A Model of River Sediment Budgets as an Element of River Health Assessment

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Abstract: We have developed a model of river sediment budgets to predict the spatial patterns of transport and deposition of suspended load and bedload, as a contribution to broader river health assessment. The model considers spatial patterns of three types of sediment source: sheetwash, gully and streambank erosion. Sediment is routed through the river network, incorporating simple physical conceptualisation of suspended load and bedload deposition. A novel feature of the model is the ability to explicitly relate locations of sediment source in a catchment to their contribution to downstream export. The model has potential for catchment and river management, addressing issues such as identifying sediment impacted river reaches, exploring the consequences of land use change and identifying the predominant sediment sources.

Keywords: Sediment budgets; Sediment transport; River basins; Catchments; Modelling

1. INTRODUCTION

The degradation of streams by increased sediment loads is a major issue in Australia. High loads of suspended sediment degrade water quality in streams, reservoirs and estuaries. High concentrations of suspended sediment inhibit respiration and feeding by stream biota; diminish light available for photosynthesis and increase nutrient loads. The formation of gullies and accelerated erosion of stream banks have also supplied vast quantities of sand and gravel to streams. Where streams are unable to transmit this increased load downstream, the sand and gravel is deposited, burying the natural substrate, and forming sheets of sand referred to as sand slugs [Rutherfurd, 2000]. Sand slugs are poor habitat, which can prevent fish passage, fill pools and other refugia. They are unstable substrates for benthic organisms [Jeffers, 1998].

This paper describes and illustrates a model for river basin sediment budgets that helps identify the above problems. The model has been applied across the more closely settled third of Australia as part of two National Land and Water Resources Audit (NLWRA) projects that assessed river condition and agricultural sustainability across Australia [NLWRA, 2001a,b]. The results of that application are summarised in Prosser et al. [2001a]. Further details can be found at http//:www.nlwra.gov.au. The model has potential to be applied in more detail to assessments of sediment transport in individual regional catchments.

2. THE SEDIMENT BUDGET MODEL

Sediment budgets are used by geomorphologists to describe the main sources, transport pathways, and sinks of sediment in a catchment. They have been applied to typical resource assessment problems, addressing questions such as: which sub-catchments are the dominant source of sediment; where is sediment stored (which often indicates an impact); which processes supply the most sediment; and, if land use is changed in part of the catchment how will that alter downstream yield.

A sediment budget offers several advantages as a modelling framework. The explicit relationship of source, to sink, to export can tightly constrain the predictions. It allows information on one aspect, such as export rates, to be used to constrain other aspects, such as the intensity of sources. Information on the ratio of fluxes in different components of a budget provides further constraint. For example, various studies have measured the ratio of suspended load to bedload.

Sediment budgets usually integrate information from a variety of sources, such as flow and sediment load monitoring, aerial photograph interpretation, mapping, historical records and modelling, but are rarely constructed as computer models for wider application.

There are very limited data in Australia on erosion rates and river sediment loads. For many basins there is no direct information available, and any assessment is therefore compelled to use a method to interpolate and extrapolate to areas without data. Fortunately, there is a good understanding of sediment transport processes, and ample data to describe the factors that control these processes. These data include comprehensive stream gauging records, digital elevation models, rainfall records, and remote sensing of land cover.

Our approach is to use as much of the available information as possible, collect our own information where practical, and use all of this in a relatively simple model of the main driving processes of large catchment sediment transport . Data collected as part of the NLWRA project included 300 measurements of river width, aerial photograph assessment of gully erosion [Hughes et al., 2001], and use of other NLWRA project output (e.g., synthetic stream flow records).

A suit of ArcInfo™ programs are used to define river networks and their sub-catchments; import required data; implement the model; and compile the results. These are referred to collectively as the SedNet model: the Sediment River Network Model. SedNet constructs a mean annual sediment budget sequentially downstream through each link of a river network. A link is the stretch of river between tributary confluences. River links and their contributing catchment areas are defined by the model using a digital elevation model (DEM). Full details of the SedNet model and its application to the NLWRA are given by Prosser et al. [2001b].

The SedNet model calculates, among other things: the mean annual suspended sediment output from each river link; the depth of sediment accumulated on the river bed in historical times; the relative supply of sediment from sheetwash, gully and bank erosion processes; the mean annual export of sediment to the coast; and the contribution of each sub-catchment to that export.

