International Congress on Environmental Modelling and Software

2nd International Congress on Environmental Modelling and Software - Osnabrück, Germany - June 2004

Jul 1st, 12:00 AM

Spatially Distributed Investment Prioritization for Sediment Control over the Murray Darling Basin, Australia

Hua Lu

Christopher Moran

Ian Prosser

Ronald DeRose

Lu, Hua; Moran, Christopher; Prosser, Ian; and DeRose, Ronald, "Spatially Distributed Investment Prioritization for Sediment Control over the Murray Darling Basin, Australia" (2004). *International Congress on Environmental Modelling and Software*. 199.
https://scholarsarchive.byu.edu/iemssconference/2004/all/199

Spatially Distributed Investment Prioritization for Sediment Control over the Murray Darling Basin, Australia

Hua Lu[ab], **Christopher Moran**[a], **Ian Prosser**[a] **and Ronald DeRose**[a]

[a] *CSIRO Land and Water, Canberra, ACT 2601, Australia*

[b] *Institute of Theoretical Geophysics, University of Cambridge, UK*

Abstract: Based on a spatially-distributed sediment budget across the Murray Darling Basin, costs of achieving a range of sediment reduction targets were estimated for a number of locations. Four investment prioritization scenarios were tested to identify the most cost-effective strategy to control suspended sediment loads. The impacts of spatial heterogeneity of sediment transport and varying the spatial scale of target locations on cost effectiveness were examined. The results show that: 1) an optimum solution of cost-effective sediment control can be determined through the spatial sediment budget; 2) appropriate investment prioritization can offer potential large cost savings as the magnitude of the costs can vary by several times depending on what type of erosion source or sediment delivery is targeted; 3) target settings which only consider the erosion source rates can potentially result in spending more money than random management intervention; and 4) prioritization becomes a more cost effective strategy as the area considered increases because of the spatial heterogeneity of contributing sediment. An interpretation of the non-linear cost to increasing sediment reduction relationship is also provided.

Keywords: Sediment control; Spatially distributed modelling; Prioritization.

1. INTRODUCTION

World-wide, suspended sediment with attached nutrients and organic matter are significant contributors to poor water quality in many waterways. Awareness of water quality degradation has led to actions in many places. Part of these actions is the setting of targets to reduce suspended sediment and pollutants. For instance, in the USA, 40%-50% reductions in nutrient export have been set [*Schleich et al.*, 1996; *WDNR*, 1988]. Nine European countries have agreed to take joint actions to achieve a 50% reduction in the total load of nutrients to the Baltic Sea [*HELCOM*, 1993]. In Australia, under the National Action Plan for Salinity and Water Quality, federal and state government agencies are working together to set targets for improving water quality [*NAP*, 2003]. A target of reduction by 30% has been set for the catchments of the Great Barrier Reef [*Environment Australia*, 2003]. However, the jurisdictions allocating resources to achieve the targets need strategic advice. That is, which areas or/and pollutant types require the greatest investment to achieve the desired outcome(s)?

Few studies have been carried out on cost effectiveness of management at a broad spatial extent. *Gianessi and Peskin* [1981] used a national water network model which took into account pollutants from both industrial and agricultural activities to simulate the effects of four policy scenarios on water quality in America. They concluded that efficient sediment-related pollution control could be achieved by focusing on one third of the nation’s agricultural regions. *Schleich et al*. [1996] used linear programming to determine whether the cost of achieving phosphorus reduction targets was different depending on the scale of the units over which management action was considered. They found that optimizing at the outlets of subcatchments was more expensive than optimizing from the basin outlet. The severe eutrophication and ecological collapse of the Baltic Sea has led to internationally-coordinated research activities seeking cost effective policies of pollutant reduction [*Gren*, 2001]. Stochastic approaches were used to examine the cost changes for a given probability of achieving a certain pollutant load target [*Gren et al.*, 2000].

The environmental properties governing pollutant generation, transport and deposition are not homogeneous over broad areal extents. There is considerable spatial and temporal variation inherent in topography, climate, soil, vegetation, management practises and land use. While heterogeneity appears to be difficult for analysis, it presents a major opportunity, *i.e.*, the possibility of cost saving through prioritized actions.

