Techniques for Assessing the Performance of a Landscape-Based Sediment Source and Transport Model: Sensitivity Trials and Physical Methods

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Abstract: Widespread degradation of aquatic habitat and water quality has occurred since European settlement of Australia. Repairing this degradation is expensive and hence on-ground management needs to be carefully focussed. The Sediment River Network model, SedNet, used for the estimation of the sources and transport of sediment spatially and at catchment scales, potentially provides a useful tool to assist land managers in focusing this work. The complete model, whilst broadly applied has not been systematically tested to assess its accuracy or sensitivity to its various model components. The aim of this paper is to propose a framework for such testing. Results from the work will be used to prioritise data acquisition, and improve the structure and parameterisation of the model where necessary. The research is also particularly relevant for shifting application of the model from continental to catchment scales. The testing will comprise two components - sensitivity assessment and accuracy assessment. This paper provides a brief introduction to the SedNet model and a framework for assessing the model. Examples of sensitivity assessment and accuracy assessment are provided and discussed.

Keywords: Sensitivity assessment; Water quality; Sediment load modelling; SedNet model

1. INTRODUCTION

Significant alteration of catchments, streams and associated ecosystems of Australia has occurred since European settlement. These changes, caused by a variety of agents, have resulted in the extensive degradation of aquatic habitat and water quality. Amelioration is time consuming, expensive and often poorly focussed. To effectively focus on-site work to repair degradation of riparian ecosystems, improved understanding and quantification of the generation of fluxes from upland catchments is required. Particularly important in land and water management applications are tools that spatially identify sources and transport of sediment.

The recently developed Sediment River Network Model, SedNet [Prosser et al., 2001a and b], provides a new and promising approach to the estimation of sources and transport of sediment at catchment scales. However, the complete model and some of its components have yet to be systematically tested. The aim of this paper is to propose a framework for such testing. Results from this work will be used to prioritise data acquisition and improve the structure and parameterisation of the model. This paper briefly describes the SedNet model, then presents a framework to be used for evaluation and improvement of the model. Initial results of simple sensitivity trials and an accuracy assessment comparison are then presented to illustrate the potential of this work.

2. THE SEDNET MODEL

The SedNet model is fully described by Prosser et al., [2001a and b]. The model is used to estimate mean annual sediment budgets sequentially through links of a river network. The outputs of the modelling can be used to address typical resource assessment questions such as determining which sub-catchments dominate the supply of sediment, where sediment is stored in a catchment, the proportion of sediment supplied by various erosion processes and importantly, how management change may alter downstream yields [Prosser et al., 2001b]. The model has been constructed for application at the continental scale; at present first-order streams have areas of 25-50km^2 and stream reach lengths of approximately 10km are modelled.

The SedNet model incorporates three sediment-source (erosion) sub-models: hillslope, gully and streambank. Suspended sediment load delivered to the river network is estimated from all three source models. Bedload sediment is estimated from only the gully and streambank models; hillslope erosion is assumed not to deliver any bedload sediment to the stream network. The transport of suspended and bedload sediment fractions are modelled separately in the river network.

Suspended sediment can be removed from the stream network by deposition, estimated using a floodplain deposition sub-model. All suspended sediment that is not deposited is routed downstream through the stream network. Coarse sediment is routed through the river network using a sediment transport capacity sub-model. Where applicable a reservoir/lake trap efficiency sub-model is included - represented as a link in the river network corresponding to the reservoir.

The SedNet model has a large number of parameters. All parameter values are provided from empirical or theoretical prior knowledge, and they are not (as yet) calibrated against field measurements [Prosser et al., 2001b]. The model, including all data handling, is coded in the ARC Macro Language, the scripting language of ARC/INFO GIS. See Figure 1 for an illustration of SedNet model results for the upper Murrumbidgee River catchment.

3. FRAMEWORK FOR EVALUATION AND IMPROVEMENT

According to [Sargent, 1993], validation can be defined as demonstrating that a model is accurate enough for its intended application. The framework for validation presented here incorporates model sensitivity trials to evaluate where accuracy assessment and further model development should be focused.

