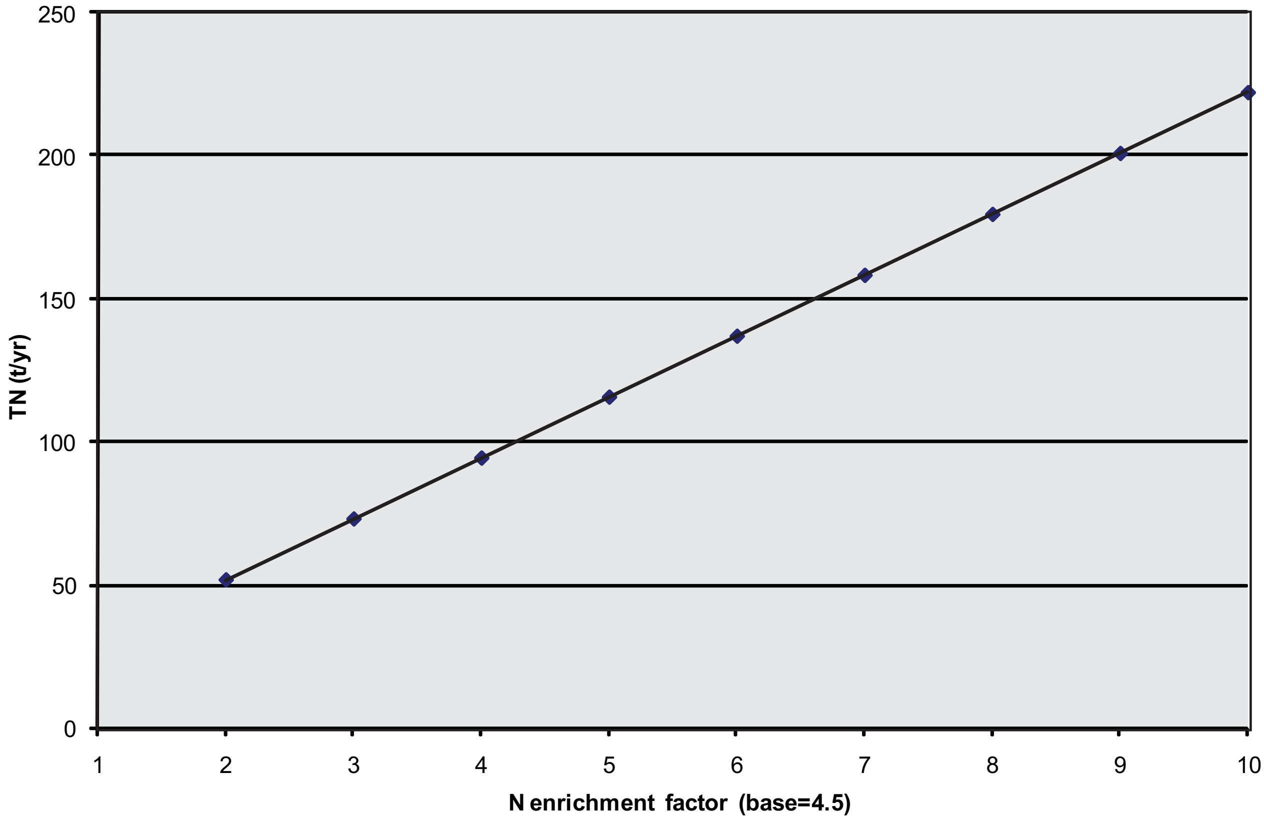


Figure 19. Model output at varying values of the attenuation factor (base = 0.4)



