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WATER RESOURCES RESEARCH, VOL. 40, W09501, doi:10.1029/2003WR002966, 2004

Investment prioritization based on broadscale spatial budgeting to meet downstream targets for suspended sediment loads

Hua Lu,[1] C. J. Moran,[2] Ian P. Prosser,[3] and Ronald DeRose

CSIRO Land and Water, Canberra, ACT, Australia

Received 19 December 2003; revised 19 May 2004; accepted 21 June 2004; published 2 September 2004.

[1] On the basis of a spatially distributed sediment budget across a large basin, costs of achieving certain sediment reduction targets in rivers were estimated. A range of investment prioritization scenarios were tested to identify the most cost-effective strategy to control suspended sediment loads. The scenarios were based on successively introducing more information from the sediment budget. The relationship between spatial heterogeneity of contributing sediment sources on cost effectiveness of prioritization was investigated. Cost effectiveness was shown to increase with sequential introduction of sediment budget terms. The solution which most decreased cost was achieved by including spatial information linking sediment sources to the downstream target location. This solution produced cost curves similar to those derived using a genetic algorithm formulation. Appropriate investment prioritization can offer large cost savings because the magnitude of the costs can vary by several times depending on what type of erosion source or sediment delivery mechanism is targeted. Target settings which only consider the erosion source rates can potentially result in spending more money than random management intervention for achieving downstream targets. Coherent spatial patterns of contributing sediment emerge from the budget model and its many inputs. The heterogeneity in these patterns can be summarized in a succinct form. This summary was shown to be consistent with the cost difference between local and regional prioritization for three of four test catchments. To explain the effect for the fourth catchment, the detail of the individual sediment sources needed to be taken into account. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1803 Hydrology: Anthropogenic effects; 1806 Hydrology: Chemistry of fresh water; 1871 Hydrology: Surface water quality; *KEYWORDS:* investment, sediment, spatial modeling

Citation: Lu, H., C. J. Moran, I. P. Prosser, and R. DeRose (2004), Investment prioritization based on broadscale spatial budgeting to meet downstream targets for suspended sediment loads, *Water Resour. Res.*, *40*, W09501, doi:10.1029/2003WR002966.

1. Introduction

[2] Worldwide, suspended sediment with attached nutrients and organic matter are significant contributors to poor water quality in many waterways. Loads and concentrations are often many times greater than those experienced under natural conditions [*Chorley et al.*, 1984; *Wasson et al.*, 1996; *National Land and Water Resources Audit* (*NLWRA*), 2001]. Increases of such magnitude impose costs on society. Economically, profit in irrigated commodity production can be reduced through increases in water prices. Fisheries and tourism can be directly impacted in freshwater and receiving estuarine systems [*Jorgensen*, 1996; *Woodroffe et al.*, 1993]. Sediment trapping can reduce the storage capacity and quality of reservoirs. The cost of water treatment for human use can also be increased [*Gianessi and Peskin*, 1981; *Holmes*, 1988]. Ecologically, sediment deposition can smother and fragment habitat, inhibit respiration and feeding of biota and alter visibility. As a result, the competitive edge can be shifted to less desirable species and cause changes in ecosystem states which are difficult to reverse [*Scheffer*, 1998]. Sediment and nutrient transport to the coast can threaten estuarine and marine ecosystems [*McCulloch et al.*, 2003] and have negative impacts on biodiversity and aesthetics. Socially, the impacts range from local losses of viability of livelihood, to increasing divides between urban and rural communities over assignment of responsibility for problems and their solutions.

[3] Awareness that water quality degradation is an important factor compromising the dual achievement of sustainable commodity production systems and ecosystems of acceptable integrity has led to actions in many places. Part of these actions is the setting of targets to reduce pollutant levels in waterways. In the USA, a 40% reduction in nutrient export to Chesapeake Bay was established by a joint agreement between Maryland, Pennsylvania, Virginia, the District of Columbia, and the U.S. Environmental

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[1] Now at Institute of Theoretical Geophysics, University of Cambridge, Cambridge, UK.

[2] Now at Centre for Water in the Minerals Industry, University of Queensland, Brisbane, Queensland, Australia.

[3] Now at Land and Water Australia, Canberra, ACT, Australia.

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0043-1397/04/2003WR002966

Protection Agency [*Schleich et al.*, 1996]. In Wisconsin, a target of 50% reduction for phosphorus reaching Lower Green Bay has been set [*Wisconsin Department of Natural Resources* (*WDNR*), 1988]. At ministerial level, 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]. Sweden has set in place the policies and supporting regulations to reduce exports from their agricultural sector to all waterways including to the Baltic Sea [*Albertsson et al.*, 1999]. In Australia, under the National Action Plan for Salinity and Water Quality (see http://www.napswq.gov.au/), federal and state government agencies are working together to set targets for improving water quality. Targets for reduction of N, P and suspended sediment are being set for the catchments of the Great Barrier Reef (see Environment Australia Web site, Reef water quality protection plan, http://www.ea.gov.au/coasts/pollution/reef/#draft).

[4] Either during the formulation of such policies or following soon after their announcement, a critical question is posed, "How can the targets be achieved with least cost?" The jurisdictions allocating resources to achieve the targets need strategic advice. That is, which areas and/or pollutant types require the greatest investment to achieve the desired outcome(s)?

[5] Studies at farm level and in small catchments have demonstrated that there is economic advantage in prioritizing the implementation of control measures in areas identified as having the greatest potential to supply pollutants. Two basic strategies for prioritization have been examined, *viz*., management of pollutants in the field (on-site control) and interception and filtering runoff (off-site control). Examples of the benefits of on-site prioritization have been demonstrated. *Dickinson et al.* [1990] showed that prioritized application of management could reduce the area requiring remediation by up to 30%. *Carpentier et al.* [1998] compared the costs of prioritized application of management to a uniform approach to reduce nutrient exports at the farm level. To achieve an average nitrogen reduction of 40%, prioritizing reduced the costs by 75%. Research to support implementation of on-site prioritizing has focused on defining Best Management Practices and their optimal spatial layout. At the simplest end, ranking of a suite of practices in terms of their reduction of export off site and cost has been suggested as a mechanism for implementing pollutant reductions [*Heatwole et al.*, 1986]. At the next level such suites have been optimally spatially located to minimize export using linear [*Greenberg*, 1995] and nonlinear [*Braden et al.*, 1989] programming and multiobjective optimization [*Das and Haimes*, 1979]. The problem of trying to determine the optimal spatial layout of the individual practices (as opposed to a bundled suite) is computationally greater. *Srivastava et al.* [2002] showed that a genetic algorithm (GA) was useful for handling the large data sets and obtaining near optimal placement of management practices.

[6] Fewer 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 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 outlet of each of 41 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]. Because of complex policy context and large uncertainties on pollutant sources and pathways to the coastal zones, stochastic approaches were used to examine the cost changes for a given probability of achieving a certain pollutant load target [*Gren et al.*, 2000, 2002]. The spatial differentiation was often considered at country level with focus on agricultural land use. The additional effects of climate, topography, and soil heterogeneity were only minimally taken into account, yet these are important determinants of sediment transport.

[7] *Shortle et al.* [1998] and *Schwabe* [2000] have examined the relative benefits of policies for on-site versus off-site actions. The theoretical and empirical analyses of *Braden et al.* [1989] have led to conclusion that the most cost-effective resource allocation requires an integrated approach which combines on-site and off-site measures. Applications of this in economic terms over regional-sized basins remain a challenge, quite often due to lack of sufficient information and large data and model uncertainties [*Ribaudo and Shortle*, 2001]. In an attempt to reduce phosphorus exports, *Faeth* [2000] tested several policy options including controlling point sources only, subsidy programs for agricultural conservation through enforcing best management practices, a point source performance requirement coupled with trading between point sources and nonpoint sources, and a trading program coupled with performance-based conservation subsidies to farmers, over three rivers in United States. He concluded that integrated programs, especially those coupled with trading were most cost-effective in improving water quality.