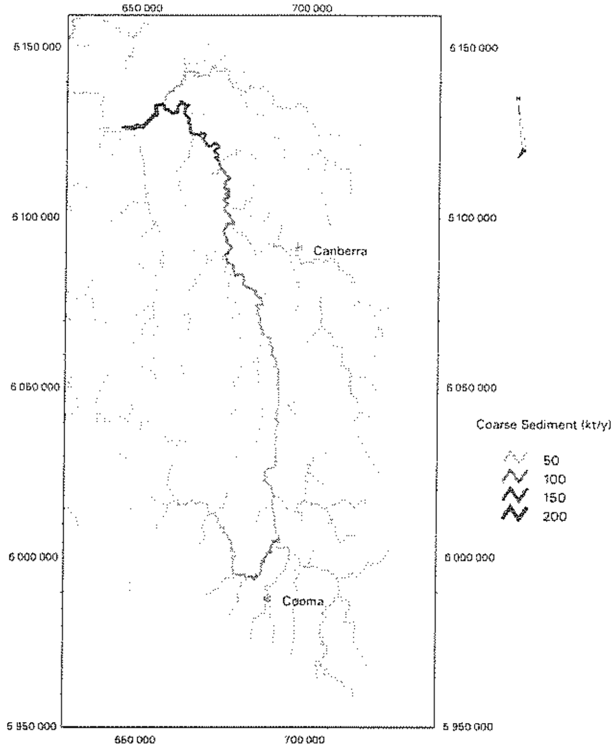

Figure 1. Example coarse sediment budget from an application of the SedNet model in the upper Murrumbidgee catchment.

Research on model sensitivity assessment is being undertaken to test, and where possible simplify and improve, the structure and parameterisation of the SedNet model. The SedNet model was originally developed for application at the continental scale. The focus in developing the SedNet model was on getting broadscale regional patterns correct. The present research interest is associated on applying the model to correctly predict sediment source and transport patterns within a catchment. This requires a better spatial resolution of the sediment sources and model input parameters. Also, some things that vary strongly at the continental scale, for example rainfall erositivity, can be relatively constant within a catchment while other factors, for example slope, vary more at the continental scale. So the question is where to focus model development for its application to catchment assessment.

Sensitivity analyses or trials are formalised procedures to identify the impact of change in model inputs and components on model output [Rose, 1993; Thornton, 1993]. Sensitivity trials provide a guide to prioritising data acquisition and model development strategies. Parameters to which the output is sensitive and which have significant uncertainty require special attention. It is important to assess, for example, the extent to which errors in parameterisation of gully and streambank sub-models in SedNet flow through to estimates of sediment load. Conversely, identification of those parameters or sub processes that have little influence on the behaviour of the model, and may thus be aggregated, modified or removed, is also important.

3.1 Conventional Sensitivity Approaches

Conventional approaches to model sensitivity find local gradients of the outputs with respect to the uncertain or variable items, by analysis of/or running the model with perturbed values of the latter. Commonly, individual model parameters and/or inputs are varied by some constant percentage whilst all others retain their original values. The relative change in model outputs is noted to determine the sensitivity of the model to the parameter change [Thornton, 1993]. Thus sensitivity is defined as the gradient of output with respect to parameters and/or inputs, normalised by the ratios of their sizes so as to relate proportional (eg percentage), rather than absolute, changes. While there is no mathematical difficulty in generalising this definition to cover sensitivity of two or more outputs simultaneously, (using a norm of the Jacobian matrix), it may not be easy to choose a norm that adequately reflects the relative importance of the outputs. To estimate the local value of the gradient (Jacobian) of n outputs with respect to m inputs or parameters takes only m+1 model runs.