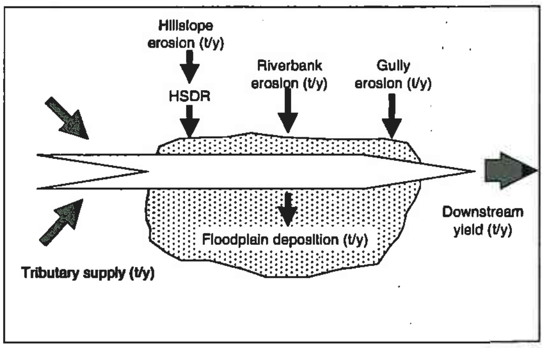

Figure 1. Conceptualisation of the suspended sediment budget for a river link.

National grids of sheetwash erosion and gully erosion were used to determine sediment inputs into each link from the surrounding catchment as part of the NLWRA project. Sheetwash erosion was modelled using the Revised Universal Soil Loss Equation, implemented with innovative use of remote sensing and climate data to incorporate seasonal effects [Lu et al., 2001], and terrain scaling rules to accommodate the low resolution of DEMs [Gallant, 2001]. Gully erosion was assessed from extensive aerial photograph interpretation which formed the basis of an empirical model for gully density [Hughes et al., 2001]. Gully density was converted to a mean annual mass of sediment derived from gully erosion using typical gully age and cross-sectional area. The other source of sediment is from bank erosion along the river link. Bank erosion rate (BE_x m/y) was assessed using an empirical relationship with bankfull discharge [Q_{bx}; Rutherfurd, 2000] and the proportion of stream bank length cleared of native riparian vegetation ($1-PR_x$) for each river link x:

$$BE_x = 0.008(1 - PR_x)Q_{bx}^{\;0.60} \,. \tag{1}$$

For the NLWRA project native riparian vegetation was mapped from the Australian Land Cover Change project at a resolution of 100 m [BRS, 2000]. This is the best available data but is still a crude measure of riparian condition.

Separate river sediment budgets are constructed for suspended sediment and bedload transport because of the quite separate transport processes, transport rates, and locations of deposition.

2.1 Suspended Sediment Budget

Figure 1 shows the conceptualisation of the suspended sediment budget for a river link. Only a small proportion of sediment predicted to be moving by sheetwash erosion is delivered to streams. The difference occurs for two reasons. First, the RUSLE is calibrated against hillslope plots considerably smaller than the scale of entire hillslopes. Much of the sediment recorded in the trough of the plots may only travel a short distance (less than the plot length and much less than the hillslope length) so that plot results cannot be easily scaled up to hillslope predictions. Second, there are features such as farm dams, contour banks, depressions, fences, and riparian zones which trap a proportion of sediment. The most common way of representing the difference between plot and hillslope sediment yields and supply to streams is to apply a hillslope sediment delivery ratio (*HSDR*) to the RUSLE results [e.g. Williams, 1977].

Suspended sediment loads of rivers are supply limited [e.g. Williams, 1989]. That is, suspended sediment yields are limited by the amount of sediment supplied to the streams, not the discharge of the river itself. Deposition is still a significant process, however, as illustrated by comparisons of suspended sediment yields with catchment area, which typically show a reduction in sediment yield per unit area with increasing catchment area, implying deposition of sediment as it is transported through the river network [Walling, 1983].

The main location for deposition of suspended sediment is on floodplains. A relatively simple conceptualisation of floodplain deposition is to consider that the proportion of suspended sediment load that is available for deposition is equal to the fraction of total discharge that goes overbank (Q_x-Q_{bx}/Q_x). This assumes uniform concentration of suspended sediment with depth. The actual deposition of material that goes overbank can be predicted as a function of the residence time of water on floodplain:

$$D_x = \frac{Q_x - Q_{bx}}{Q_x}\left(TIF_x\right)\left(1 - e^{-\left(\frac{vA_{fx}}{Q_x - Q_{bx}}\right)}\right) \quad (2)$$

where TIF_x is the total incoming sediment, and ν is the settling velocity of suspended sediment. For the NLWRA project floodplain area (A_{fx}) was mapped from the national 9" DEM using a steady-state hydraulic model as described in Pickup and Marks [2001]. Sediment deposition in reservoirs is incorporated in the model as a function of the mean annual inflow into the reservoir and its total storage capacity [Heinemann, 1981].

