Targeting erosion control using spatially distributed sediment budgets

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Abstract There is a growing interest in restoring rivers; however, the restoration work required often exceeds the resources available. Consequently, management actions need to be targeted to achieve the greatest benefit. A thorough knowledge of local sediment budgets could represent a substantial management technique in this regard. The SedNet model has been used extensively to construct local sediment budgets throughout river networks. In the model, sediment is supplied to each link of the network from hillslope erosion, gully erosion, and channel bank erosion, and then routed through the network, with deposition occurring in river channels, on flood plains, and in reservoirs. The model enables the determination of the contribution from each erosion source, at each point in the river network. The SedNet model is applied to the Murrumbidgee River, and shows how spatially distributed sediment budgets can be used to target erosion control activities.

Key words riverbank erosion; sediment budget; sediment tracing; SedNet; targeting

INTRODUCTION

The extent and diversity of physical habitat is an important determinant of the health of river ecosystems. Physical habitat includes the size and shape of the channel, the form of the bed sediments, the quality of the water, and the supply of nutrients, all of which are influenced by the supply and characteristics of the sediments (Prosser *et al.*, 2001a). European settlement, 100–200 years ago, brought widespread changes in land-use across the southeast of Australia, which massively increased the supply of sediment to the rivers (e.g. Olley & Wasson, 2003). Today, increased sediment supply continues to affect the health of many Australian rivers.

Unfortunately, the magnitude of work required to reduce sediment loads to "natural", pre-European settlement rates exceeds the resources available. To maximize the benefit from investment, erosion control works must, therefore, be targeted to the most important sediment sources in the river basin. In this paper, spatially distributed sediment budgets are used to assess the relative magnitude and spatial patterns of sediment sources in the Murrumbidgee Basin, in southeastern Australia. Two contrasting methods for targeting erosion control activities are discussed herein.

Basin description

The Murrumbidgee River drains approximately 84 000 km^2 of the Murray-Darling Basin (Fig. 1). Its catchment has three distinct geomorphic regions: upper, middle, and

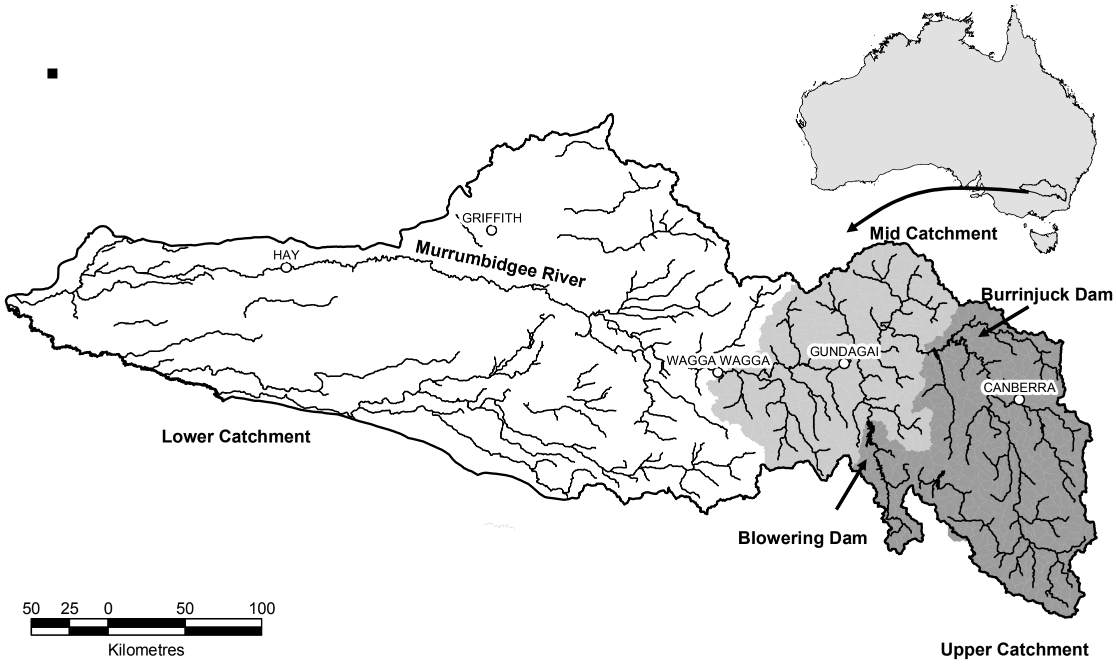

Fig. 1 Map of the Murrumbidgee River basin showing key locations.

