Testing the capability of a sediment budget model for targeting remediation measures to reduce suspended-sediment yield

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Abstract Targeting and achieving reductions in suspended-sediment yield (wash load) requires identification of the sediment sources and their connectivity to the catchment outlet. This paper assesses the strengths and limitations of a spatially-distributed model of suspended-sediment budgets (SedNet) for targeting remediation actions by reviewing five recent Australian model applications. Compared with suspended-sediment yields estimated from river discharge and concentration data, the root-mean-square relative error in predicted yield is 36–99% for catchments below 2000 km^2 in area and 24–32% for larger catchments. Spatial variation in sediment supply within each river basin is 2–9 times larger than model error, and so the model can reliably differentiate between the areas contributing most and least to basin yield. Quality input data on vegetation cover, gully extent and bank erosion rates are important to obtain reliable model predictions. Geomorphic studies and sediment tracing can provide process understanding to test model predictions and refine parameter values.

Key words sediment budget; modelling; erosion; land use; watershed management; uncertainty

INTRODUCTION

Targets are being set for end-of-catchment suspended-sediment yields (wash loads) for natural resource management regions across Australia (e.g. Cogle *et al*., 2006). Many of the targets are set below present yields, to ensure the health of downstream water ecosystems. Identifying the sediment sources and their spatial locations within a catchment is a prerequisite for effectively targeting limited resources to achieve reductions in suspended-sediment yield. Much of the sediment eroded in catchments is deposited within the catchment on flood plains and in reservoir impoundments (Dunne *et al*., 1998; Trimble & Crosson, 2000), and so the connectivity of sources to the catchment outlet must also be assessed, to enable scaling from local erosion to downstream fluxes and basin yield. It is not feasible to use field measurements to assess the spatial patterns of erosion across large river basins. Empirical relationships between observed sediment yield and catchment area or other basin attributes do not provide the process understanding of sources and provide poor predictive capacity outside the data sets used to construct the relationships (Boomer *et al*., 2008). Sediment tracing can identify source areas and erosion processes; however, cost limits the spatial resolution that can be achieved across large river basins.

Given the above limitations, modelling the primary sources and sinks of suspended sediment in spatially-distributed budgets provides a cost-effective and repeatable method to assess the contribution of sources and their connectivity to the basin outlet. It also provides a framework for applying knowledge of erosion and deposition processes that has been gained from catchment studies using sediment tracers and geomorphology studies over larger spatial scales. The SedNet model (Prosser *et al*., 2001a,b; Wilkinson *et al*., 2004, 2009) assesses the primary sources (hillslope, gully and riverbank erosion) and sinks (flood plain and reservoir deposition) of suspended sediment in rural catchments (Fig. 1). The model constructs separate budgets for each link in a river network, using spatial data sets and algorithms that represent the main controls on each process. Each link has a sub-catchment draining directly to it, of median area 10–100 km^2 depending on basin size. Hillslope sediment supply to each link is predicted using the Revised Universal Soil Loss Equation (RUSLE; Renard *et al*., 1997; Lu *et al*., 2003) and a hillslope sediment delivery ratio (HSDR); gully erosion by apportioning total mapped gully volume over the gully age and accounting for contemporary activity levels; riverbank erosion as proportional to bank full stream power, reduced by 90–95% in areas of intact riparian vegetation and by 100% in bedrock gorges; flood-plain deposition as proportional to incoming load, over bank flooding and residence

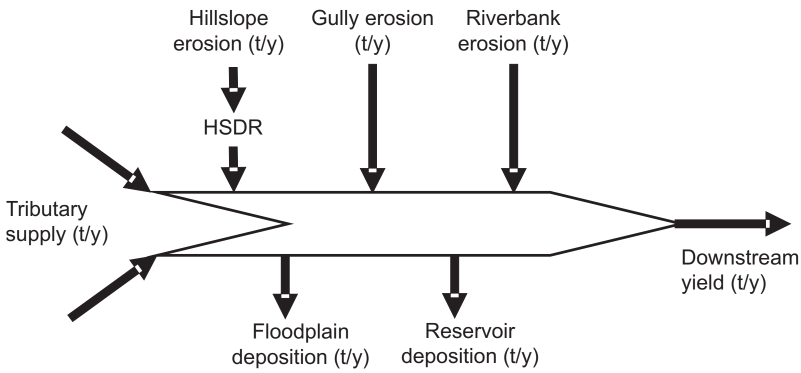

Fig. 1 Sources and sinks represented in the SedNet suspended-sediment budget for each river link in a river basin.