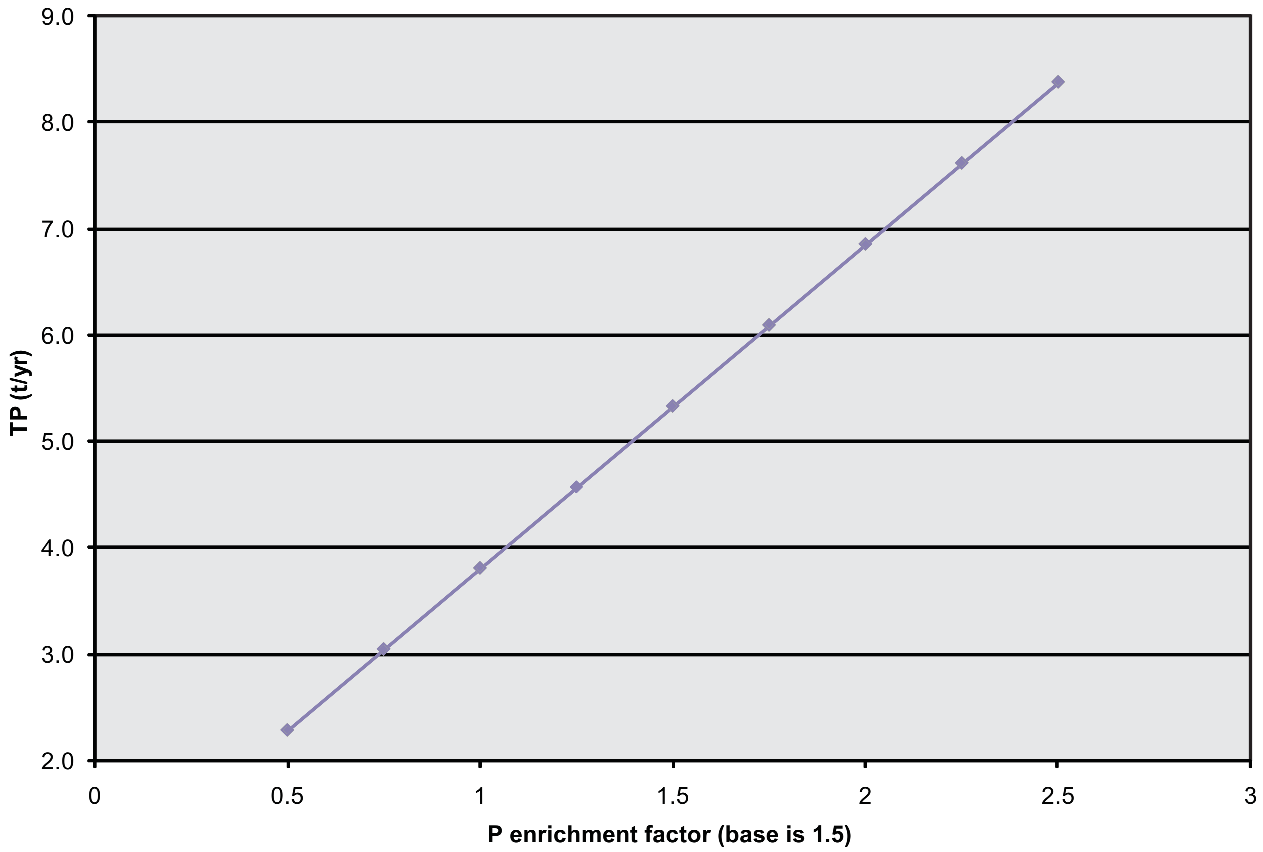


Figure 20. Model output at varying values of the nutrient enrichment factors

Table 16. Relative change in output (%) under different management effectiveness assumptions