One of the strongest interests in suspended sediment transport at present is the potential impact on a receiving waterbody from sediment supplied from upstream. Waterbodies of interest include lowland rivers, reservoirs, estuaries, and the marine environment. Because of the extensive opportunities for floodplain deposition along the way, not all suspended sediment delivered to rivers is exported to the coast. There will be strong spatial patterns in sediment delivery to a waterbody because some tributaries are confined in narrow valleys with little opportunity for deposition, while others may have extensive open floodplains. There will also be strong, but different patterns in sediment delivery to streams.

The contribution of each sub-catchment to the mean annual suspended sediment export from a river basin was calculated using a probabilistic approach to sediment delivery through each river link. Each internal link catchment area delivers a mean annual load of suspended sediment (LF_x) to the river network. This is the sum of gully, sheetwash and riverbank erosion delivered from that sub-catchment. The sub-catchment delivery contributes to the load of suspended sediment (TIF_x) received by each river link. Each link yields some fraction of that load (YF_x). The rest is deposited. The ratio of YF_x/TIF_x is the proportion of suspended sediment that passes through each link. The suspended load delivered from each sub-catchment will pass through a number of links and the amount delivered to the mouth is the product of LF_x and the probability of passing through each river link:

$$CO_x = LF_x x \frac{YF_x}{TIF_x} x \frac{YF_{x+1}}{TIF_{x+1}} x......x \frac{YF_n}{TIF_n} \quad (3)$$

where n is the number of links *en route* to the outlet. The proportion of suspended sediment passing through each river link is ≤ 1. A consequence of (3) is that all factors being equal the further a sub-catchment is from the mouth the lower the probability of sediment reaching the mouth. This behaviour is modified by differences in source erosion rate and floodplain extent between links.

2.2 Bedload Budget

Bedload is deposited in streams when the loading over time exceeds the sediment transport capacity of the stream (Figure 2). Sediment transport capacity is the maximum amount of sediment that a river can carry given its discharge, slope, width and hydraulic roughness. All sediment in excess of capacity is deposited. If the total loading over time is less than the transport capacity then all sediment is delivered downstream. To predict the location of sand slugs, we expressed bedload deposition as the depth of accumulation since European settlement.

Sediment transport capacity (STC) is a function of the river width (w_x), slope (S_x), discharge (Q_x), particle size of sediment and hydraulic roughness of the channel. Yang [1973] found strong relationships between unit stream power and STC. Using Yang's [1973] equation, and average value for Mannings roughness coefficient of 0.025, we predicted sediment transport capacity in a river link (t/y) from:

$$STC_x = \frac{86 S_x^{1.3} \sum Q_x^{1.4}}{\omega w_x^{0.4}} \quad (4)$$

where ω is the settling velocity of the bedload particles (m/s). $\Sigma Q_x^{1.4}$ represents mean annual sum of daily flows each raised to a power of 1.4 ($ML^{1.4}$/y). This represents the disproportionate increase in sediment transport capacity with increasing discharge.

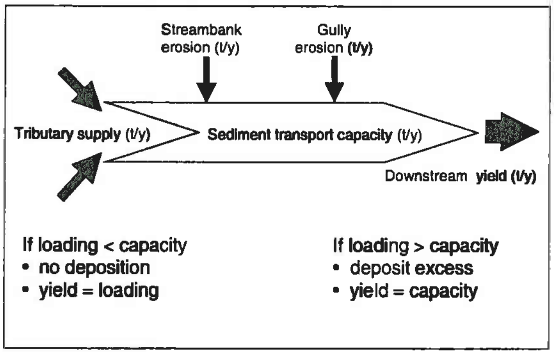

Figure 2. Conceptualisation of the bedload budget for a river link.

The sediment budget methods require calculation of hydrological parameters such as mean annual flow, bankfull flow, and the contribution of discharge to bedload transport. Methods used to derive these from gauging records using hydrological regionalisation are given by Young [2001].

3. IMPLEMENTING THE MODEL

To implement the SedNet model requires a DEM; spatial mapping of vegetation, gully erosion and sheetwash erosion; and regionalisations of hydrological variables. These are all available either nationally or for the NLWRA assessment area. There are no pure calibration parameters in the model. All parameters have either empirical or theoretical values and they have physical meaning which aids in their selection. The bedload sediment budget requires, for example, a sediment settling velocity for bedload. This can be derived from observed mean particle size of historical bed accumulations, which are usually coarse sand or fine gravel.