time; and reservoir deposition as a function of inflow and capacity (Prosser *et al.*, 2001a,b; Wilkinson *et al.*, 2009). Streamflow in each link is represented using regionalisations of mean annual runoff and flood quantiles (Wilkinson *et al.*, 2006b, 2009). The model also constructs separate bed material budgets to predict locations of bed material accumulation (Wilkinson *et al.*, 2006a).

The simulated suspended-sediment budget is expressed as long-term mean annual values for the specified conditions, including the effects of climate and hydrological variability. The model also allows alternative source-reduction strategies to be simulated to help identify the most effective way to achieve reductions in sediment yields; including hillslope and riparian revegetation (Lu *et al.*, 2004; Wilkinson *et al.*, 2005a,b).

The purpose of this paper is to help guide future constructions and applications of spatially distributed sediment budget models such as SedNet, which can be applied in watershed management to reduce sediment yields. The paper reviews the uncertainty in spatial variations in suspended-sediment yield that are predicted by SedNet and used to target remediation activities. The strengths and limitations of sediment budget modelling of SedNet are discussed.

METHODS

The uncertainty in the spatial pattern of predicted suspended-sediment yields was assessed for several SedNet studies (Fig. 2). The studies generally had some input data at 25 m resolution (DEM, land use, riparian vegetation), with most other input data at 250 m resolution (rainfall, RUSLE R and K factors); apart from the Murray Darling Basin (MDB) study for which all input data were of 250 m resolution. The uncertainty in the spatial variation of predicted suspended-sediment yield was assessed by comparing predicted yield against independent estimates of mean-annual suspended-sediment yield, at multiple locations within each basin. The independent yield estimates were derived using several decades of measured discharge data, and rating curves fitted to measured total suspended-sediment (TSS) concentrations. The rating curves were of the form:

$$\log(C) = a + b\log(Q) \tag{1}$$

where C is concentration, Q is discharge and a,b are fitted parameters.

The model uncertainty was quantified using three metrics. Firstly, the root-mean-squared relative error across the gauges in the catchment (*RRMSE*) was used to provide an intuitive error metric:

$$RRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{p_i - o_i}{o_i}\right)^2} \tag{2}$$

where n is the number of river gauges, o_i and p_i represent observed (rating curve) and predicted

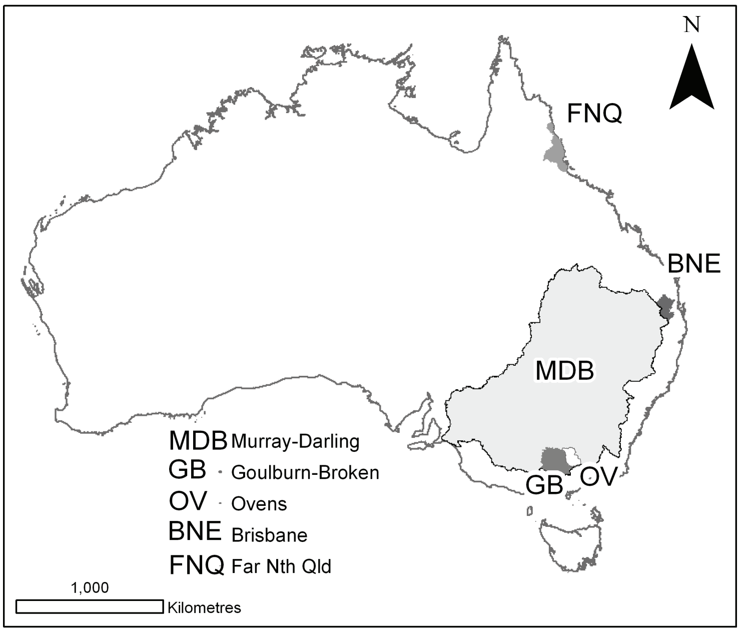

Fig. 2 Location and extent of the SedNet studies for which the uncertainty in predicted yield was evaluated.