Scenario 1 – Revegetation on 50% of all non-forest riparian zone			
erip_hill	*TP*	*TN*	*TSS*
–40%	5.99	4.89	4.62
–30%	4.49	3.67	3.47
–20%	2.99	2.45	2.31
–10%	1.50	1.22	1.16
base	0.00	0.00	0.00
+10%	–1.50	–1.22	–1.16
+20%	–2.99	–2.45	–2.31
+30%	–4.49	–3.67	–3.47
+40%	–5.99	–4.89	–4.62
Scenario 2 – Engineering works on 50% of all mapped stream-bank erosion sites			
eeng	*TP*	*TN*	*TSS*
–20%	1.67	0.67	0.99
–15%	1.25	0.50	0.75
–10%	0.83	0.34	0.50
–5%	0.42	0.17	0.25
base	0.00	0.00	0.00
+5%	–0.44	–0.18	–0.26
Scenario 3 – Revegetation on 50% of all mapped stream-bank erosion sites			
eeng	*TP*	*TN*	*TSS*
–20%	1.29	0.53	0.78
–15%	0.97	0.39	0.58
–10%	0.65	0.26	0.39
–5%	0.32	0.13	0.19
base	0.00	0.00	0.00
+5%	–0.32	–0.13	–0.19
+10%	–0.65	–0.26	–0.39
+15%	–0.97	–0.39	–0.58
+20%	–1.29	–0.53	–0.78

Scenario analysis

The George catchment model was not developed as a forecasting tool, but rather to assist understanding of the relative magnitude and direction of changes in sediment and nutrient loadings in response to changes in catchment management actions (Jakeman and Letcher, 2003). Scenarios that can be run in CatchMODS include:

- Land use change
- Stream-bank engineering works
- Riparian zone revegetation

Additional scenarios that can be added to the framework include:

- Climate variability
- Gully engineering works
- Changes in point source pollution

This section demonstrates the simulation results for two scenarios: (1) the impacts of changing land use from agriculture and native production forestry to plantation forestry, and (2) riparian zone revegetation.

Land-use change

Model simulations were run to test the impacts of land use changes on sediment and nutrient loadings in the George catchment. In the scenario described here, the area of plantation forestry was changed in an upstream and a downstream sub-catchment of similar size and land uses. Both the Ransom River sub-catchment and the Lower George sub-catchment have approximately 15% agricultural area at present but no plantation forestry (Table 4).

To demonstrate the impacts of changing land use in the CatchMODS model, agricultural areas and production forests were changed to plantation forest in 5% increments until all agricultural area would be converted (Table 17). A further increase in plantation forestry at the expense of production forest was modelled until 50% of the sub-catchment area would be converted into forestry plantations. The model sensitivity to an increase in plantation area

Table 17. Percentage change compared to the base case in Mean Annual Flow, Total Suspended Sediment, Total Nitrogen and Total Phosphorus loadings to Georges Bay, given equal conversion of agriculture and native production forest into forestry plantation.

Sub-catchment	Indicator	Base	10% plantation	20% plantation	30% plantation	40% plantation	50% plantation
Ransom River	MAF (ML)	0.00	–0.24	–0.47	–0.69	–0.69	–0.69
	TSS (t/yr)	0.00	0.13	0.27	0.40	1.20	2.01
	TN (t/yr)	0.00	–0.14	–0.28	–0.42	0.05	0.52
	TP(t/yr)	0.00	–0.45	–0.89	–1.34	–0.91	–0.49
Lower George	MAF (ML)	0.00	–0.15	–0.29	–0.43	–0.43	–0.43
	TSS (t/yr)	0.00	0.03	0.06	0.09	0.25	0.41
	TN (t/yr)	0.00	–0.04	–0.08	–0.11	–0.02	0.08
	TP(t/yr)	0.00	–0.09	–0.19	–0.28	–0.19	–0.11

was tested with respect to the MAF and sediment and nutrient loadings into the Georges Bay. A number of assumptions were made in the model that should be kept in mind when interpreting the results (see Section 8 for a discussion):

1. It was assumed that conservation areas would not be converted because most of the conservation areas are protected from clear-felling under national or state legislation.
2. The simulated flows and loads of sediment and nutrients are steady-state annual averages, meaning that the effects of the transition period from agriculture or production forest to plantation forestry on model outputs as the trees establish is not considered.
3. The impacts of land management practices are not modelled. It should be noted that the way in which the land is managed within a particular land use could result in substantial differences in sediment and nutrient generation.
4. It is assumed that forestry areas have fully vegetated riparian zones, whereas agricultural areas do not. This means that the efficacy of the riparian zone in trapping hill-slope erosion and runoff is by definition higher in forested land use areas.