The conceptual and practical simplicity of gradient-based sensitivity assessment accounts for its popularity, but it has severe limitations. First, ratios of output changes to input or parameter perturbations are useful only if the extent of the uncertainties in the latter are known fairly precisely, allowing representative perturbation sizes to be chosen. Failing that, if the relations between perturbed and output variables can be assumed linear, so that effects scale with perturbation size, the combined effects of changes in two or more parameters or inputs can be found by superposing their individual effects. Generally neither is true: uncertainties often cannot be confidently quantified in advance, and perturbation-output relations are generally non-linear, perhaps sharply. A second fundamental limitation of conventional approaches is that only the size, not the nature, of the output change is considered - an important consideration in the assessment of the SedNet model where for management applications, the pattern of sediment source, transport and deposition is more important than quantifying sediment loads in absolute terms. This is particularly restricting if the time course of the output, rather than its value at one time, is of interest, or when certain types of output change or error are much more acceptable than others. A simple example is prediction of a river-flow peak, where erring on the low side may be disastrous but high-side errors merely inconvenient. A third limitation of conventional sensitivity assessment is that gradient information is local; knowing a sensitivity for given perturbations about a given initial value does little to answer questions such as whether some quite different values would produce similar output behaviour, or what range of parameters or inputs would yield output behaviour which meets given conditions.

The restricted scope of conventional sensitivity assessment points to the need for an alternative approach. One possibility, which offers considerable flexibility, is outlined below.

3.2 Alternative Sensitivity Approaches

In simulation modelling, the size and complexity of models has increased as our understanding of processes has become more sophisticated [Rose, 1993]. SedNet illustrates this point. The sophistication and complexity of SedNet stems from its structure and method of application, not from the complexity of its component parts. SedNet interconnects a large number of relatively simple models for individual river links, forming a complex structure with a very large number of potential interactions. Conventional sensitivity assessment falls well short of what is needed to investigate models such as SedNet. The spatially distributed nature of the outputs of the SedNet model further challenges conventional approaches.

An alternative approach for complex models is to find the set of values of the uncertain quantities over which the outputs remain within a specified range. This and the issues of Section 3.1 suggest that successful sensitivity trials for large models require:

- a clearly defined and unambiguous methodology;
- parameters to be varied simultaneously (because superposition cannot be assumed to apply); and
- incorporation of prior information on the variability of parameter estimates. This may be difficult or unfeasible in practice.

Our approach to sensitivity assessment of the SedNet model has been first to identify all parameters of the model and, as far as possible, their possible ranges. The sensitivity of change in data inputs has not been considered in this initial phase. Similarly, interdependencies between parameter uncertainties are not considered, as little is known about them yet. Table 1 lists the SedNet parameters, their current value and possible ranges. Values for probable ranges were estimated from published values, for example from Prosser and Rustomji, 2000], or estimated directly.

Table 1. Summary of SedNet parameters and probable ranges.

Param	Sub-model	Description	Value	Probable Range
α	Gully	Gully cross section area	10 m^2	1 - 30
τ	Gully	Gully age	100 yrs	20 - 200
ρ	Gully & Bank	Sediment bulk density	1.5 tm^{-3}	0.9 - 1.8
P	Gully & Bank	Suspended to bedload ratio	0.5	0.1 - 0.9
a	Bank	Constant	0.008	See Rutherford [1999]
c	Bank	Exponent	0.6	
h	Bank	Bank height	3 m	1 - 10
HSDR	Hillslope	Sediment delivery ratio	0.05	0-1
β	STC	Exponent	1.4	1 - 2
γ	STC	Exponent	1.4	1 - 2
SSV	Flood plain	Sediment settling velocity	10^{-6} ms^{-1}	10^{-7} - 10^{-5}

Following identification of the model parameters, all data inputs will be identified and an assessment made of their uncertainty. The estimated ranges and uncertainties of the parameters and data inputs will be used to guide a conventional sensitivity assessment. Its results will be used to select components of the SedNet model to be examined in an alternative and more thorough sensitivity assessment. Improvements to the structure of the model and suggestions for improving data input will result from this procedure.

4. SENSITIVITY: AN EXAMPLE

As an example of sensitivity assessment, the sensitivity of the model output to the hillslope delivery ratio (HSDR) and the sediment settling velocity (SSV) has been investigated. Both of these parameters influence the suspended sediment load, and both are considered by Prosser et al., [2001b] to be poorly known.