yields for the ith river station. Where errors are large relative to observed values, *RRMSE* can be biased. The second, unbiased metric was a logarithmic standard error ratio s_r:

$$s_r = 10^{\sqrt{\frac{1}{n}\sum_{i=1}^{n}[\log(p_i)-\log(o_i)]^2}} \tag{3}$$

where s_r = 1 indicates zero error, s_r = 1.2 indicates predictions are within approx. 20% of observations and s_r = 2 indicates that predictions are within a factor of two of observations. *RRMSE* and s_r are identical for total and area-specific yields. At small catchment areas (<1000 km^2), deposition is generally small relative to sediment supply and in that case *RRMSE* and s_r apply to spatial variations in supply (erosion) as well as yield. Errors in predicted yield affect the capacity of the model for targeting remediation measures to hotspot areas when they are large relative to the magnitude of spatial variation across the basin. The third metric quantified the magnitude of spatial variation as the ratio of the 80th percentile divided by the 20th percentile of predicted sub-catchment specific suspended-sediment supply (t/km^2/year). This ratio was compared against s_r.

The model's contribution to aid understanding of sediment sources and process understanding was reviewed relative to other models. The main data sets, parameters and model algorithms to which uncertainty in model predictions was attributed in each study was also reviewed.

RESULTS AND DISCUSSION

Uncertainty in predicted suspended-sediment yield

The error in predicted suspended-sediment yield is smaller for larger catchment areas (Table 1; Fig. 3). For catchments below approx. 2000 km^2 in area, *RRMSE* ranges from 36 to 99% and s_r is 1.6–2.5. For larger catchments, *RRMSE* is 24–32% and s_r is 1.3–1.4. This indicates that we can generally be confident about predicted differences in yield between areas in a river basin that are larger than a factor of approximately two, or 30% for large areas; but predicted differences of smaller magnitude are less robust. There is also uncertainty in the rating curve yield estimates; estimated at 13–50% in the Goulburn-Broken River basin (Wilkinson *et al.*, 2009) using rating

Table 1 Root mean square relative errors RRMSE and standard error ratio s_r for the predicted suspended-sediment yields. n is the number of river gauges evaluated in each catchment. The 80/20% ratio is the ratio of the 80th to 20th percentile predicted sub-catchment specific suspended-sediment yield.

River basin (State)	Source	Catchment area range (km^2)	n	*RRMSE* (%)	s_r	80/20% ratio
Goulburn-Broken (VIC)	(Wilkinson *et al.*, 2009)	100–700	8	62	2.1	14
Far Nth Queensland (QLD)	(Hately *et al.*, 2006)	800–2200	7	75	1.7	na
Ovens (VIC)	(DeRose *et al.*, 2005a)	100–500	5	99	2.5	4.9
		1000–7000	5	32	1.4	4.5
Brisbane (QLD)	(Prosser *et al.*, 2003)	100–1000	6	36	1.6	3.3
		2000–10 000	3	24	1.3	12
Murray-Darling (VIC-NSW)	(DeRose *et al.*, 2004)	500–2200	5	100	2.0	2.3
		4200–75 000	16	37	1.4	5.8