As shown in Table 17, the impacts are greatest in the upstream sub-catchment. Converting agricultural land and production forestry to forestry plantations has very little impact on flow, total nutrient or sediment loadings into the Georges Bay. Mean annual flow reduces by less than 1%. Sediment loadings increase as a result of plantation establishment, while changes in nutrient loadings vary. This is expected because the runoff from agricultural areas is higher than that from plantation forestry, leading to an increase in nutrient loadings. On the other hand, the runoff from plantations is higher than the runoff from production forests given the shorter rotation time. This combined effect of changing agricultural and production forest areas leads to the mixed results in nutrient loadings.

In Table 18, the results of converting either agriculture into plantations or converting production forest are displayed for the Ransom River, demonstrating a decrease in both total suspended sediment and nutrient loadings when plantations are established on agricultural land, but an increase in loadings when production forest is converted. This indicates that changes in flow, sediment and nutrient loadings from plantation development are likely to depend on the previous land use.

Riparian revegetation

A second series of scenarios was run, in which the riparian zone was revegetated to trap hill-slope erosion. Some important assumptions were made when simulating the impacts of riparian revegetation actions:

1. Following the requirement of buffer strips along water course in all forestry areas as stipulated in the Forest Practices Code (Forest Practices Board, 2000), it was assumed that all forested areas have fully-vegetated riparian zones.
2. It was further assumed that the proportion of land use in the riparian zones of each sub-catchment were equivalent to the total proportional areas of land use in each sub-catchments (Table 4).
3. No distinction is made between alternative types of riparian vegetation (see Section 8 for a discussion).

Multiplying the total sub-catchment stream length (Table 7) with each sub-catchment's proportional area of grazing, irrigation and urban land use, the total length of non-forest riparian zone in the George catchment is approximately 20km under the base scenario. The scenario demonstrated in this section simulates the impacts of revegetation actions

Table 18. Percentage change compared to the base case Mean Annual Flow, Total Suspended Sediment, Total Nitrogen and Total Phosphorus loadings to Georges Bay, given separate conversion of agricultural land into plantation forestry or conversion of native production forest into forestry plantations.

Converting only agricultural area up to 15% of the sub-catchment					
Sub-catchments	*Indicator*	*Base*	*5% plantation*	*10% plantation*	*15% plantation*
Ransom River	MAF (ML)	0.00	–0.24	–0.47	–0.69
	TSS (t/yr)	0.00	–0.27	–0.53	–0.80
	TN (t/yr)	0.00	–0.37	–0.74	–1.11
	TP(t/yr)	0.00	–0.66	–1.31	–1.97
Converting only native production forest up to 30% of the sub-catchment					
Sub-catchments	*Indicator*	*Base*	*10% plantation*	*20% plantation*	*30% plantation*
Ransom River	MAF (ML)	0.00	0.00	0.00	0.00
	TSS (t/yr)	0.00	0.80	1.60	2.40
	TN (t/yr)	0.00	0.47	0.93	1.40
	TP(t/yr)	0.00	0.42	0.85	1.27

from 10 to 100% of the non-forested stream-banks zones, with revegetation equally spread across the sub-catchments.

Results of these scenario runs are presented in Figure 21. Because riparian vegetation does not affect the IHACRES model, there are no changes in mean annual flows. Total suspended sediment, total nitrogen and total phosphorus loadings decrease linearly with an increase in riparian vegetation on non-forested stream-banks. Riparian vegetation traps the runoff from hill-slope erosion, reducing TSS loadings to the George catchment streams. Since the particulate nutrient fractions are associated with TSS, a reduction in sediment load also decreases total nutrient loadings into the Georges Bay. At most, a 26.1% reduction in TP loadings is achieved when all riparian zones are vegetated.