There are two poorly defined variables in the suspended sediment model which directly influence the magnitude or patterns of suspended sediment load. The supply to streams from sheetwash erosion is modulated by the hillslope sediment delivery ratio (HSDR). While such a ratio is widely used and is needed it remains poorly defined by measurements in any catchment. Increasing HSDR increases the suspended sediment load per unit catchment area. The intensity of deposition of suspended sediment through a river network is determined by the value chosen for the settling velocity of sediment on the floodplain. A faster settling velocity means that more sediment will settle out of the flow for a given residence time on the floodplain. This increases the rate of deposition, decreases the rate of growth of suspended sediment yield with catchment area and reduces sediment export from the basin.

For the NLWRA project we calibrated hillslope sediment delivery ratio and sediment settling velocity globally against observed suspended sediment yields in Australia. The best results were produced by using a settling velocity equivalent to a silt sized particle (0.033 mm), and a hillslope sediment delivery ratio of 0.05-0.1, which is supported by available data [Edwards, 1993]. It is possible to set a high a value for hillslope sediment delivery ratio and compensate for this by simulating very strong deposition on floodplains, thereby still producing the correct basin sediment yield. There are three indicators which we used to prevent this situation. The first is the ratio of sediment derived from hillslopes to that derived from gully and bank erosion. Fallout radionuclide concentrations of sediment can be used to separate hillslope sediment sources from bank and gully erosion. They indicate that gully and bank erosion are at least as significant as hillslope erosion in gullied catchments and that gully and bank sources dominate strongly in parts of SE Australia [Wallbrink et al., 1998].

The second indicator is the rate of floodplain deposition, which should be of the order of 1 m per 1000 y, or less on average. We produced rates at or below this over >90% of the area we assessed. The third indicator is the slope of regression lines of the log of sediment yield against the log of catchment area. A review of Australian data suggest values of 0.85 – 1, and we reproduce these values in all regions.

A further indicator of reasonable patterns in a river sediment budget is the ratio of bedload to suspended load. Gully and bank erosion contribute evenly to each budget but at the outlet of river basins, bedload makes up <10 % of the total load, meeting common observation.

4. EXAMPLE RESULTS

Figure 3 gives an example of use of the bedload sediment budget to predict the location of sand slugs in the Glenelg R. of Western Victoria. Mapped sand slugs for the river basin [Rutherfurd, 1999] are also shown. There is good correspondence between mapped sand slugs and predictions given the coarseness of the 9" DEM

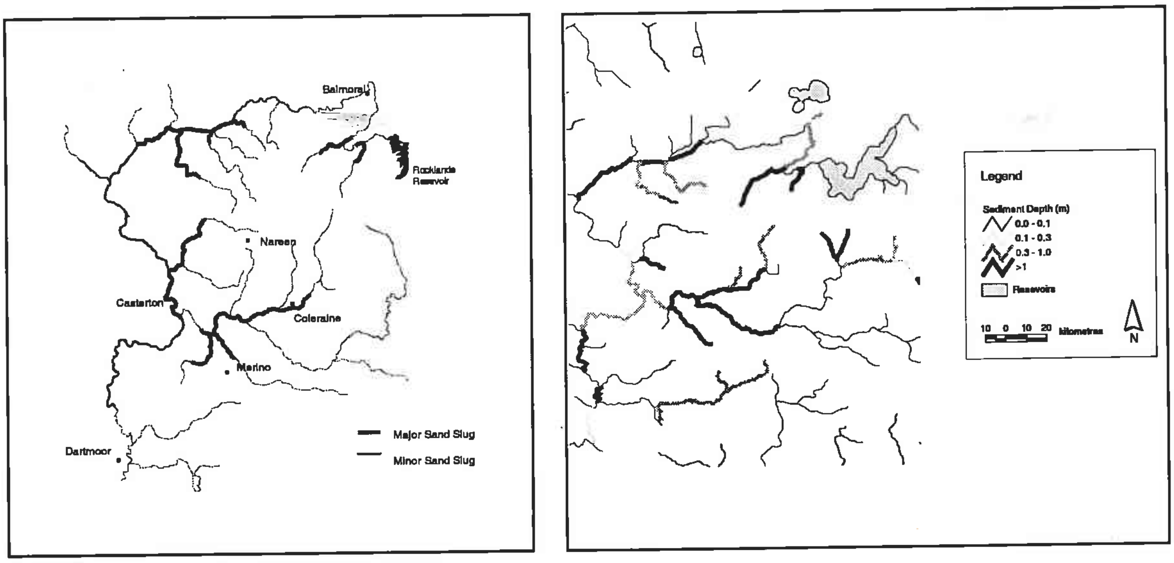

Figure 3. Observed [Rutherfurd, 1999] and predicted location of sand slugs in the Glenelg R. basin.