The HSDR parameter scales the hillslope erosion estimate (predicted from plot scale data) to the amount of material that reaches the stream. At present the HSDR has no spatial complexity in the model and is simply applied uniformly across a catchment however, it could be spatially varied within the structure of SedNet. The sensitivity of moving towards a spatially distributed HSDR may also be tested. The ratio has a range between 0 and 1, 0 indicating no sediment contribution from hillslopes, and 1 indicating that all eroded material reaches the stream. Currently the HSDR parameter is adjusted according to the characteristics of each specific region. For example in the Murrumbidgee catchment, the HSDR has a value of 0.05 [Prosser et al., 2001a]. The SSV determines the rate at which sediment is deposited on the floodplain. Its value has been assumed to be that for a silt-sized particle.

To investigate sensitivity to the HSDR and SSV the model was run with these parameters systematically perturbed. A regular grid of values was selected with HSDR ranging from 0 - 1 in increments of 0.1 and SSV ranging from 0 to $2x10^{-6}$ ms^{-1} in increments of $1x10^{-7}$ (a total of 231 trials). No other model parameters were varied from the values used by Prosser et al., [2001a].

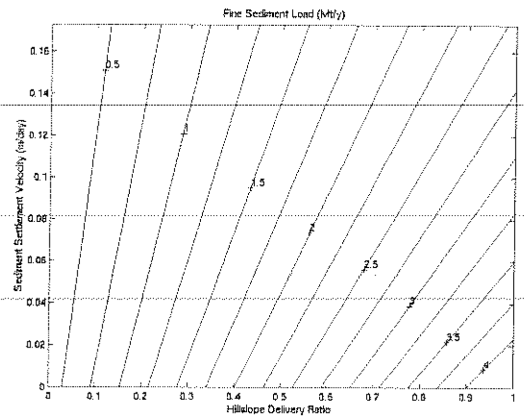

Figure 2. Contour plot of fine sediment load from combined sensitivity trials on hillslope delivery ratio and sediment settling velocity.

Figure 2 shows the results of the sensitivity trial. The results shown are for a reach of the Murrumbidgee River immediately upstream of Burrinjuck Reservoir. The plot shows that, as expected, fine sediment load increases as the HSDR increases and the sediment settling velocity decreases. At low HSDR, the sensitivity of the load to the settling velocity is low. The sensitivity of fine sediment load increases as HSDR increases.

These results show non-linear relations between load and settling velocity at constant HSDR, and between load and HSDR at constant velocity, yet linear boundaries of all level sets for the load (i.e. all load contours).

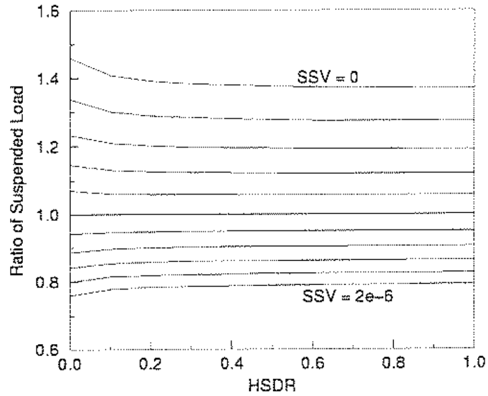

Figure 3. Plot of suspended load divided by a reference load (SSV = $1 \times 10^{-6} ms^{-1}$) against HSDR.

If the HSDR and SSV parameters do not interact, then for appropriate functions of f and g the suspended load can be given by:

$$Load = f(HSDR)\, g(SSV) \quad (1)$$

Taking a reference SSV value (SSV_0),

$$Load_0 = f(HSDR)\, g(SSV_0) \quad (2)$$

which gives

$$Load/Load_0 = g(SSV)/g(SSV_0) \quad (3)$$

Thus $Load/Load_0$ should be independent of HSDR. Figure 3 shows that for large values of HSDR, $Load/Load_0$ is essentially independent of HSDR (but still dependent on SSV). However for small values of HSDR, the load ratio is dependent on HSDR, demonstrating that there is interaction between the two parameters for HSDR ≤ 0.2.

Later trials will attempt to identify the boundaries, in the space of selected significant parameters, of the regions within which any parameter values give rise to sediment loads meeting specified criteria (which need not be simple). For example, it will be of interest to find the ranges of erosion-parameter values over which observed sediment depositions are matched by the model to within a chosen tolerance; this would allow assessment of how far erosion rates may be inferred from deposition, and whether any erosion mechanisms may be omitted or combined.