[8] The objective of this paper is to demonstrate, in a quantitative and spatially distributed manner, the proposition that to reduce suspended sediment loads in rivers for the least cost, using spatially resolved sediment budgets is superior to using estimates of the strength of sediment source(s), i.e., conventional soil erosion intensity and/or hazard maps. This is because in any large catchment a significant proportion of eroded sediment is deposited and does not contribute to annual downstream load. Deposition is variable across a catchment so some erosion sources have a much stronger connection to downstream sediment loads than others.

[9] We consider a large regional basin of $\sim 1.1 \times 10^6$ km^2, the Murray-Darling Basin in eastern Australia. The focus is on how the sediment budget can be used to prioritize investment in works toward meeting downstream targets for annual suspended sediment loads. Rather than provide estimates for meeting a particular target, we estimate the cost for reducing sediment in 5% increments until sediment loads prior to European settlement are reached. Using the cost functions we are able to show how to estimate the cost of achieving certain sediment reduction targets and conversely, identify what targets are achievable for a given level of investment. In the process, we derive maps of how

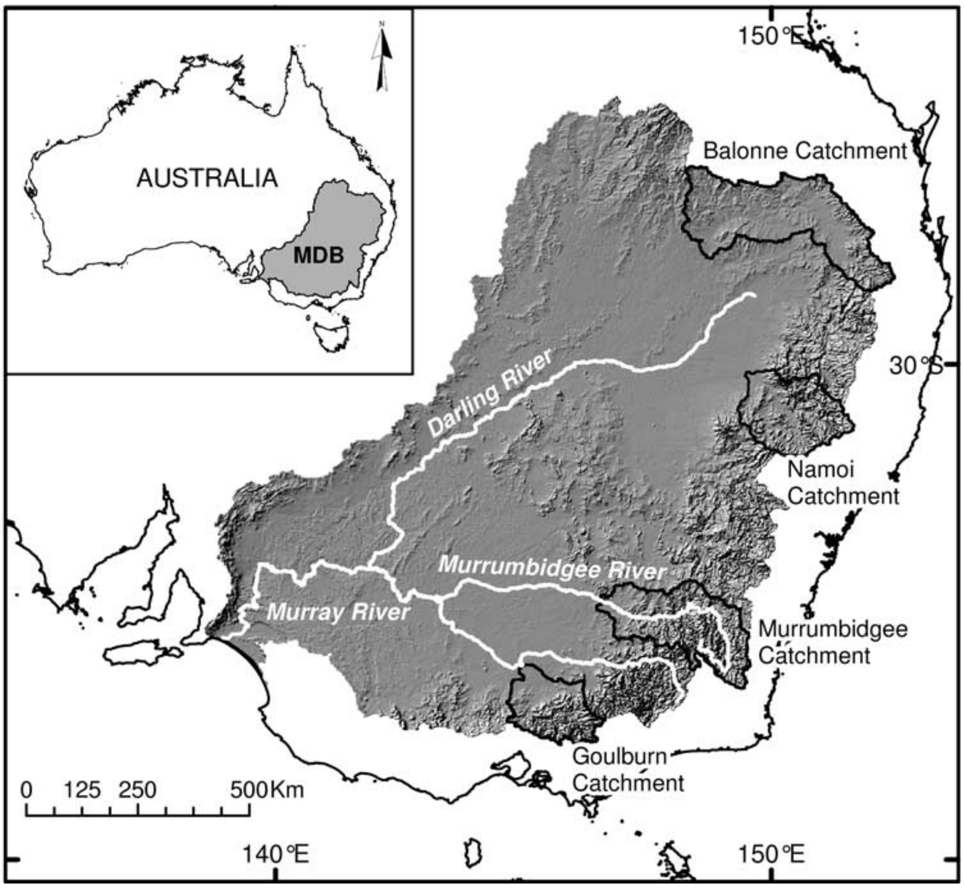

Figure 1. Location of the Murray-Darling Basin (MDB) in Australia. A hill-shaded version of the DEM in the background highlights the low relief of the MDB.

resources could be allocated spatially and against what type of management action. We simulate a number of management strategies. The strategies are derived from successive inclusion of more information from the sediment budget. The strategies also mimic some management strategies commonly employed in many regions in Australia and internationally. It is expected that different costs will be encountered to achieve the same target setting using different strategies. We can then determine the strategy which reduces suspended loads for the least cost (the most cost-effective strategy).

2. Methods

2.1. Study Area

[10] The Murray-Darling Basin (MDB) covers an area of 1.1 ± 10^6 km^2 (about 14% of Australia, Figure 1). The climate is temperate in the southeast, cool humid on the eastern uplands, subtropical in the northeast, and semiarid in the large western plains with annual precipitation ranging from 185 to 2500 mm. Topographically, upland catchments including the mountains of the Australian Alps and steep hills and colluvial slopes of the Great Dividing Range are mainly located in the southeast of the basin. Much of the rest of the basin consists of the Murray-Murrumbidgee Riverine plain, the Darling Downs, Darling River floodplain, Liverpool Plains and alluvial floodplains of other tributaries. The basin has the three longest rivers in Australia (Murray, Darling and Murrumbidgee).

[11] Development of the region for production has resulted in environmental stresses being placed on the river systems when compared to pre-European conditions [*NLWRA*, 2001]. Water quality has changed as a result of dry land and irrigated agriculture, e.g., increased number of days with higher than acceptable salinity concentration in the Lower Murray, river regulation creating cold water pollution affecting biological populations, and increased coarse sediment deposition. Flow regimes have been inverted (irrigation demands most water in summer from rivers whose dominant rainfall supply is in winter) to supply water for irrigation. Flows to the river mouth, lakes and estuary have decreased overall and no longer show the seasonal and decadal variations of the unregulated river. A combination of these activities has resulted in declines in some native fish populations. Temperature stratification of the water column, particularly in weir pools, combined with clear water as a result of slow flow and sedimentation of fine materials, and sufficient nutrient supply has led to increased frequency and extent of toxic algal blooms [*Webster et al.*, 2000].

[12] The predominant land use types in the basin are dry land grazing, winter cereal cropping and pasture rotation, open forest, and agroforestry. The basin contains around 75% of Australia's irrigated land and accounts for 40% of national agricultural production [*Australian Bureau of*

Statistics (*ABS*), 2002]. Two million people, about 10% of the national population, inhabit the basin.

2.2. Sediment Budget

[13] The investment prioritization analysis was carried out using the results of spatial modeling 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.*, 2001b]. 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, morphology and mapping of erosion processes [*Prosser et al.*, 2001b]. The application of SedNet to the MDB is reported in detail by *DeRose et al.* [2003], and only a summary is given here.

[14] The river network of the MDB was defined from the 9″ digital elevation model (DEM) of Australia (see M. F. Hutchinson et al., Upgrade of the 9 second Australian digital elevation model, http://cres.anu.edu.au/dem) and divided into around 10,000 river links, separated by tributary junctions or nodes. Each link of the river network has an associated drainage area of around 50–100 km^2. The river links are the basic elements of the sediment budget model. The area contributing to the link is referred as a 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 sheet wash and rill erosion (E_i) in the link element. Rates of each erosion process were estimated from detailed mapping of the controlling environmental factors. Bank erosion is a function of stream discharge, gradient, valley width and riparian vegetation [*Hughes and Prosser*, 2003]. Gully erosion was estimated using rule-based statistical extrapolation of air photo measurements of gully density [*Hughes and Prosser*, 2003]. Sheetwash and rill erosion was estimated using the RUSLE model [*Renard et al.*, 1997] parameterized using the DEM, daily rainfall data, remote sensing and soil property mapping [*Lu et al.*, 2003b].