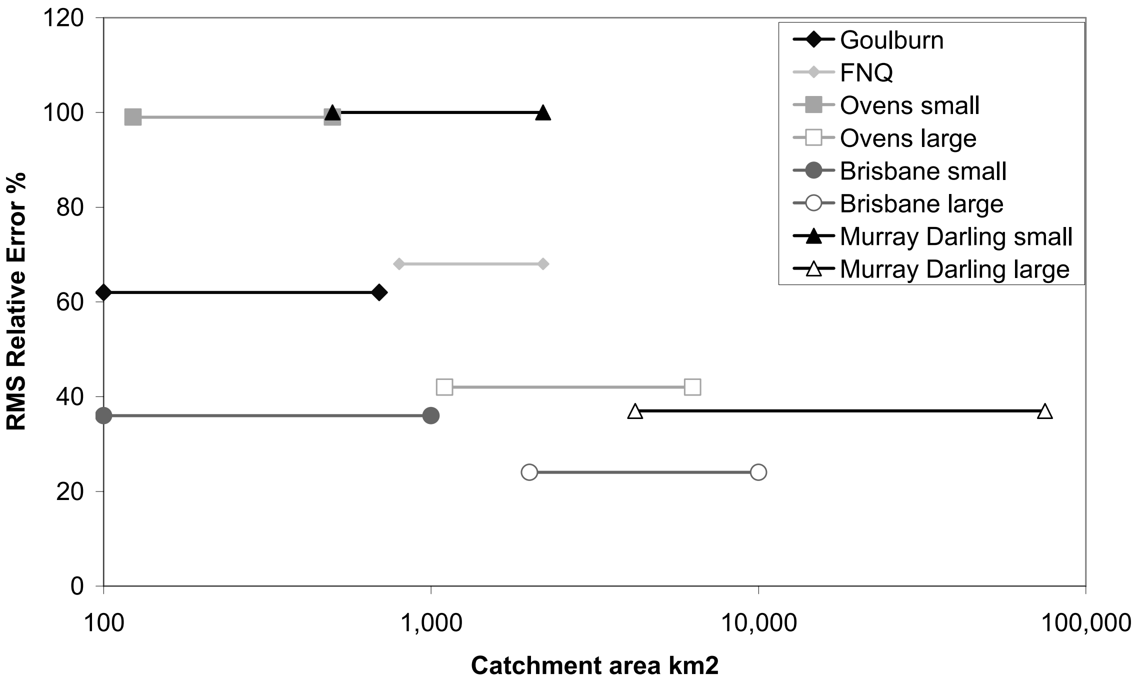

Fig. 3 Root-mean-square relative error for predicted suspended-sediment yield at multiple points in each river basin.

curves based on bootstrap re-sampling (Rustomji & Wilkinson, 2008); but not estimated for the other studies.

The reduced model errors for larger catchment areas can be attributed to spatial averaging of random errors in input data and parameter values. Finer resolution input data results in smaller model uncertainty; e.g. at the 1000 km^2 catchment area scale, the *RRMSE* is lower for the Ovens River study than for the Murray Darling Basin (MDB) within which the Ovens is located (Fig. 2). The DEM used in the Ovens River study had a 25 m pixel size, resulting in better estimates of hillslope and channel gradient, and flood-plain extent than the MDB study, which used a 250-m DEM. There were also similar differences in the resolutions of riparian vegetation and hillslope vegetation cover data sets. Improving accuracy over smaller areas would require finer resolution and higher-quality input data sets.

The main features of the predicted spatial variations are reliable, despite the model errors. The 80/20% ratios are 2–6 times the standard error ratios s_r for catchments of 100–2000 km^2 (Table 1).

Therefore, the model can, as a minimum, reliably identify the 20% of each basin with the highest erosion rates from the 20% with the lowest erosion rates, with a resolution as fine as 100 km^2. The MDB study is an exception, where the 80/20% ratio is only 1.15 times s_r for small catchments; indicating lower model reliability at a 100 km^2 scale when coarser resolution input data sets are used. At coarser scale above 2000 km^2 (4000 km^2 for the MDB study), more of the predicted spatial pattern is reliable; with the 70/30% ratio (not shown) being at least two times s_r, meaning that the 30% with the highest erosion rates can be reliably identified from the 30% with the lowest erosion rates. In general, the predicted spatial variations are most robust when the differences in predicted yield are largest; which occurs when environmental gradients are large relative to the uncertainties in data inputs and process representations.