lower. The upper Murrumbidgee is mountainous and hilly, and is separated from the mid-region by two large storage reservoirs, Burrinjuck and Blowering (Fig. 1), which trap most of the sediment delivered from the upper basin (Wasson *et al.*, 1987) and regulate the flow downstream.

The mid-basin has undulating terrain dissected by incised stream and gully networks. Several radionuclide sediment tracing studies have shown erosion of these networks to be the primary source of sediment delivered to the lower Murrumbidgee River (e.g. Wallbrink *et al.*, 1998; Olley & Wasson 2003). A strong rainfall gradient exists across the basin; average annual totals vary from 1600 mm in the upper catchment down to 300 mm at the catchment outlet. The 29 000 km^2 upper and middle catchment is the primary sediment source area for the basin (Olive *et al.*, 1996), and targeting erosion control in this region only, is discussed. The main land-use in the upper and middle basin is grazing, with some cropping, forestry, and national parks.

Constructing the sediment budget

The SedNet model, developed for the National Land and Water Resources Audit (NLWRA; Prosser *et al.*, 2001b), is a physically-based process model. It constructs sediment budgets for a river network and identifies the major sources, sinks, and loads of material. In the model, the river network is divided into a series of links which are the basic unit of calculation for the sediment budget. Each link extends between adjacent stream junctions or nodes, and has a sub-catchment that drains into the link between its upper and lower nodes (Fig. 2). ArcInfo^{TM} AML scripts are used to define the river network and sub-catchments from a 25 m Digital Elevation Model (DEM). Using this environment, separate budgets for bedload and suspended sediment are then computed for each link. The sediment yield (Y_x) from a link is given by:

$$Y_x = H_x + G_x + B_x + T_x - C_x - F_x - R_x \quad (1)$$

Sediment inputs to each link come from hillslope (H_x), gully (G_x), and riverbank (B_x) erosion, and from upstream tributaries (T_x) (Fig. 3). Sediment is either deposited within the channel (C_x), on flood plains (F_x), in reservoirs (R_x), or is transported downstream and delivered to the next link (Y_x). This process is carried out in each river link, from first to highest Shreve order (Shreve, 1966), so that Y_x for the outlet link, represents mean annual export.

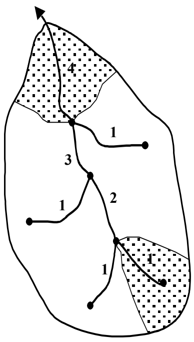

Fig. 2 A river network showing links, nodes, Shreve magnitude of each link (Shreve, 1966) and the internal sub-catchment areas of an order one and an order four link.

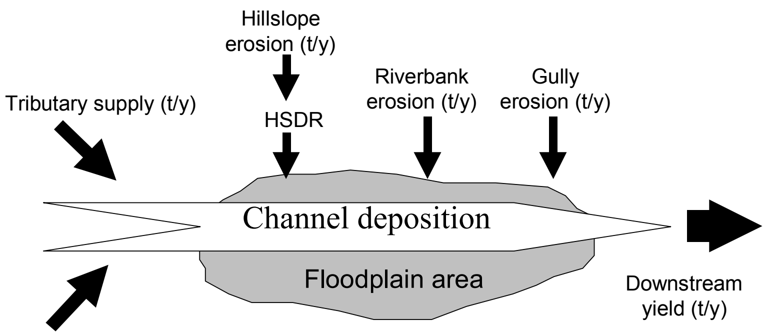

Fig. 3 Conceptual diagram of the SedNet sediment budget for a river link.