[15] Only 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 ($hsdr_i$) for each link element. The approach we used to estimate hsdr relates long-term averaged sediment delivery ratio to the catchment temporal hydrological control through parameters of the statistics of rainfall, catchment topographic attributes, land use, vegetation cover and particle size distributions [*Lu et al.*, 2003a].

[16] The mean annual yield of suspended sediment from the link is the total supply of suspended sediment to the link (S_i, t yr^{-1}) less deposition on floodplains or in reservoirs (D_i, t yr^{-1}). Deposition in major reservoirs was modeled using the empirical Brune curve [*Brune*, 1953] and floodplain deposition was modeled by a conceptualization of sediment settling rate and residence time of floodwaters on the floodplain [*Prosser et al.*, 2001a, 2001b]. In summary the suspended sediment budget for a link is:

$$Y_i = S_i - D_i = T_i + I_i - D_i \qquad (1)$$

where T_i is the sediment supplied by upstream links, $I_i = E_i \times hsdr_i + G_i + B_i$ is the total sediment supply from the link element i and has the units of tons per year (t yr^{-1}).

[17] The mean annual delivery of sediment from a link element i to the sediment control location k (λ_{ik}, t yr^{-1}, the location at which reductions in sediment load are to be measured) is the sediment supply from the link element (I_i) multiplied by the sediment delivery efficiency through all river links along the route to k:

$$\lambda_{ik} = I_i \prod_{j=1}^{M_{ik}} \gamma_j \qquad (2)$$

where

$$\gamma_j = Y_j/S_j = 1 - D_j/S_j$$

where M_{ik} is the total number of river links along the route from link i to the sediment control location k. Essentially, γ_j is the probability of sediment passing through a river link j, as determined by the amount of deposition. If all probabilities are equal then contribution of a link element to the sediment control location k is proportional to the travel distance from the sediment control location k to the outlet of link element i. In reality, the probabilities are far from equal because deposition varies markedly through a river network. The total suspended sediment yield at the sediment control location k can then be calculated by:

$$T_k = \sum_{i=1}^{N} \lambda_{ik} \qquad (3)$$

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

[18] Gully and riverbank erosion contribute to bed load as well as suspended load in rivers, and both loads are modeled by SedNet. We consider only the suspended load budgets in this paper as that is the component of current primary concern for water quality. While the budget is expressed in terms of mean annual loads, the influence of extremes in flood behavior is incorporated by using modeled 100 y time series of daily flow to predict total floodplain deposition and sediment transport capacity across the time series [*Prosser et al.*, 2001b].

2.3. Selection of Sediment Control Locations

[19] Our sediment budgets show that most sediment is generated and transported from the upland catchments located in the east and north part of the MDB [*DeRose et al.*, 2003]. There are greater concerns over the possible consequences for this sediment on lowland rivers of the riverine plain and floodplains than on delivery to the ocean. Therefore assessment at the MDB outlet provides little information for sediment control through management of the deteriorated upland subcatchments. Instead, we selected sediment control locations using the following rules: (1) locations corresponded to the outlet of the Australian Water Resources Council [*AWRC*, 1987] basins; (2) only eastern, southeastern, and northern perimeter basins were used as they were identified as the major sources of sediment to the main channels; (3) the control location must lie on the last link of the tributary basin, not on the main channel; (4) in the case of the large river basins, the control location was set back from the basin outlet, where there was a topographic change from the dissected uplands to the riverine plain; (5) streams not contributing sediment to the main channel network of the Murray-Darling Rivers were excluded; and (6) the control locations are located upstream

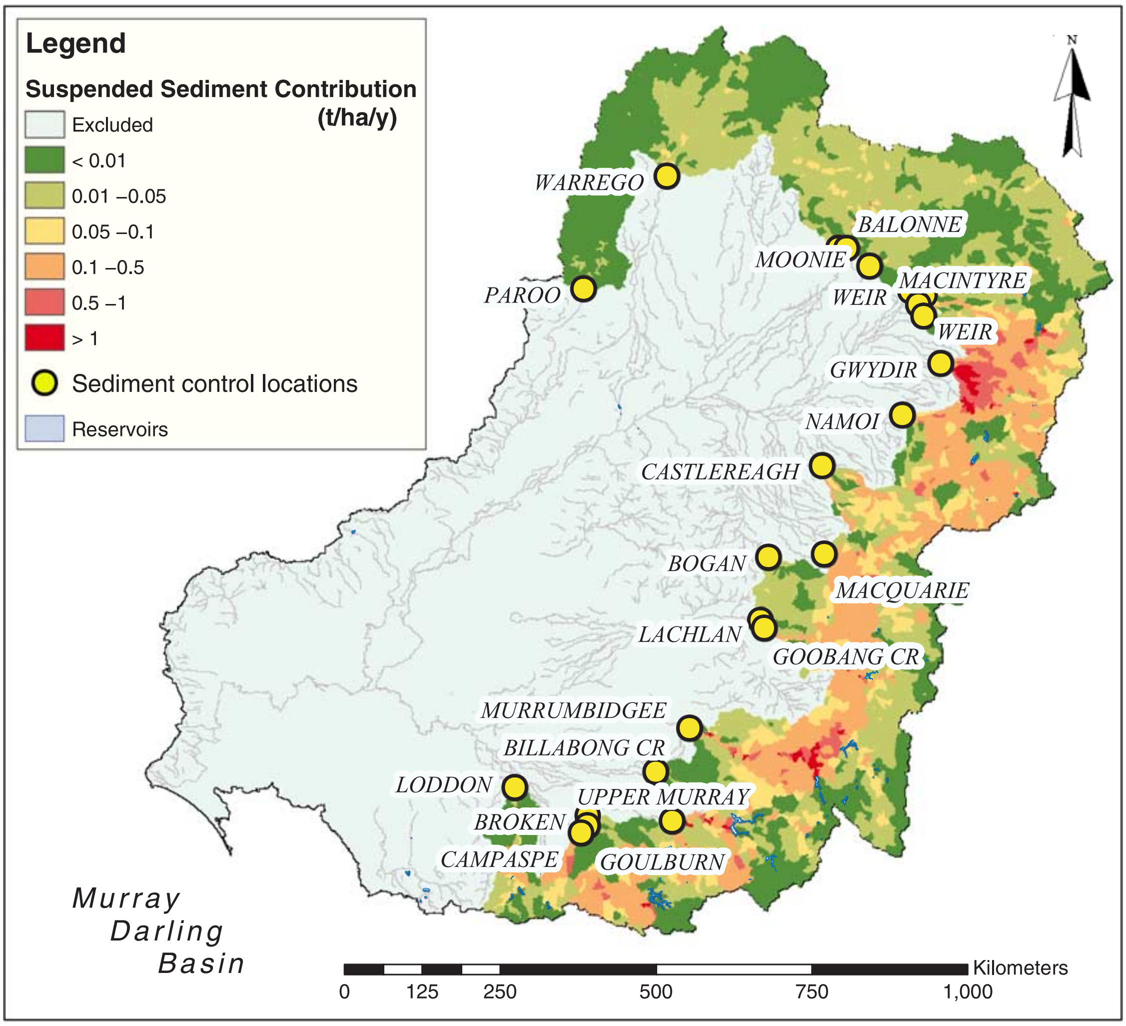

Figure 2. Specific sediment contribution (t ha^{-1} yr^{-1}) to control locations as estimated using SedNet for the major upland catchments. Sediment control locations used in this study are also shown.

of major reservoirs. The selected control locations together with the estimated specific sediment contribution (t ha^{-1} yr^{-1}) to those control locations using SedNet are shown in Figure 2. There are 23 sediment control locations and 3233 upstream link elements. Many of these coincide with places where catchment sediment targets are now being set.