Proper representation of the linkage between location and nature of pollutant sources and their downstream impacts is also critical. When considering sediment in terms of water quality impact, the management concern is how to control the sediment load at a point of interest downstream and the erosion sources are often several hundreds of kilometres upstream. Only a proportion of soil erosion reaches the channel network and only a proportion of that sediment is transported downstream as sediment can be intercepted by riparian vegetation and deposited on foot slopes and floodplains and in reservoirs and lakes.

This paper proposes a method for spatially distributed investment prioritization. We consider a large regional basin – the Murray-Darling Basin in eastern Australia. Heterogeneity of contributing sediment and linkages between sources and targets are explicitly represented through spatially-resolved sediment budgets [*Prosser et al.*, 2001]. The spatial accounting of sediment budgets enables us to distinguish the sediments that made the way to a sediment control location from those which deposit before reaching the control location. By comparing the cost-effectiveness of a range of management strategies, we show how resources could be allocated spatially under certain management action.

2. METHODS

2.1 Study Area

The Murray-Darling Basin (MDB) covers an area of 1.1×10^6 km^2 (about 14% of Australia, Fig. 1) and it is an important agricultural centre. It contains around 75% of Australia's irrigated land, accounts for 40% of Australian agricultural production and inhabits two million people, about 10% of the national population [*ABS*, 2002]. It also has the three longest rivers in Australia (Murray, Darling and Murrumbidgee). The river system is showing signs of environmental stress: salinity, reduction in both water quality and quantity, sedimentation, loss of fish species and algal blooms [*NLWRA*, 2001].

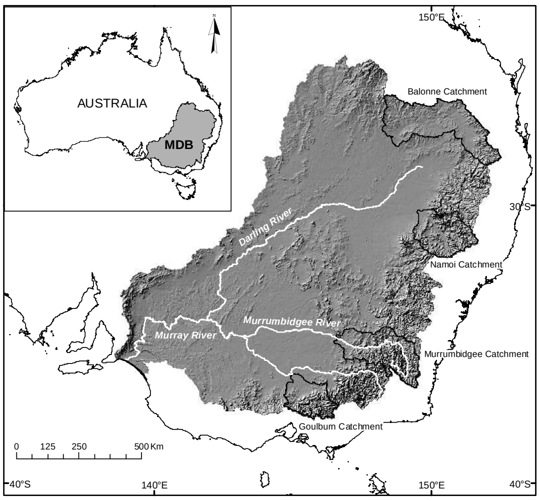

Fig. 1. Location of the Murray–Darling Basin (MDB) in Australia. A hill-shaded version of the DEM in the background highlights the low relief of the MDB.

2.2 Sediment Budget

The investment prioritization analysis was carried out using the results of spatial modelling of sediment budgets across the MDB. The sediment budgets assess current patterns of the major erosion, river sediment transport and deposition processes in the Basin, using the *SedNet* model [*Prosser et al.*, 2001]. *SedNet* is a set of GIS programs that define river networks and their associated catchments and route sediment through the network as a function of river hydrology and mapping of erosion processes [*Prosser et al.*, 2001]. The application of *SedNet* to the MDB is reported in detail in *DeRose et al.* [2003].

The river network of the MDB was defined from the 9" digital elevation model (DEM), Australia (http://cres.anu.edu.au/dem) and divided into river links, separated by tributary junctions or nodes. Each link of the river network has an associated catchment area of around 50 - 100 km^2. The river links are the basic elements of the sediment budget model and the area contributing to the link is referred as link element hereafter. Each link, i, receives a mean annual supply of suspended sediment from upstream tributaries (T_i), from bank erosion along the link itself (B_i), and from gully erosion (G_i) and hillslope sheetwash and rill erosion (E_i) in the link element. Rates of each erosion process were estimated from detailed mapping of the controlling environmental factors. [*Hughes and Prosser*, 2003; *Lu et al.*, 2003b]. A fraction of the gross amount of hillslope erosion in the catchments is delivered to rivers and this is accommodated through calculation of a hillslope sediment delivery ratio (γ_i) for each link area [*Lu et al.*, 2003a].

The mean annual yield of suspended sediment from the link is the total supply of suspended sediment to the link (S_i) less deposition on floodplains or in reservoirs (D_i). The suspended sediment budget for a link is:

$$Y_i = S_i - D_i = T_i + \left(E_i \gamma_i + G_i + B_i\right) - D_i \qquad (1)$$

where the term in brackets is the total sediment supply (I_i) from the link element i.