Hillslope erosion The input from hillslope erosion is estimated using the Revised Universal Soil Loss Equation, as applied in the NLWRA (Lu *et al.*, 2001). Most soil eroded on hillslopes deposits elsewhere on the hillslope, and so only a small amount of the eroded sediment is delivered to streams. Hence, H_x is modified by the hillslope sediment delivery ratio (*HSDR*). A *HSDR* of 0.05 has been found to provide good agreement between hillslope erosion and yield in regions dominated by hillslope processes (Prosser *et al.*, 2001b). All hillslope sediment is assumed to contribute to the suspended sediment budget.

Gully erosion The linear extent of gully erosion in the Murrumbidgee basin has been mapped from aerial photographs by the New South Wales Department of

Infrastructure, Planning, and Natural Resources. Assuming negligible gully erosion prior to the arrival of Europeans, the average rate of suspended sediment supply since, from gullies in each sub-catchment (G_x), is the product of gully length (l_x), cross-sectional area (a =12 m^2), and sediment dry bulk soil density (ρ_s =1.5 t m^{-3}), divided by the average time over which gullies have developed (τ = 120 years):

$$G_x = \frac{\rho_s a}{\tau} \times l_x \qquad (2)$$

Sediment from gullies and riverbanks is distributed equally to separate bedload and suspended load budgets. The channel network extension that occurred in response to European land-use change is, today, largely complete. Suspended sediment supply from gullies is therefore reduced, in the model, from the long-term average by 50%, to reflect a decline in the sediment yield, indicated by a historical survey in the Murrumbidgee (Wasson *et al*., 1998), and recent measurements (Caitcheon, 2004).

Riverbank erosion Following DeRose *et al.* (this volume), bank erosion rate, BE_x (m year^{-1}), is determined from an empirical model as:

$$BE_x = 0.0001 \rho g Q_{bf} S_x (1 - PR_x)(1 - \exp(-0.008 F_w)) \qquad (3)$$

Negligible bank erosion has been assumed in the proportion of the link length that has fully intact riparian vegetation (PR_x), as determined from LANDSAT imagery with 30 m pixels (Barson *et al*., 2000). The coefficient (0.0001) was calibrated to achieve a maximum bank erosion rate of 0.5 m year^{-1}; in accordance with observed channel widening in some highly eroded, steep and non-vegetated streams. The value used differs from the coefficient (0.00002) used elsewhere (DeRose *et al*., this volume), which indicates that the bank erosion model may be relatively poorly constrained. The amount of sediment supplied from bank erosion, $B_x = \rho_s h L_x (BE_x)$, where h is bank height (3 m) and L_x is link length.

Flood plain deposition Deposition of suspended sediment on flood plains, F_x (t year^{-1}), was determined as a function of flood plain area, and median overbank flow (Prosser *et al*., 2001a). Flood plain mapping for each river link utilised hydrological and hydraulic modelling, (Pickup & Marks, 2001). Bankfull flow was estimated as the flow with a recurrence interval of 2.27 years (Page, 1988). Using daily river gauge records, bankfull and median overbank flow were regionalized as power functions of mean annual flow, which was also regionalized (Wilkinson *et al*., 2005). Downstream of reservoirs, regionalized flow was adjusted to reflect flow regulation.

Channel deposition Where bedload supply to a link exceeds transport capacity (Prosser & Rustomji, 2000), the excess bedload (C_x) is deposited in the channel.

Deposition in reservoirs Sediment deposition in reservoirs (R_x) is predicted using an empirical function of the mean annual reservoir inflow and its total storage capacity (Heinemann, 1981).