2.4. Investment Prioritization Scenarios

[20] We defined four management scenarios (or strategies) which utilize the spatially distributed sediment information derived from our sediment budget model. As setting management strategies (or policies) often heavily depends on the level of sediment information available [*Faeth*, 2000], our management scenarios were tailored to gradually increase the level of sediment information. First, we considered sediment source strength (i.e., E_i, G_i, and B_i) only, then included the local delivery efficiency (i.e., *hsdr*), and finally larger-scale delivery (i.e., γ_i).

[21] Our first strategy (herein called scenario A) is random management, where parts of river basins and particular erosion processes were chosen at random for treatment. This is a first-come, first-served management strategy that has been commonly applied in the past [*Dickinson et al.*, 1990; *Carpentier et al.*, 1998; *Horan and Shortle*, 2001]. Random management was not merely a comparison datum but mimicked real strategies based on local incentives and other schemes such as ensuring any landholder who wishes to participate in erosion mitigation, for example, was encouraged to do so (C. Binning, Greening Australia, personal communication, 2003). In terms of policy design, such a strategy is also attractive due to its simplicity and low administration costs [*Ribaudo and Shortle*, 2001], especially where the pollutant export rates tend to be more or less uniform.

[22] Our second strategy (herein termed scenario B) prioritized expenditure on the areas with the highest erosion rates. This was not only a portion of the sediment budget but mimicked erosion hot spot policies which have been used in many countries to reduce erosion often with the assumption that they will be effective in reducing down stream loads [*Ribaudo*, 1992]. As a departure from conventional policies using this approach which tend to only include hillslope erosion, we included river bank and gully sources.

[23] The third strategy (herein termed scenario C) included the information in the budget on hillslope sediment delivery ratio. This means we acknowledged that a spatially variable

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 ton)	130
Riverbank (per ton)	34
Hillslope (per ton)	80
hsdr (per 1% of current *hsdr*)	9900

proportion of the material that was eroded on hillslopes each year was not delivered to the channel system and therefore does not contribute to downstream loads. We separate the channels within link elements from the channel system represented explicitly in the budget. This means that our hillslope sediment delivery ratio should not be considered as just transport to the edge of fields but transport to the main channel system (as described above and detailed by *Prosser et al.* [2001b]). This mimicked the strategies that have tended to be employed to deal with problems at large spatial extent [e.g., *Schleich et al.*, 1996; *Faeth*, 2000; *Gren et al.*, 2000, 2002]. These prior examples have not tended to distinguish between delivery ratios which describe transport to the channel system and those which deal with the transport through the channels. This becomes particularly important when considering large areas where the source of sediment and the location where the target is set are potentially far apart. Our fourth scenario (herein termed scenario D) is designed to deal with this case. We accounted for the series of deposition processes that may remove sediment and thereby reduce expected downstream loads. Investment was prioritized in areas and on the sources that were estimated, through the sediment budget, to contribute to downstream loads. The management practices simulated and their costs are described below.

[24] We hypothesize that each strategy will achieve reduction in suspended sediment loads at the control locations at different cost per increment of sediment reduction. The resulting costs may exhibit a different functional form across the range of percentage reduction from 0% to 100% or until it is equivalent to that under natural conditions. The strategy that produces the lowest cost consistently across a range of reduction percentages would be the most cost effective strategy for investment prioritization to control suspended sediment loads at the control locations. Computationally, we simulate the four scenarios as follows.

2.4.1. Scenario A

[25] Randomly select a link element and one of hillslope, gully, river bank or hillslope sediment delivery ratio. Reduce the chosen value by a small percentage (say 1%). This reduction is achieved by applying the appropriate management practice with its associated cost (Table 1). Reestimate the suspended sediment yield to the control location using equation (1) and accumulate the cost. Repeat the procedure until the required total percentage of suspended sediment reduction at the control location is reached. The procedure was iterated 10 times for each simulation to provide an estimate of variation with this algorithm.

2.4.2. Scenario B

[26] Select the erosion source type with the lowest unit cost and select the link element with the largest value among three erosion types (hillslope, gully, and bank). Reduce the chosen value by a small percentage (say 1%). Reestimate the suspended sediment yield to the control location using equations (1) to (3) and accumulate the cost. If the values of the selected erosion type are equal to their natural rates for all link elements, move to another erosion source type with the second lowest unit cost and repeat the procedure. Repeat the procedure until the required total percentage of suspended sediment reduction at the control location is reached. This strategy focuses on erosion “hot spots” at source level.

2.4.3. Scenario C

[27] Select the link element i with the largest value of total sediment export rate (t yr^{-1}) to the outlet of that link element. Calculate the cost C_{ij} of reduction of a certain erosion type or control option j, $j = 1$ (hillslope), 2 (hsdr), 3 (gully), and 4 (bank) by a certain percentage β (say 1%) for each link element i. Estimate the difference in suspended sediment load at its outlet by $\Delta I_{ij} = I_{i,old} - T_{i,new}$ due to the reduction. Calculate the suspended sediment delivery efficiency $e_{ij} = C_{ij}/\Delta I_{ij}$. Implement the reduction only for the erosion type or management options with the smallest e_{ij} only if it is larger than its natural rates. Repeat the procedure and accumulate the cost until the required total percentage of suspended sediment reduction at its outlet is reached. Reestimate the suspended sediment yield to the downstream sediment control location using equations (1) to (3) and accumulate the total cost. Repeat the entire procedure and accumulate the cost until the required total percentage of suspended sediment reduction at the control location is reached or the local export rates are equal to their natural rates. The strategy focuses on cost effectiveness at local link element level.

2.4.4. Scenario D

[28] Calculate the cost C_{ij} of reduction of a certain erosion type or control option j (same as that given in scenario C) by a certain percentage β (say 1%) for each link element i. Estimate the difference in suspended sediment load at control location k by $\Delta T_{ij} = T_{k,old} - T_{k,new}$ due to the reduction at link element i and due to reduction of sediment of j type, where both $T_{k,old}$ and $T_{k,new}$ are estimated using equation (3). Calculate the suspended sediment delivery efficiency $e_{ij} = C_{ij}/\Delta T_{ij}$. Implement the reduction only for the link elements and erosion types with the smallest e_{ij} only if it is larger than its natural rates. Repeat the procedure and accumulate the cost until the required total percentage of suspended sediment reduction at the control location is reached. This strategy includes all components of the sediment budget.

[29] We implemented the scenarios A to D for each five percent incremental reduction (5–100%) in suspended load from current conditions to pre-European. The units to which we applied the control strategies were the link elements ($\sim$50–100 km^2) as defined for the SedNet modeling of sediment budgets across the basin. The cost curves thereby derived consider the combined contributions of three erosion types.

[30] To derive the cost functions we summed the total expenditure for each five percent incremental reduction in suspended load from current conditions to pre-European.