CatchMODS is designed to identify critical nutrient and sediment source areas and can assist catchment managers to focus on remediation actions in specific sub-catchments. To demonstrate the impacts of targeted remediation actions, consider the impacts of revegetating the total length of riparian zones spread equally across the catchment, versus revegetation of critical source areas. For example, it is estimated that revegetation of 5km of the total length of riparian zones spread across the catchment would result in a reduction in total phosphorus loads to the Georges Bay from 5.50 to 4.98t/yr (approximately 9.5%). Significantly higher reductions can be achieved through targeted revegetation in areas with major stream-bank erosion sites. Were the same total length of riparian zone revegetated in the Ransom-Groom and North-, South-, Upper- and Lower-George sub-catchments, the model suggests that reduction in total phosphorus loadings into the Georges Bay would be nearly 15% (from 5.50 to 4.72 t/yr).

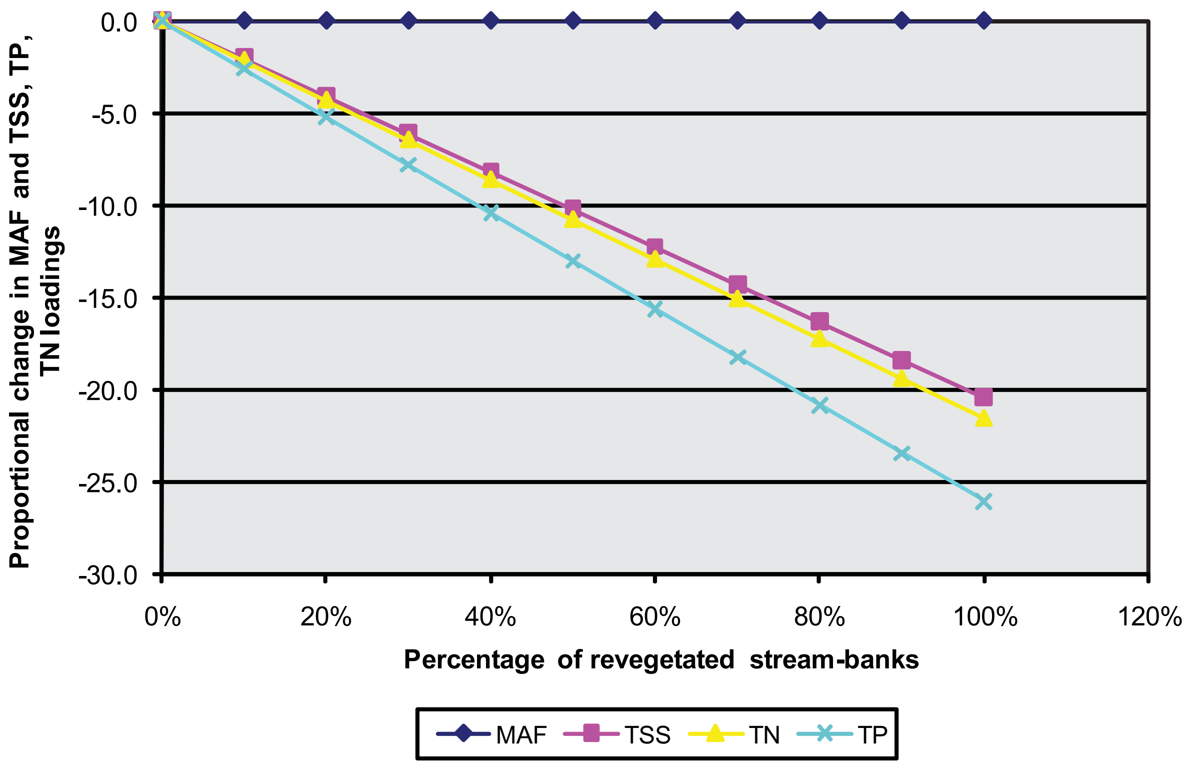


Figure 21. Proportional change in MAF, sediment loads and nutrient loadings (compared to the base of no vegetation) at increasing levels of revegetated zone (as a percentage of total non-forested stream zones)

Discussion and conclusion

Many modelling approaches are available to estimate water-quality changes in Australian catchments. In this study, the catchment-scale modelling framework known as CatchMODS was used to develop a sediment and nutrient model for the George catchment in Tasmania.