Uncertainty in the spatial variation of individual sources can be determined by comparison against erosion measurements, and is somewhat higher than uncertainty in yield; which sums all sources and sinks. The predicted RUSLE hillslope erosion rates have uncertainty of approximately one order of magnitude at 100 m^2 plot scale (Lu *et al.*, 2003); with uncertainty in the predicted mean erosion rate for 10 km^2 sub-catchments (equivalent to 10 000 plots) being a small fraction of plot-scale uncertainty; probably less than a factor of two. Comparisons with radionuclide tracer studies indicate that the model predicts the relative contributions of surface and sub-surface erosion reasonably well in the temperate Murrumbidgee catchment (Wallbrink *et al.*, 1998; Wilkinson *et al.*, 2005b), and the sub-tropical Brisbane River catchment (Prosser *et al.*, 2003; Wallbrink, 2004).

Considerations for model application elsewhere

The uncertainty in simulated sediment yield is related to the uncertainty in input data sets and to the limited process understanding represented in the model uncertainty. The studies to date provide important information on the input data sets which are most likely to cause uncertainty in sediment budget modelling. Input data sets can be ranked approximately with regards to their importance, although relative importance is also dependent on the relative size of the sources in a given catchment:

– The gully extent grid: where complete spatial coverage of gully mapping from air photos is unavailable, a modelled grid of gully density (km/km^2) is constructed using empirical models fitted to the gully density mapped for isolated air photos within the basin (Hughes *et al.*, 2001). The uncertainty in the model predictions is influenced by the spatial heterogeneity of the landscape and the proportion of the area for which mapping is available to fit the model. For example, when air photo mapping covers only 1% of a 100 000 km^2 basin, the resulting gully modelling has an uncertainty of 50–200% at the sub-catchment scale (Kuhnert *et al.*, 2007).
– The RUSLE vegetation cover factor grid: this data set should represent spatial variation between and within land uses, and seasonal variations (Lu *et al.*, 2003).
– Mapping of riparian condition: tree cover is an appropriate surrogate where livestock are excluded from tree-ed riparian zones (e.g. see Wilkinson *et al.*, 2009); but does not represent trampling under riparian tree cover in rangelands; where field condition assessment would be more appropriate.
– The hydrology regionalisations: acceptable prediction of streamflow requires that regionalisations are applied over sufficiently homogeneous areas, and multiple regionalisations may be required in large basins (Wilkinson *et al.*, 2006b).
– The particle size composition of subsoil sources: this may vary between different geologies; however, available Australian data sets do not reliably represent spatial variation in this parameter (Rustomji, 2006).

The main areas of process understanding which limit model performance are:

– Spatial variations in the hillslope sediment delivery ratio are not represented because of the difficulty of identifying and representing its local controls at basin scale (Wilkinson *et al.*, 2009).

- Predictions of spatial variation in bank erosion require further testing against measured erosion rates (DeRose *et al.*, 2005b).
- Historical changes in land management can result in decadal-scale phases of gully enlargement and stabilisation, with consequent effects on sediment yield (Wasson *et al.*, 1998; Valentin *et al.*, 2005). Some knowledge of this history is required to set a contemporary suspended-sediment yield parameter in the gully erosion model.
- Riparian vegetation is presumed to reduce bank erosion rates by 80–90%; however, there is little data to substantiate this (Micheli *et al*., 2004; Wilkinson *et al*., 2009).
- The SedNet model was designed primarily for rural, agricultural and pastoral environments. Suspended-sediment yields are under-predicted in steep forested areas, where further process investigation is required (Rustomji *et al*., 2008; Wilkinson *et al*., 2009).
- The results indicate that the model can identify spatial patterns in sediment yield, and areas to target field investigation and remediation measures for catchments larger than 100–1000 km^2; rather than at scales of individual model sub-catchments, properties, or even specific hillslope locations.
- The uncertainty estimates are for Australian studies and different levels may be obtained with different data sets and in different environments elsewhere.