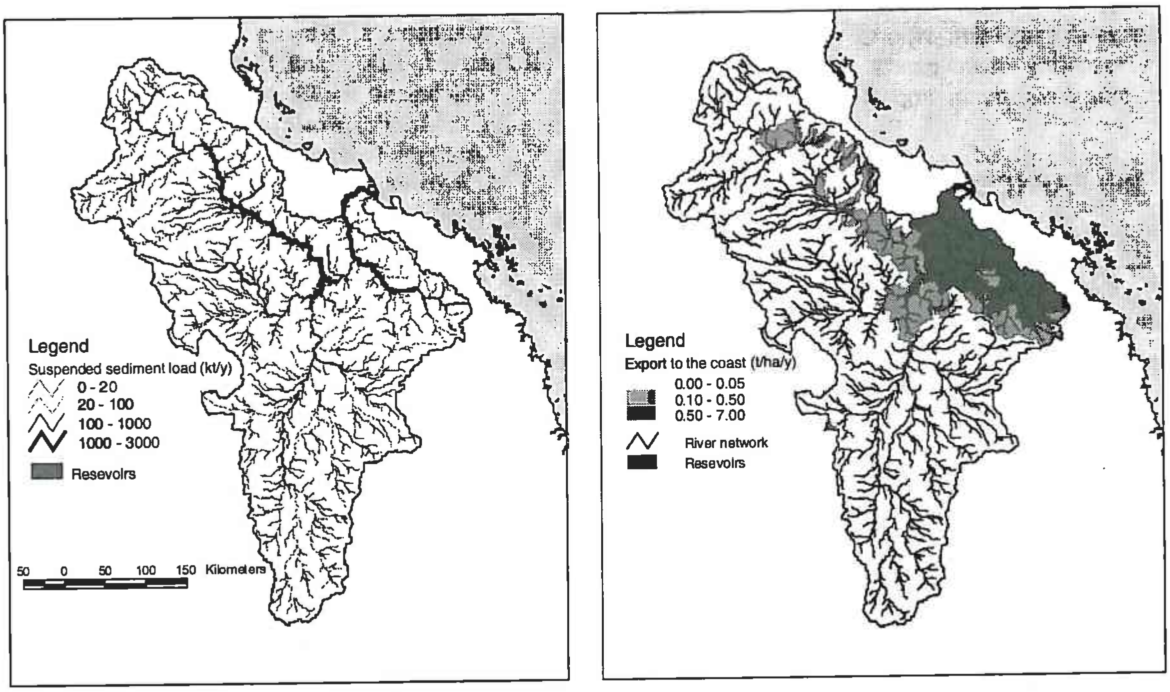

Figure 4. Example output maps from the suspended load budget of the SedNet model.

and resultant stream network in this case. Areas of sand slugs occur where there is gully erosion upstream as a source of sediment and where the sediment transport capacity is low, through either flow regulation, low discharge or low stream gradient. Locating sand slugs can be used to target erosion control works, environmental flow needs, or places for river restoration.

The Burdekin River basin on the north Queensland coast is shown as an example of the suspended sediment results (Figure 4). The mean annual suspended sediment load is dominated by the northern and eastern parts of the basin because of both high erosion and limited deposition in those areas. The southern part of the catchment has extensive lowland floodplains and lower average erosion rates. When these results are expressed as contribution of each sub-catchment to export at the mouth we find that 95% of sediment export comes from just 13% of the basin area. Export is dominated by sub-catchments below the Burdekin Falls Dam and the most eastern sub-catchments. Much of the drier distant catchment contributes very little to export. These analyses can help target restoration activities aimed at reducing sediment export to the marine environment.

5. CONCLUSIONS

A sediment budget model has been described which focuses on the spatial patterns and potential impacts of sediment transport in Australian catchments. The model considers sheetwash, gully and streambank erosion which are all significant sources of sediment to streams in Australia [Prosser et al., 2001b]. To accurately forecast mean annual sediment loads it is necessary to explicitly model deposition. The model does this by simplified process representations. The deposition of bedload is also one of the key impacts in Australian rivers.

Explicit linking of sediment sources to exports, via spatial patterns of deposition, allows us to predict the spatial contribution of sediment sources to catchment exports. This has potential for assessing management options aimed at reaching downstream targets.

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