2.4.5. Constraints

[31] Scenarios A to D described above share some common constraints. The constraints are (1) $\underline{T_k} \le T_k \le \overline{T_k}$, where $\underline{T_k}$ and $\overline{T_k}$ are the suspended sediment delivery

loads to the control location k at natural and current conditions, respectively, and (2) $\underline{X_i} \leq X_i \leq \overline{X_i}$ for any link element i, where X_i represents any type of erosion sources (sheet and rill, gully, and bank) or hillslope control option (in this case, *hsdr*). This means that, at each link element i, erosion reduction is only allowed to happen between its minimum rate $\underline{X_i}$ (assumed here to be that under natural conditions) and its current rate $\overline{X_i}$ for any type of erosion and hillslope sediment delivery ratio. We assumed a minimum $hsdr_i$ for all the link elements of zero.

2.5. Cost Estimation

[32] For a given link element, the costs involved to reduce sediment can be written as:

$$C_E = (E_{old} - E_{new})s_E \tag{4}$$

$$C_{hsdr} = \frac{(hsdr_{old} - hsdr_{new})}{hsdr_{old}} s_{hsdr} \tag{5}$$

$$C_G = (G_{old} - G_{new})s_G \tag{6}$$

$$C_B = (B_{old} - B_{new})s_B \tag{7}$$

where s_{E}, s_{hsdr}, s_{G} and s_{B} are the per unit costs for reducing hillslope sheet and rill erosion, sediment delivery ratio (per 1% reduction), gully erosion and bank erosion, respectively. The per unit cost of reducing erosion rate at the sources and local hillslope interception options (e.g., through reduction of hillslope sediment delivery ratio *hsdr*) were estimated by first identifying the primary management practices and the costs associated with the implementation of the management practices to reduce one unit of sediment generated. Management interventions considered to estimate the per unit costs include conventional fencing, tree planting, plant watering (for gully and bank erosion reduction), tillage/residue management on agricultural lands and cell grazing (for sheet and rill erosion reduction), and riparian revegetation near the stream network (for reduction of hillslope sediment delivery ratio). The average per unit costs of reducing erosion rate for three types of erosion sources and hillslope sediment delivery ratio are summarized in Table 1.

[33] The total cost for a link element can then be estimated by $C_E + C_{hsdr} + C_G + C_B$. Accumulating the cost for all link elements results in the total cost required for a certain amount of sediment reduction at control locations.

2.6. Optimization Using a Genetic Algorithm

[34] A spatial optimization formulation using a genetic algorithm was implemented to test how far the simulation scenarios depart from an optimal solution. We were only able to test this on selected areas within the basin because of the computational intensity of applying the GA to the whole basin. A second reason for formulating the GA was as a proof of concept for dealing with multiobjective problems, e.g., coinvestment for reduction of phosphorus and suspended sediment loads.

[35] To achieve the lowest cost for a certain amount of sediment reduction at each control location, the spatial optimization can be formulated as:

$$\begin{gathered}
\min \sum_{i=1}^{N} (\mathrm{C}_{\mathrm{E_i}} + C_{hsdr_i} + C_{G_i} + C_{B_i}) \\
\mathrm{s.t.}\, \underline{T_k} \leq T_k \leq (1-\alpha)\overline{T_k} \\
E_i \in \left[\underline{E_i}, \overline{E_i}\right], \quad \forall i \\
hsdr_i \in \left[\underline{hsdr_i}, \overline{hsdr_i}\right], \quad \forall i \\
G_i \in \left[\underline{G_i}, \overline{G_i}\right], \quad \forall i \\
B_i \in \left[\underline{B_i}, \overline{B_i}\right], \quad \forall i
\end{gathered} \tag{8}$$

where $C_{E,i}$, $C_{hsdr,i}$, $C_{G,i}$, and $C_{B,i}$, are the costs involved in controlling sediment by reducing hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion, respectively for link element i, α is the percentage of suspended sediment reduction (valued from 0 to 1 with 0.05 increment each time), and $\forall i$ means for any link element i. Other variables are the same as previously defined. The nonlinear relationships between T_k and the variables E_i, h_{sdri}, G_i and B_i (defined by our budget model, equations (1)–(3)) make equation (8) a nonlinear programming problem. As we are dealing with a large number of variables, instead of using traditional optimization solvers, a well-established genetic algorithm [*Koziel and Michalewicz*, 1998] was used to solve the above optimization problem.

3. Results

[36] *DeRose et al.* [2003] provided a critical appraisal of the quality of sediment budget results across the basin. In summary, we used three approaches to assess the quality of the sediment budget outputs. First, we compared directly measured and modeled data. Continent-wide our estimates of hillslope erosion were well correlated with the available plot measurements ($r^2 = 0.64$); our models of gully density fitted acceptably with mapped gully data ($r^2 \sim 0.7$); and our model of pre-European vegetation cover matched reasonably the remnant vegetation used as training data ($r^2 \sim 0.8$). Overall, where data were available for rivers (or sections thereof) across the MDB our estimates of suspended sediment loads were acceptable ($r^2 = 0.74$, see Table 2). Second, the use of a sediment budget framework means that all the inputs are balanced by stores or losses. Therefore predictions from one part of the budget help constrain and inform other parts. We set up a series of internal logic checks using the relationships between budget terms to alert us to anomalies. Third, comparison with measurements not explicitly in a sediment budget framework can provide insight. For example, radionuclide tracer studies previously carried out at various locations across the basin [*Wallbrink et al.*, 1998; *Olley and Scott*, 2002] showed consistency with our estimates for the south of the MDB but indicated that the model may underestimate river bank and/or gully erosion in some regions in the north. Therefore what appears initially to be a model that is somewhat imprecise was made more exact and testable using several types of information.

[37] The suspended sediment budget is a framework, based on fundamentals of geomorphology, for organizing

Table 2. Comparison of Modeled and Measured (Area) Specific Suspended Sediment Loads for Rivers of the MDB[a]

Site	Measured, t km^{-2} yr^{-1}	Modeled, t km^{-2} yr^{-1}
Lake Eildon at Outflow Gauge	2	1
Loddon River at Kerang	2	4
Campaspe River at Rochestor	3	14
Broken River at Gowangardie	5	10
Goulburn River at Shepparton	6	15
Lancoorie (Lake)	7	9
Broken Creek at Rices Weir	8	2
Cotter River	11	5
Delatite River at Tonga Bridge	11	31
Murrumbidgee River at Gundagai	17	21
Ovens River	20	17
Murrumbidgee River at Wagga	22	23
Yass River	25	38
Kiewa River	29	33
Burrinjuck (lake)	32	29
Lachlan at Wyangala	59	57

[a] Data are mostly available from the southern portion of the basin. A linear fit to these data is modeled = 1.07 × measured with an $r^2 = 0.74$.

spatially variable erosion, transport and deposition processes. We have expended a great deal of effort on estimating the sediment sources (hillslope, gully and river bank), their propagation through and deposition within the channel network. It is only from the combination of these factors that the coherent patterns in suspended sediment delivery to control locations emerges (Figure 2). These spatial patterns are not evident in, or dominantly determined by, any one of the input or transport information layers. Some regions show little spatial variation, particularly in the north of the basin. By contrast, strong patterns with large magnitude of delivery are evident in the east, e.g., Gwydir, and southeast, e.g., Murrumbidgee.

[38] Figure 2 can be aggregated to produce a cumulative area contribution function (Figure 3). This was constructed by ranking link elements in order of decreasing suspended sediment contribution and then comparing the cumulative total contribution against the cumulative percentage total area occupied. We define the degree of curvature of this relationship as our measure of the internal heterogeneity of the contributing sediment sources. The more heterogeneous the contributing sources the more convex the function. For example, an area which is dominated by contributing hillslope erosion at similar rates in most locations would be considered relatively homogeneous. In such a case, the cumulative area contribution curve would be approximately linear. In contrast, a heterogeneous area might have one or two subareas with gully erosion contributing the majority of the downstream load. Visually, heterogeneous areas exhibit strongly delineated regions in the contributing sources maps.