Uncertainty in the sediment yield response to changes in land management is additional to the uncertainty in predicting the present-day suspended-sediment yields, and there are fewer data to estimate the response than the baseline erosion rates. In addition to uncertainty in the yield response to changing model inputs (e.g. pasture cover), there is also uncertainty in the effect on model inputs resulting from management change (e.g. livestock numbers). Measurements that establish relationships between land management and erosion rates provide the most reliable basis for estimating the percentage reductions in erosion rate from remediation measures (e.g. see Bartley *et al.*, 2006; Hawdon *et al*., 2008, this volume). Sediment budget modelling then provides a rational basis to compare the effectiveness of different remediation options at basin scale. The effect of gully rehabilitation on sediment yield is related more to the level of adoption of remediation measures than their effectiveness; although effective gully rehabilitation techniques are available "they are rarely adopted by farmers in the long run and at a large scale" (Valentin *et al*., 2005). It can be expected that riparian revegetation will reduce bank erosion rates, but they will remain higher than prior to riparian clearing if river channel capacity has increased through historical bank erosion; thus estimating a 50% reduction in bank erosion from riparian revegetation may be more realistic than the 80–90% effect on bank erosion of riparian vegetation in reaches where it has always been protected.

The model predicts long-term suspended-sediment yields, accounting for climate and hydrological variability. This must be considered when comparing model predictions against independent yield estimates. Given the inter-annual variability of river sediment yields and the time required for revegetation to reach full effectiveness, it may take many years for predicted yield reductions to be realised.

Model strengths and alternatives

Sediment budget modelling has many features which provide advantages for targeting remediation actions over alternative watershed modelling techniques. The model described has modest data requirements, allowing it to be parameterised over large river basins. Additional data from sediment tracer studies or measured erosion rates can be used to test process understanding, and to refine parameter values (Rustomji *et al*., 2008; Wilkinson *et al*., 2009). Channel erosion is an important source at basin scales (Wallbrink *et al*., 1998; Walling, 2005). However, many other watershed models consider only hillslope erosion (de Vente & Poesen, 2005), which can give erroneous predictions of the spatial location of sources within river basins (e.g. see Boomer *et al*., 2008). A sediment budget model predicts long-term yields that are limited by upstream erosion, which is consistent with measured loads and TSS concentrations (Olive & Walker, 1982; Williams, 1989). Erosion is driven by many factors including terrain, soils and vegetation cover. In contrast, models based on measured discharge and concentrations often predict load as proportional to discharge. This implicitly assumes that yield is limited by transport capacity rather than upstream erosion. Yield predictions based on discharge are thus prone to erroneous spatial variations. Discharge-concentration models also do not identify source processes, and they rely on the availability of sufficient measurement records to represent long-term behaviour. For a given spatial resolution, sediment budget modelling provides much faster run times than time-stepping models, which is important for comparing alternative land management scenarios. "Natural" scenarios can also be simulated to provide a benchmark for the much smaller responses that are realistically achievable by changing management practises but retaining existing land uses. Modelling bed material budgets is also useful for assessing and managing at basin scale the effects of erosion on bed material accumulation (Wilkinson *et al.*, 2006a), and its impact on macro-invertebrate community composition (Harrison *et al.*, 2008).

CONCLUSIONS

The SedNet model for suspended-sediment budgets is capable of identifying the hotspot areas supplying downstream sediment yields in large river basins in temperate and sub-tropical Australia. The predicted spatial differences are most reliable for catchments larger than 2000 km^2, but even for areas around 100 km^2, the model reliably identifies the 20% catchment areas having the highest specific sediment supply from the 20% catchment area with the lowest sediment supply; hence it is useful for spatially targeting remediation measures. The model can also help to identify the major sediment sources (hillslope, gully and river bank erosion). While the data requirements of the model are modest relative to many river basin models, the model relies on good quality input data on gully extent, hillslope vegetation cover, bank erosion measurements and riparian condition assessment. The effect of changes in land management on sediment yields varies between environments and field measurement of their effectiveness is important. Sediment budget modelling provides a rational method to model the impact of remediation options at basin scales on reduced basin suspended-sediment yield.

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