Using sediment budgets for targeting erosion control Where the objective is to improve water quality throughout the river network, the total sediment supply to the network should be reduced. This is most effectively achieved by targeting the erosion process(es) that supply the most sediment. Long term averages generally are sufficient for catchment planning, and maximum reduction in sediment supply is achieved by spatially targeting control measures to the sub-catchments and river-links with the highest rates of erosion. In contrast, if the objective is to reduce sediment export from a catchment, the sub-catchments contributing the greatest amount of sediment to the catchment outlet should be targeted. Methods of determining the areas contributing to export are described more fully in Wilkinson *et al*. (2005) and Lu *et al*. (2004). This study illustrates how the SedNet model can be used to locate erosion control measures to achieve these two different management objectives.

RESULTS AND DISCUSSION

The modelled stream network in the Upper and Middle Murrumbidgee catchment has a total length of 5600 km. The network is composed of 745 river links; of 6.5 km average length. The predicted long-term average suspended sediment load at Wagga Wagga is 578 kt year^{-1}, which is similar to the observed load of 600 kt year^{-1} (Olive *et al*. 1996). Summing each term in the bedload and suspended sediment budgets for all links in the river network identifies riverbank and gully erosion as dominant sediment sources (Table 1); this agrees with radionuclide tracer observations of suspended sediment (Wallbrink *et al.*, 1998). Therefore, erosion control to reduce the total supply of sediment, and also sediment contribution to export, should target both riverbank and gully erosion.

The link-average riverbank erosion rate is reduced in links with high proportions of existing bank vegetation. To calculate the bank erosion rate along the non-vegetated portion of the link, bank erosion hazard (t km^{-1} year^{-1}) is calculated, by setting PR_x in equation (3) to zero, then dividing B_x by link length. This hazard represents the potential erosion rate, whether or not it has been realised to date. There are strong spatial patterns evident in bank erosion hazard (Fig. 4). It is highest along main streamlines and in steeper foothill areas, and lowest in the flat plains of the northwest.

Spatially distributed sediment budgets can be used to help target erosion control to meet different management objectives. The predicted results from two contrasting scenarios, each involving the same management action; stabilisation of 500 km of eroding riverbank, and 500 km of gullies, are compared. In the first scenario, the objective is to reduce total sediment supply to the stream network. To achieve this

Table 1 Predicted relative proportions of sediment sources and losses in the upper-mid Murrumbidgee catchment.

Inputs	% of total	Outputs	% of total
Hillslope suspended supply	19	Flood plain suspended deposition	9
Gully suspended supply	12	Channel bedload deposition	21
Gully bedload supply	24	Reservoir suspended deposition	20
Riverbank suspended supply	23	Reservoir bedload deposition	16
Riverbank bedload supply	23	Export suspended sediment	24
		Export bedload sediment	9
Total supply	100%	Total output	100%

objective, the actions need to be targeted at the links with the highest bank erosion hazard and the sub-catchments with the greatest gully density (Fig. 4). The objective of the second scenario is to reduce catchment export of suspended sediment. In this case,

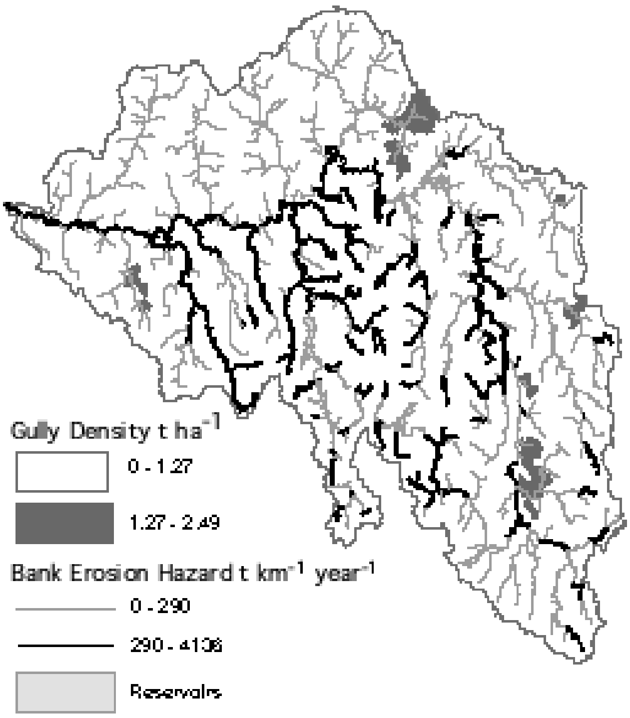

Fig. 4 Bank erosion hazard (t^{-1} km^{-1} $year^{-1}$) and Gully erosion (t^{-1} ha^{-1} $year^{-1}$).