CatchMODS includes hydrologic, stream sediment and nutrient export models that enable an assessment of changes in nutrient and sediment loadings to the Georges Bay under alternative management scenarios. Model runs suggest that hill-slope erosion is likely to be the greatest contributor to sediment and nutrient loads in the George catchment. Consequently, management actions such as revegetation that reduce or trap hill-slope erosion are most likely to reduce nutrient and sediment in the bay.

An advantage of CatchMODS lies in its flexible structure that can readily incorporate additional sub-models and can be updated as new knowledge becomes available. The George catchment model is an integrated biophysical modelling framework that incorporates land-use and riparian-management drivers. The model can readily be extended to include climatic or land-management changes. An economic module can also be included to account for the costs of management changes. The economic module was not populated for the George catchment because of the lack of information on management costs. Ongoing consultations with regional policy stakeholders and local landholders are envisaged to provide data about the costs of management interventions and the opportunity costs of land-use changes. This information can readily be incorporated in the framework when cost data becomes available. The inclusion of local costs for management interventions in an additional economic module would provide the opportunity for decision-makers to target the most cost-effective decision interventions in the George catchment.

Some comments can be made about the underlying structure of the George catchment model. Firstly, the use of the RUSLE and mean annual hill-slope erosion neglects the often seasonal patterns in rainfall and vegetation. Lu et al (2001) propose a modification of the RUSLE that calculates monthly soil losses, which could be included in the modelling framework. Second, assessment of the ways in which sediment and nutrients are trapped in riparian buffers is coarse in the George catchment model. Hill-slope erosion is assumed to be trapped by the riparian buffer zone, at a constant efficacy rate set by the model developer (e_{rip_hill}). This means that there is no distinction between types of vegetation planted in the riparian buffer strip. To improve the assessment of riparian-trapping efficiency, it is possible to add an additional riparian sub-model. An additional module could allow an assessment of the efficacy of riparian buffers of different widths and vegetation composition in trapping sediment and nutrients. Previous work has recommended the use of an additional Riparian Particulate Model to assess the effectiveness of riparian buffers in reducing stream particulate inputs (Newham et al, 2007). Thirdly, the spatial representation of land uses is limited to dividing the catchment in multiple sub-catchments. It is assumed that land uses adjacent to the George catchment streams are proportional to the distribution of land use in each sub-catchment. Evidently, this has implications for predicted sediment and nutrient loadings, as the land use directly bordering a stream will have a stronger influence than upland land uses.

Several challenges were encountered in the George catchment model development. The lack of reliable local data necessitated assumptions regarding model parameters based on previous applications in mainland Australia which may not be suitable for Tasmanian catchments (Baginska et al, 2003). For example, there is limited knowledge about soils in the George catchment, up-to-date land-use information or detailed mapping of riparian vegetation or active stream-bank erosion in the catchment. The calibration of the George catchment water-quality model was performed without knowledge of the extent and type of riparian vegetation along stream banks (Section 7.1). The current model assumes that none of the riparian zones in agricultural or urban areas is vegetated. Incorporating information on existing riparian vegetation in these areas would alter the calibrated parameter values, which in turn would require an increase in enrichment factors for the predicted nutrient concentrations in the George catchment streams to match observed data. The model's sensitivity analysis (Section 7.3) revealed that increased information on soil nutrient concentrations would have limited impact on model outputs. However, better information on soil bulk density and generation rates in Tasmanian catchments as well as additional water-quality monitoring data would improve the model calibration and make the model more reliable for future applications in Tasmania. Another project within Landscape Logic is using gauging station data from 34 catchments to provide more accurate generation rates for Tasmanian land use. When this information becomes available, it could be used to improve the accuracy of the simulations in this George catchment model.

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