[39] Heterogeneity is an indication of the likely benefit to be gained from prioritizing investment in controlling contributing sources to reduce suspended sediment loads. For example, Figure 3 shows that 75% of the suspended sediment load is produced from only 20% of the total catchment area. This illustrates the potential power of the contributing sediment source map. There is little reason to expect that, in a large catchment, a similar ordering function of one or other erosion estimate would relate to effectiveness of prioritizing investment for controlling downstream loads.

[40] 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 Figure 1. Table 3 provides a summary of the erosion and delivery status of each of the catchments (as well as the basin as a whole), i.e., catchment area, base and natural erosion rates, amount delivered to the control locations from each erosion type, and, for *hsdr*, the range, maximum, minimum, mean, median and standard deviation of the link elements. They are also summarized in terms of the curvature of the accumulative area contribution curves in Figure 4; Murrumbidgee has the greatest heterogeneity followed by Goulburn, Namoi and then Balonne.

[41] In the Goulburn the sources of sediment are predominantly from riverbank and gully erosion (Figure 4a). In the Murrumbidgee, river bank and hillslope erosion dominate contributions to downstream loads (Figure 4c). In the Namoi and Balonne catchments, the contributing sources are predominantly from hillslope erosion (Figures 4b and 4d).

[42] Each of the four scenarios was run for each of the four example catchments to (1) determine the most cost effective strategy, (2) explain how cost functions are affected by the source of contributed sediment, (3) visualize the effect of the heterogeneity of contributing sediment on the pattern of expenditure for the most cost effective strategy, and (4) examine the effect of variable contributing source heterogeneity on cost effectiveness.

[43] Figure 5 shows the cost curves derived for each scenario for the four example catchments. For all cases, scenario D is the least cost for a given reduction for all or most levels of reduction. We term this the most cost-effective strategy. Scenarios B and C are not necessarily better than random selection (scenario A) (e.g., Figures 5b and 5d).

[44] When the sources of contributed sediment are predominantly sheet and rill erosion (Namoi and Balonne catchments, Figures 5b and 5d) scenarios which only consider the erosion source rates (with and without local sediment delivery efficiency) can result in spending more

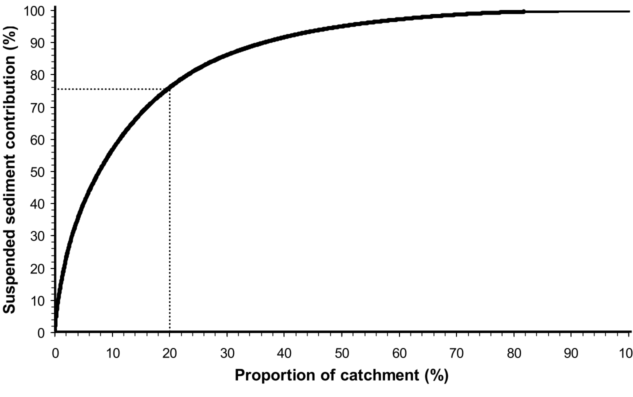

Figure 3. The accumulative area contribution of suspended sediment across the MDB derived using the contribution information and control locations shown in Figure 2.

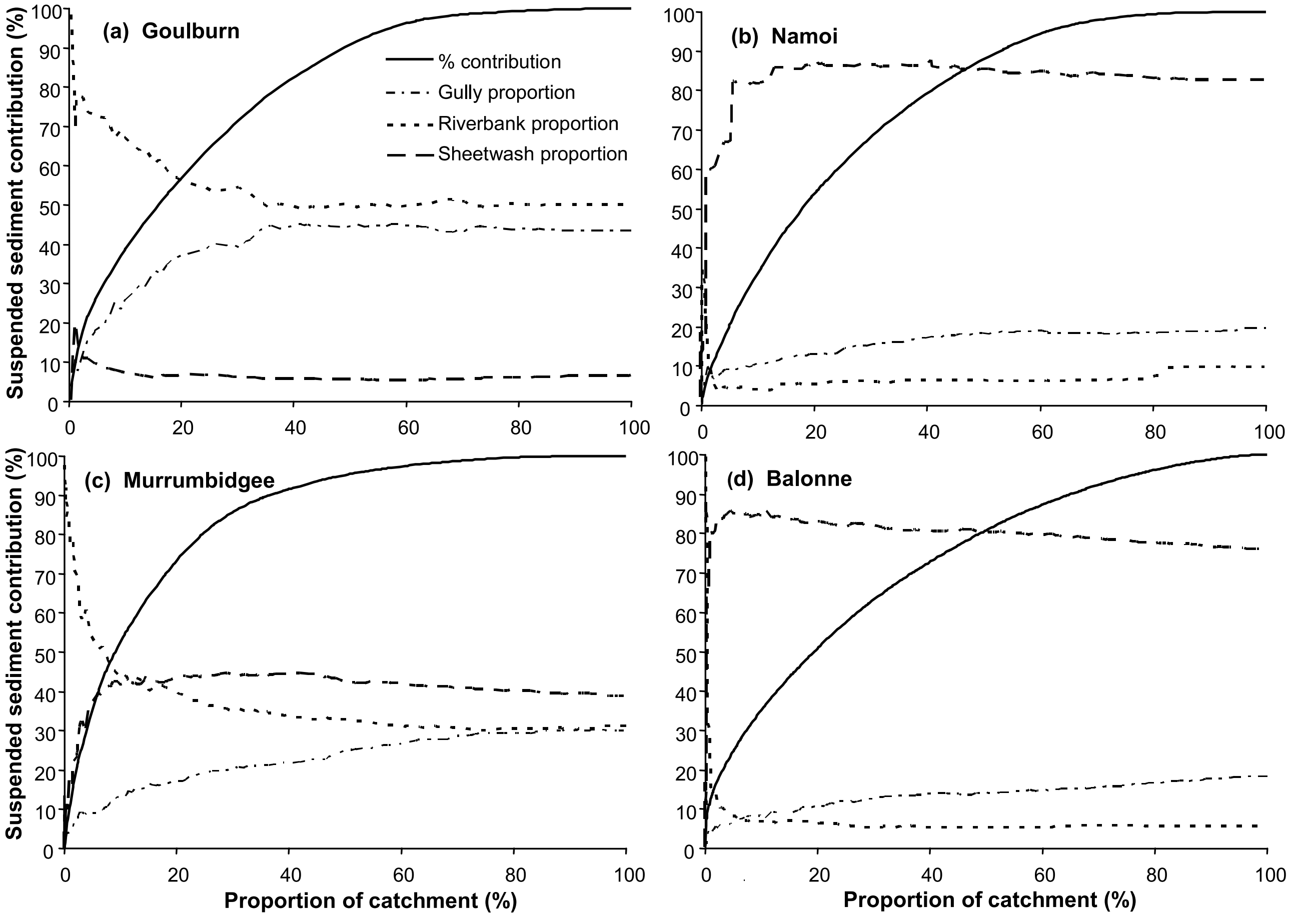

Figure 4. Estimations of accumulative area contributions of suspended sediment in the (a) Goulburn, (b) Namoi, (c) Murrumbidgee, and (d) Balonne catchments. The relative proportions of suspended sediment contribution from each of the main erosion processes are also shown. The locations of the four catchments can be found in Figure 1, and the spatially distributed sediment contribution is given in Figure 2.