5. ACCURACY ASSESSMENT: COMPARISON WITH COLLATERAL INFORMATION

A second component of this work will include assessment of the accuracy of results produced using the SedNet model through comparison with collateral knowledge. Examples include:

- suspended sediment load modelling using event-based water-quality data and long-term hydrologic modelling, a regression model to relate concentration to discharge is to be used to interpolate between observations;
- streambank erosion assessment through aerial photo interpretation techniques, historic stream cross sections and/or strategic establishment of erosion pins;
- published long-term sediment load calculations and catchment sediment budgets; and
- magnetic and radionuclide sediment tracing techniques.

In the case of the hydrologic modelling currently invoked by SedNet, more intensive work in individual catchments with rainfall-runoff and routing algorithms will provide improved estimates of flow and hence sediment loads, for each river link. For the Murrumbidgee catchment, Newham et al. [2000] have already constructed a predictive capacity at sub-catchment scale. Regionalisation techniques (based on relationships between landscape attributes and calibrated flow model parameters) will be required to re-scale such sub-catchment scale estimates to the river link scale.

As an example accuracy assessment we have made comparisons of SedNet loads with results from sediment tracing in the Murrumbidgee catchment, this is discussed in the following section.

5.1 Sediment Tracing Comparison

Wallbrink et al. [1998] have undertaken sediment tracing work in the upper Murrumbidgee catchment. Their approach was to use both magnetic and radionuclide tracing techniques at stream confluences to determine the relative sediment contribution of each of the catchments. Three stream confluences are available for comparison with the results of SedNet (see Table 2 for details). Wallbrink et al. [1998] analysed two sediment size fractions. For the purposes of assessing the SedNet model we have compared the <63μm fraction with the suspended load and the 125-250μm fraction with the bedload.

Caution must be exercised when comparing the results of sediment tracing and SedNet. Tracing results can be strongly influenced by individual events; these events are effectively aggregated in the SedNet modelling. In addition sediment tracing assessment is based on many assumptions and are also modelled results.

Table 2. Comparison of relative contribution of stream confluences; Wallbrink et al. [1998] tracing and SedNet modelling comparison.

Confluence	Suspended load		Bedload	
	Tracing (%)	SedNet* (%)	Tracing (%)	SedNet (%)
Ballalaba	100±60	44	34±12	42
Yandygunulah	40±17	31	-	31
Hoskinstown	38±21	41	0±10	41

* HSDR = 0.05, SSV = 1×10^{-6} ms^{-1}

The comparison presented in Table 2 shows general agreement between modelled results and sediment tracing estimates. With the exception of the bedload estimate for Hoskinstown Creek, all SedNet estimates are within the uncertainty estimated for the sediment tracing.

Accuracy assessment is important not only to judge our confidence in the model output but also to assist in the attachment of bounds to the outputs needed for identification of uncertainties in model inputs and parameters.

6. CONCLUSION

If reliable conclusions are to be drawn from large models such as SedNet, it is crucial that the sensitivity of outputs to uncertainty in inputs, parameters and features of the model structure be properly assessed. Sensitivity and accuracy assessment will assist in showing how SedNet can be simplified or improved. Due to the complexity in structure of the SedNet model, gradient based approaches to sensitivity assessment are considered useful only for providing a guide to more advanced assessment. Approaches such as finding the set of values of uncertain quantities over which the outputs remain within a specified range are more appropriate for assessment of the SedNet model.

A limited evaluation of the sensitivity of two of the SedNet parameters, HSDR and SSV, has shown that there is interaction between these parameters, strongest at low HSDR values. The results also show that the sensitivity to fine sediment load increases as HSDR increases. These results provide only an example of some of the potential of this work. Accuracy assessment has shown that the SedNet model can compare well with sediment tracing approaches, generally within the uncertainty of the tracing estimates.

Ongoing accuracy and sensitivity assessment of the SedNet model will be used to prioritise improvements in model structure, parameterisation and data acquisition. These improvements are important to continue the development of methods for predicting the sources, transport and potential impacts of environmental pollutants in catchments.

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