The mean annual delivery of sediment from a link element to a contribution point downstream (λ_i, t/y) is the sediment supply from the link element (I_i) multiplied by the sediment delivery efficiency through all river links (j = 1…M) along the route to the contribution point:

$$\lambda_i = I_i \prod_{j=1}^{M} Y_j \big/ S_j \qquad (2)$$

The suspended sediment yield at a single sediment control location k can then be calculated by:

$$Y_k = \sum_{i=1}^{N} \lambda_i \qquad (3)$$

where N is the total number of link elements contributing to sediment control location k.

2.3 Investment Prioritization Scenarios

We used four scenarios to mimic the types of management strategies that are currently being implemented or are under consideration: *Scenario* A: random management, where parts of river basins and particular erosion processes were chosen at random for treatment; *Scenario* B: investment prioritized to sediment sources, those places in the catchment with the highest erosion rates; *Scenario* C: prioritized to delivery to nearest streams, by combining information of erosion sources and hillslope sediment delivery, thereby seeing where it is effective to trap eroding soil, as opposed to preventing it from eroding upslope; and *Scenario* D: prioritized to delivery to control points, by fully utilizing the information resulting from the sediment budget including broad scale sediment deposition, *i.e.*, focusing on the areas with particular erosion processes that contribute most to the suspended sediment loads.

The four scenarios were implemented for each five percent incremental reduction (5-100%) in suspended load from current conditions to the conditions before European Settlement (minimum erosion and sediment transport activities which were predominated by natural processes only). The units to which we applied the control strategies were the link elements.

2.4 Cost Estimation

The costs of the primary management practices were obtained from the Goulburn-Broken Catchment Management Authority, Australia. The average per unit costs of reducing erosion rate for three types of erosion sources and hillslope sediment delivery ratio are summarized in the Table 1.

Table 1. Estimated per unit costs for three types of erosion sources and per 1% of current hillslope sediment delivery ratio.

	Unit Cost ($)
Gully (per tonne)	130
Riverbank (per tonne)	34
Hillslope (per tonne)	80
γ (per 1% of current γ)	9900

3. RESULTS

To understand the relationship between sediment sources and their linkage to control locations we examine four catchments in some detail. The locations of the catchments are shown in Fig. 1.

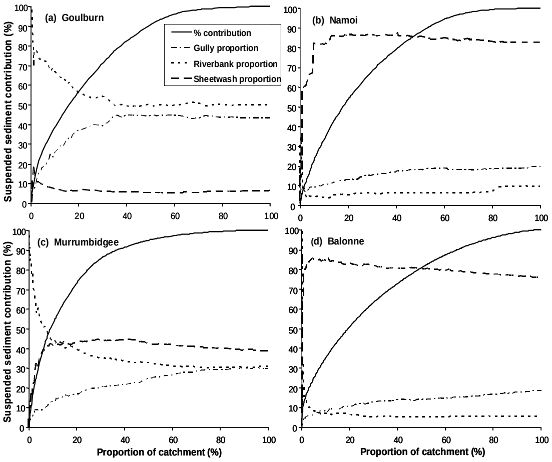

Fig. 2. Estimations of accumulative area contributions of suspended sediment in the (a) Goulburn, (b) Namoi, (c) Murrumbidgee and (d) Balonne catchments respectively. The relative proportions of suspended sediment contribution from each of the main erosion processes are also shown. The locations of the four catchments can

In the Goulburn and Murrumbidgee catchments the sources of sediment are predominantly from riverbank erosion (Fig. 2a). In the Namoi and Balonne catchments the contributing sources are predominantly from hillslope sheet and rill erosion (Fig. 2b). The Goulburn and Namoi catchments have approximately the same degree of heterogeneity of the contributing sediment. The Murrumbidgee (Fig. 2c) has a strong degree of heterogeneity of sediment contribution compared to the more homogeneous Balonne (Fig. 2d), as indicated by the curvature of the accumulative sediment contribution by area (solid lines).

Each of the four scenarios was run for each of the four example catchments. Fig. 3 shows the cost curves derived for each scenario for the four example catchments. Scenario A was run ten times for each catchment to give an indication of the random error range. For all cases, *Scenario D* represents the most cost-effective strategy. For some cases, *Scenarios B* and *C* are not necessarily better than random selection (*Scenario A*) (*e.g.*, Fig. 3b,d).