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 predominantly gully and river bank (Goulburn catchment, Figure 5a), scenario A is the least effective. However, scenarios B, C, and D do not show the same magnitude of difference to one another as is the case for Namoi and Balonne catchments that are dominated by hillslope sheet and rill erosion (Figures 5b and 5d). In the budget model we assume that all river bank and gully erosion is delivered directly to the stream network. In reality, we expect complete delivery from river banks but delivery efficiency from gullies to be less than 100%. Therefore the cost curves represent one extreme. However, delivery efficiency of suspended sediment from gullies will generally be larger than from hillslopes so that this uncertainty will not significantly alter the results. For catchments with mixed

Table 3. Summary of Soil Erosion Rates and Hillslope Sediment Delivery Ratio for the Four Test Catchments (Figure 1) and the Catchment Area Above Each Control Location (Figure 2)[a]

		Sheet and Rill Erosion Rate, 10^3 t yr^{-1}			Hsdr, %				Gully Erosion Rate, 10^3 t yr^{-1}			Bank Erosion Rate, 10^3 t yr^{-1}			Annual Sediment Yield, 10^3 t yr^{-1}	
Catchment	Area, 10^3 km^2	Base	Natural	Delivered	Range	Mean	Median	SD	Base	Natural	Delivered	Base	Natural	Delivered	Base	Natural
Goulburn	20.2	426.1	52.9	11.7	0.1–62	13	8	14	607.3	0.0	86.4	594.3	29.0	86.4	203.6	3.7
Namoi	28.8	21627.2	271.2	249.7	0.1–56	11	8	9	1231.0	0.0	80.2	496.5	12.8	80.2	372.9	1.1
Murrumbidgee	37.1	8785.2	380.2	220.4	0.1–71	12	8	11	1264.3	0.0	121.8	1310.3	58.6	207.3	549.4	5.7
Balonne	53.5	19505.5	345.7	71.1	0.7–55	6	4	7	628.2	0.0	24.8	191.1	6.5	14.4	110.4	0.6
All	398.8	127764.9	6109.9	1620.0	0.1–70	8	5	9	9432.0	0.0	863.8	6478.8	266.9	889.4	3373.1	29.4

[a] Base is erosion or sediment yield rate under current conditions; natural is erosion or sediment yield rate under natural conditions; delivered is delivery rate to control locations under current conditions.

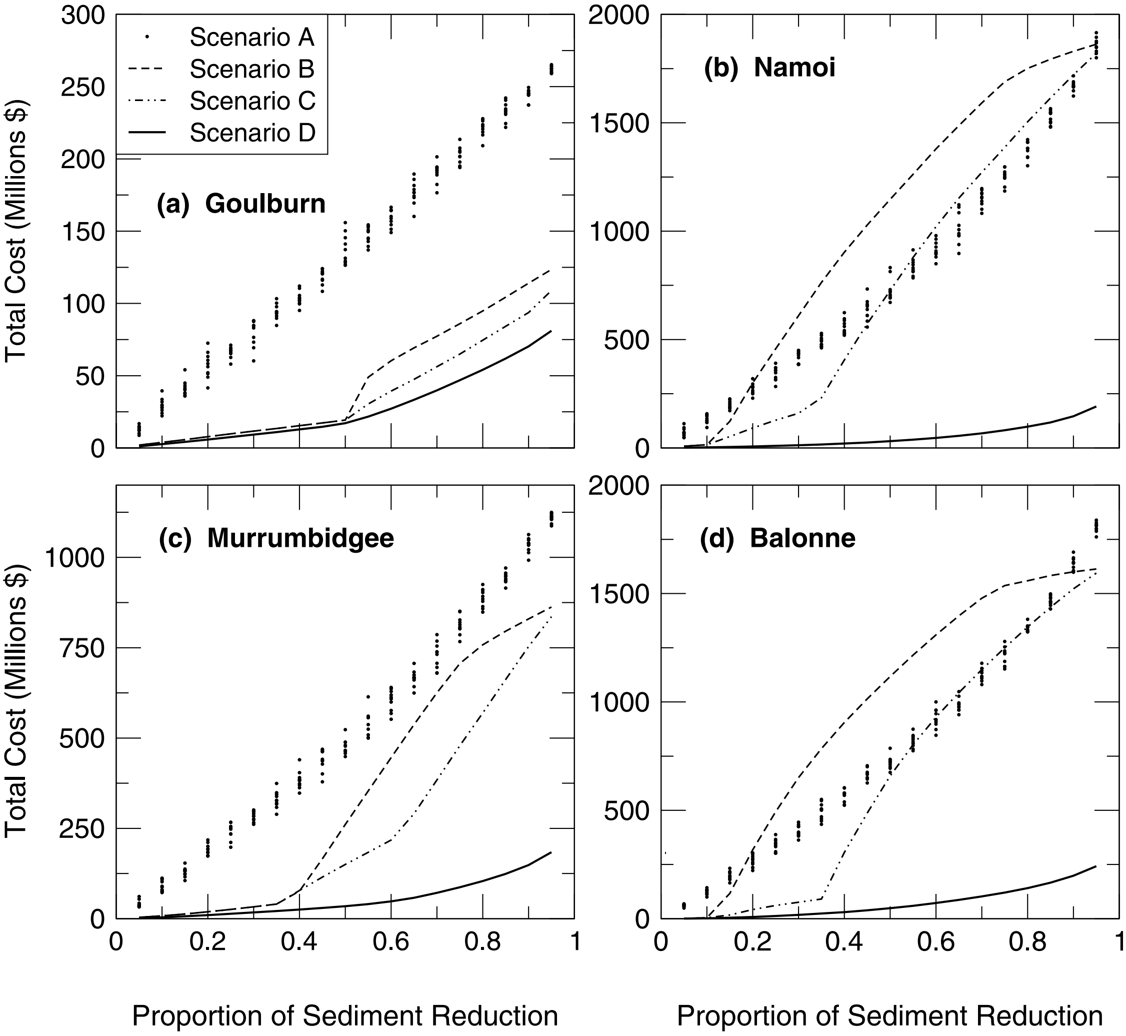

Figure 5. Cost versus sediment reduction curves (cost curves) for the four example catchments shown in Figure 1.

sediment sources, the relative differences between scenario D and the other scenarios often lie between the two extreme cases (Goulburn and Namoi catchments). However, it is more difficult to generalize the relative differences among scenarios A, B, and C because of the relationship between the relative magnitudes of sources and their cost per ton of reduction (Table 1).

[45] Maps can be produced from each scenario of total expenditure, reductions of hillslope erosion, hillslope sediment delivery ratio (where considered), gully erosion and bank erosion. Figure 6 shows the most cost effective strategy (scenario D) for a 70% reduction in suspended sediment loads at the catchment outlet. The Murrumbidgee catchment (Figure 6, left) has a greater concentration of proposed expenditure than the Balonne catchment.

[46] We looked at the relationship between contributing sediment heterogeneity and cost effectiveness 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 subnodes. The 10–20 subnodes were arbitrarily chosen along the major tributaries within each catchment. Each subnode receives sediment from around 30–50 upstream link elements and the aim is to reduce the total load summed across all the subnodes. There are some link elements that directly contribute to the catchment main control locations rather than any subnode. We treated these link elements as an additional subcatchment. In each case we used scenario D.

[47] Figure 7 shows that total expenditure by setting targets at subnode level is higher than by treating the catchments as a whole, for all percentage reductions. This is consistent with previous findings [e.g., *Schleich et al.*, 1996]. Balonne, the largest catchment, has the least difference between the two cost curves and Goulburn, the smallest catchment, shows the greatest response. The heterogeneity of the catchments (as expressed through Figure 4) is consistent with the degree of change in the cost curves for Balonne, Namoi and Murrumbidgee but does not explain the large effect for Goulburn.