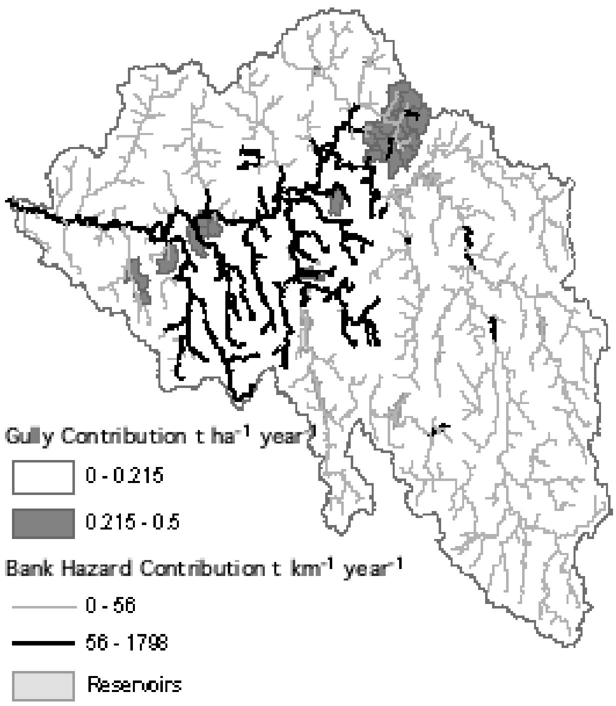

Fig. 5 Contribution from bank erosion hazard and gully erosion, to export of suspended sediment.

Table 2 Comparison between scenarios with different objectives for targeting erosion control.

Targeting Objective	Reduction in total sediment supply $\sum(H_x + G_x + B_x)$ (%)	Reduction in suspended sediment export (%)
Reduce sediment supply	18	23
Reduce suspended sediment export	16	26

actions should be targeted to links with the highest bank erosion hazard contribution to export, and sub-catchments with the highest gully contribution to export (Fig. 5).

In each treated link and sub-catchment, the scenarios simulate stabilization of 50% of the non-vegetated portion of the link, and stabilization of 50% of gully erosion. (Figs 4 and 5 indicate, in dark shade, links containing 1000 km of non-vegetated river link, and 1000 km of gully erosion). This partial treatment accounts for two pragmatic considerations. Firstly, erosion rates will vary within links and sub-catchments, and 50% erosion control may be sufficient to stabilize erosion hotspots within links and sub-catchments. Also, not all landholders will want to be involved in erosion control.

The two scenarios are compared in Table 2. The different effect on suspended sediment export between the scenarios demonstrates the importance of carefully identifying the objective of targeting erosion control. The sediment-supply scenario targets bank erosion control to links with high stream power throughout the river system, whereas the contribution-to-export scenario targets bank erosion downstream of the major reservoirs.

Spatially distributed sediment budgets can be modelled at a range of scales, depending on the area over which erosion control is being targeted, and the spatial resolution required. For example, the method also has been applied to the Murray-Darling Basin; of which the Murrumbidgee is a subset (Lu *et al*., 2004). Sediment tracing techniques (Olley, 2004), can be used to test the model predictions.

CONCLUSIONS

Spatially distributed sediment budgets are a useful modelling framework for identifying sediment sources and sinks in a river basin. The SedNet model can be used to target erosion control activities to the dominant erosion process, and to erosion hotspots, to achieve different management objectives. It also can be used to test the efficacy of different management scenarios. It is currently being used to plan erosion control in the Murrumbidgee catchment.

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