When the sources of contributed sediment are dominantly sheet and rill erosion (Namoi and Balonne catchments, Fig. 3b,d) scenarios which only consider the erosion source rates (with and without local sediment delivery efficiency) can result in spending more money than random management. However, when the variable linkage between sediment source and the target control location is taken into account a radical improvement in cost-effectiveness can be achieved (*Scenario D*). This highlights the difference between erosion control for on-site productivity maintenance and off-site suspended sediment delivery. When the source is dominantly gully and river bank (Goulburn catchment, Fig. 3a), *Scenario A* is the least effective (Fig. 3b,d).

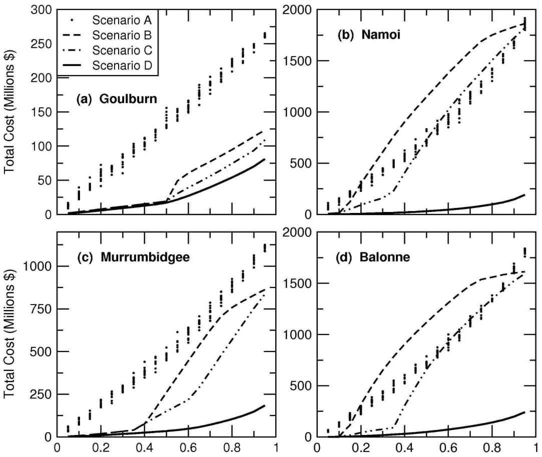

Fig. 3. Cost versus sediment reduction curves (cost curves) for the four example catchments shown in Fig. 1.

We examine the effect of spatial scale on cost by altering the position of sediment control locations (where sediment targets will be set). Separately, in each catchment, we compared the total expenditure when sediment control locations are positioned at the catchment outlet with the case where they were nested within the catchment at particular channel sub-nodes. The 10-20 sub-nodes were arbitrarily chosen along the major tributaries within each catchment. Each sub-node receives sediment from around 30 – 50 up-stream link elements and the aim is to reduce the total load summed across all the sub-nodes. There some link elements that directly contribute to the catchment main control locations rather than any sub-node. We treated these link elements as an additional sub-catchment.

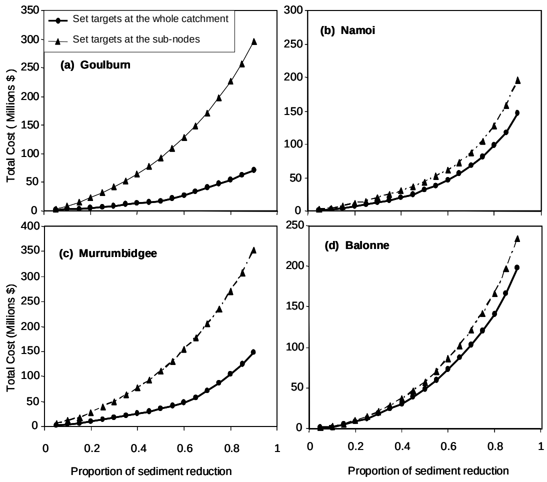

Fig. 4. Comparison of cost curves when control locations for suspended sediment targets are set at sub-nodes defining sub-catchments within the catchment, and at the catchment outlet for (a) Goulburn, (b) Namoi, (c) Murrumbidgee and (d) Balonne catchments respectively.

By implementing *Scenario D* only, Fig. 4 shows that total expenditure by setting targets at sub-node level is higher than by treating the catchments as a whole, for all percentage reductions. These results are consistent with the findings of *Schleich et al.* [1996]. Fig. 4 also shows that the difference is greater in some catchments than others. Larger cost savings are achieved in the Goulburn and Murrumbidgee catchments by treating the catchment as a whole (shown in Fig. 4a,c). The differences are caused by the patterns of the main sediment sources, their relationship to the control locations, and the choice of control locations themselves. Unlike the Namoi and Balonne catchments (Fig. 4b,d) where most of the sediment is contributed by sheet and rill erosion in uplands, most of the sediment in the Goulburn and Murrumbidgee catchments (Fig.4a,c) is contributed by bank erosion from the link elements along the major channels. For catchments like the Goulburn and Murrumbidgee, setting the same percentage of sediment reduction targets at sub-nodes within the catchment often misses the opportunity to prioritize investment along the main channels, where sediment is directly transported to the main control locations, resulting in unnecessary expenditure in the upland areas, in which eroded sediment is deposited locally. Apart from the internal heterogeneity of contributing sediment, the relative differences in total expenditure can be also influenced by other factors such as the number of reservoirs, floodplain deposition and the amount of regulated flow for irrigation (*e.g.* sediment lost in the system due to the loss of the flow).

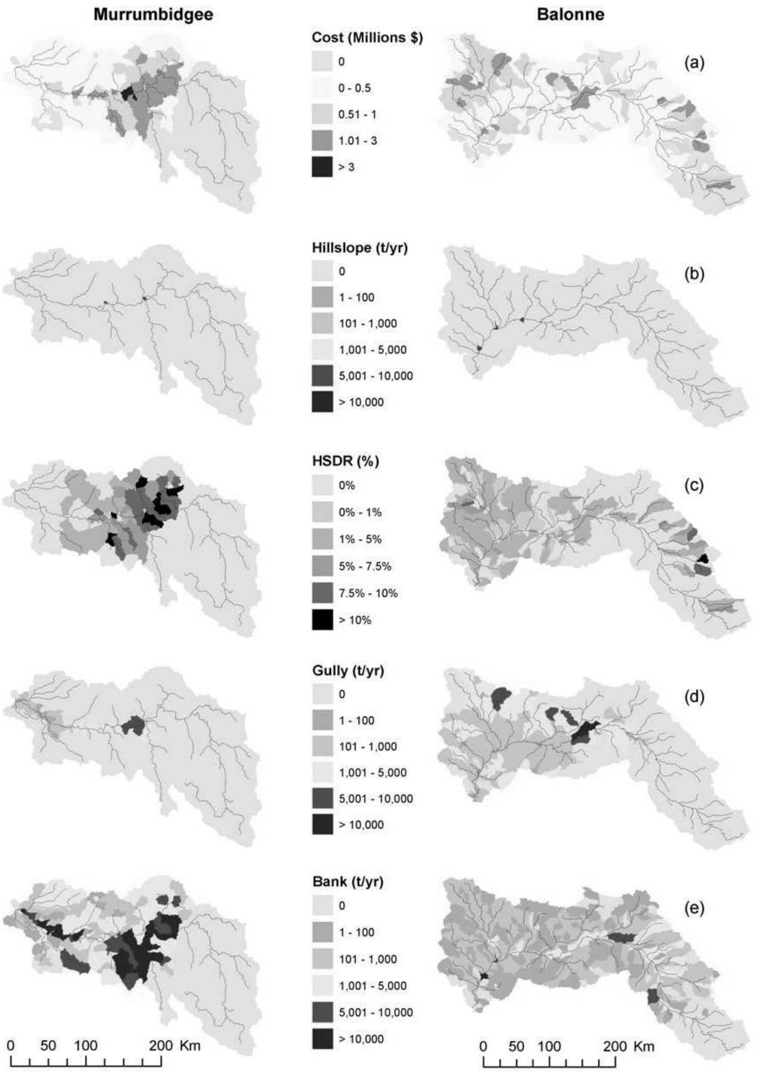

Fig. 5. Spatial distribution of investment to achieve a 70% reduction in suspended sediment with the control location set at the catchment outlet. Two catchments are shown – the one to the left (Murrumbidgee) has greater heterogeneity of spatial distribution of sediment contribution to the control location than the one to the right (Balonne). (a) total expenditure, (b) hill slope erosion reduction (in difference, the same hereafter), (c) hillslope sediment delivery ratio reduction, (d) gully erosion reduction, (e) bank erosion reduction.

Maps can be produced from each scenario of total expenditure, and reductions of hill slope erosion, hill slope sediment delivery ratio (where considered), gully erosion and bank erosion. Fig. 5 shows the most cost effective strategy (*Scenario D*) for a 70% reduction in suspended sediment loads at the catchment outlet. The Murrumbidgee catchment (on the left side in Fig. 5) has a greater concentration of proposed expenditure than the Balonne catchment. This reflects that greater curvature of the accumulative area contribution function, which indicates a more heterogeneous sediment contribution, results in a more concentrated pattern of expenditure.

4. DISCUSSION AND CONCLUSION

We proposed a range of investment prioritization scenarios to identify the most cost-effective strategy to control suspended sediment loads. We demonstrated that a spatially-distributed sediment budget approach provided a rational basis to determine an optimum strategy for cost-effective sediment control. We showed that appropriate investment prioritization can potentially offer large cost savings as the magnitude and distribution of costs can vary by several times depending on what type of erosion source or sediment delivery is targeted in a spatially varying manner. Target settings which only consider the erosion source rates can potentially result in spending more money than random management intervention.

Heterogeneity of sediment contribution is the physical factor leading to potential cost saving. We have shown that the greater the degree of internal heterogeneity, the larger the cost saving through prioritization. It is more cost-effective to prioritize the investment at large basin area than at sub-catchment level because it better utilizes spatial heterogeneity. This raises the prospect that bodies responsible for setting suspended targets could benefit greatly from examining the trade-offs between cost savings in control measures and the costs of installing or moving monitoring stations, for example. Another consideration is how the results might be used to inform the market in provision of the services required to control sediment sources at different spatial scales. It is likely that other issues will exhibit spatial heterogeneity, *e.g.*, pollutant sources, and opportunities for maximizing the value from investment in control could be realized by considering scale and heterogeneity in selecting locations for target setting.

5. ACKNOWLEDGEMENT

This study was partially funded by the Murray Darling Basin Commission under Project D10012.

6. REFERENCES

ABS, Environment condition of Australia’s freshwater resources, Year book Australia, Australian Bureau of Statistics, 2002.

DeRose R. C., I. P. Prosser, M. Weisse, and A. O. Hughes, Summary of sediment and nutrient budgets for the Murray-Darling Basin, Technical Report 15/01, CSIRO Land and Water, Canberra, 2003. http://www.clw.csiro.au/publications/technical 2003.

Environment Australia, Reef Water Quality Protection Plan, 2003.

Gianessi, L. P., and H. M. Peskin, Analysis of national water pollution control policies 2. Agricultural sediment control, Water Resour. Res., 17, 803-821, 1981.

Gren, I. M., International versus national actions against nitrogen pollution of the Baltic Sea, Environ. and Resour. Econo., 20, 41-59, 2001.

Gren, I. M., G. Destouni, and H. Scharin, Cost effective management of stochastic coastal water pollution, Environ. Modelling and Assessment, 5, 193-203, 2000.

HELCOM, The Baltic Sea joint comprehensive environmental action programme, Baltic Sea Environmental Proceedings, No. 48, Helsinki, Finland, 1993.

Hughes, A. O., and I. P. Prosser, Gully and riverbank erosion mapping for the Murray-Darling Basin, Technical Report 3/03, CSIRO Land and Water, Canberra, 20p., 2003. http://www.clw.csiro.au/publications/technical 2003.

Lu, H., C. J. Moran, and I. P. Prosser, Modelling sediment delivery ratio over the Murray Darling Basin. Proceedings of MODSIM 2003, Townsville, 485-491, 2003a.

Lu, H., I. P. Prosser, C. J. Moran, J. Gallant, G. Priestley, and J. G. Stevenson, Predicting sheetwash and rill erosion over the Australian continent, Aust. J. Soil Res., 41, 1-26, 2003b.

NAP, National Action Plan for Salinity and Water Quality, Commonwealth of Australia, 2003. http://www.napswq.gov.au/

NLWRA, Australian Agriculture Assessment. National Land and Water Resources Audit, Canberra, 2001.

Prosser, I. P., B. Young, P. Rustomji, C. Moran, and A.O. Hughes, Constructing river basin sediment budgets for the National Land and Water Resources Audit, Technical Report 15/01, CSIRO Land and Water, Canberra, 2001.http://www.clw.csiro.au/publications/technical2001.

Schleich, J., D. White, and K. Stephenson, Cost implications in achieving alternative water quality targets, Water Resour. Res., 32, 2879-2884, 1996.

Wisconsin Department of Natural Resources (WDNR). Lower Green Bay remedial action plan: Desired future state. WDNR Doc. PUBLR-WR-175-87, Madison, 1988.