[48] When dealing with large areas it is likely that there will be a range of stakeholders with differing and potentially conflicting objectives. There may also be a variety of funding sources. One common configuration is local committees responsible for individual catchments and a body with overall responsibility. We use this example to demonstrate

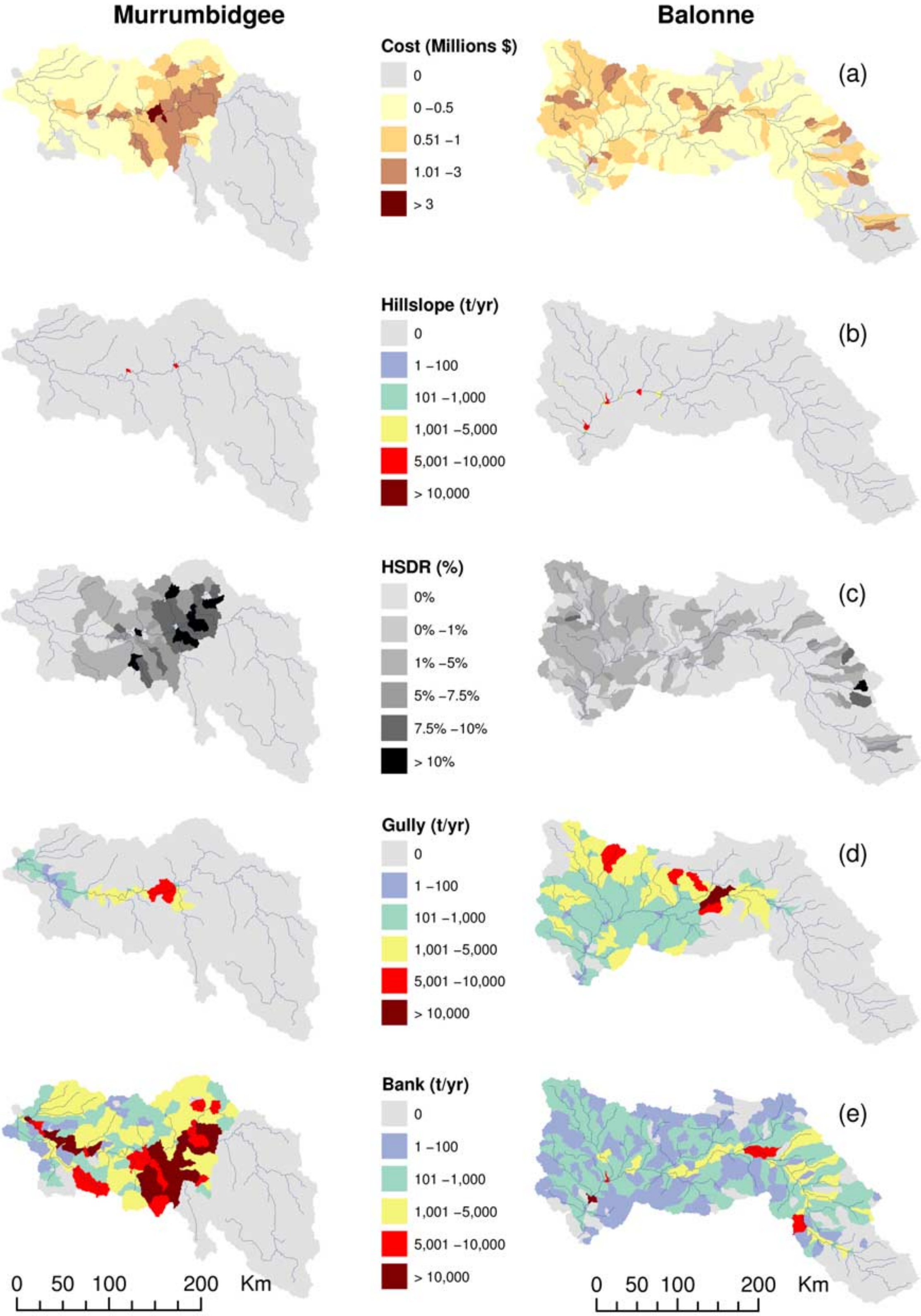

Figure 6. Spatial distribution of investment to achieve a 70% reduction in suspended sediment with the control location set at the catchment outlet. Two catchments are shown: (left) Murrumbidgee has greater heterogeneity of spatial distribution of sediment contribution to the control location than (right) Balonne. (a) Total expenditure, (b) hillslope erosion reduction (in difference, the same hereafter), (c) hillslope sediment delivery ratio reduction, (d) gully erosion reduction, and (e) bank erosion reduction.

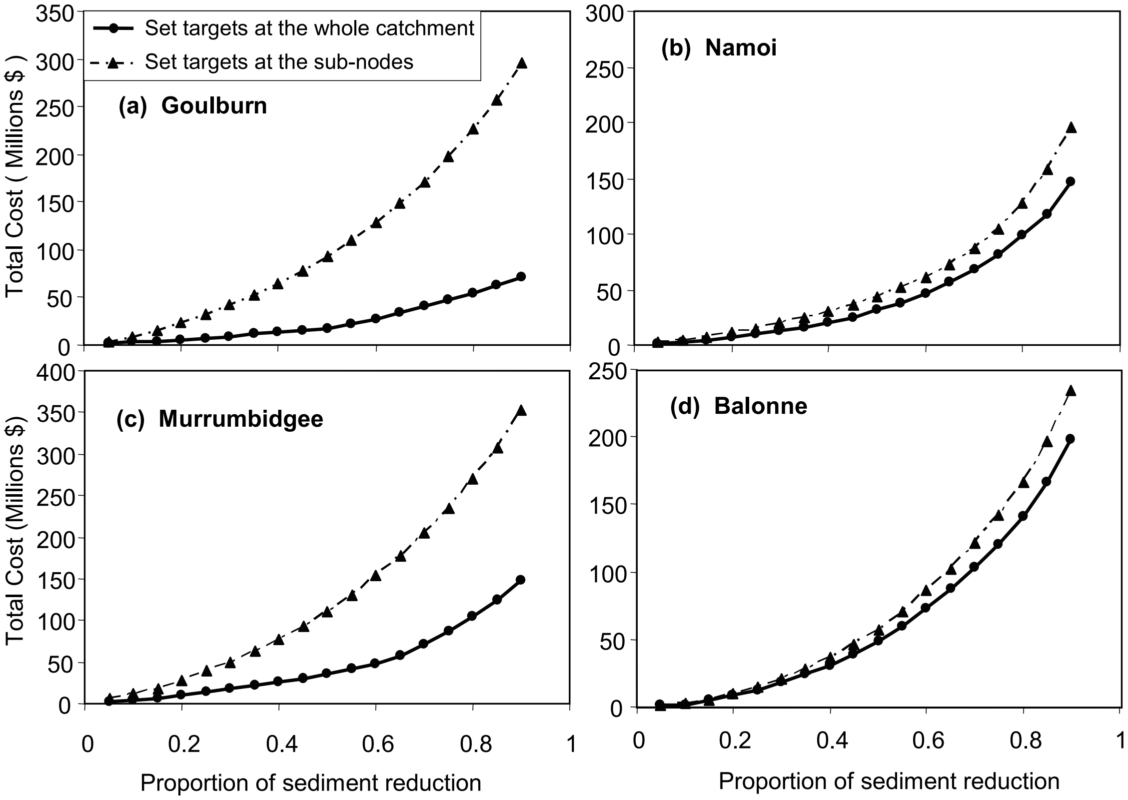

Figure 7. Comparison of cost curves when control locations for suspended sediment targets are set at subnodes defining subcatchments within the catchment and at the catchment outlet for (a) Goulburn, (b) Namoi, (c) Murrumbidgee, and (d) Balonne catchments.

that meeting the different objectives may call for different levels of expenditure. First (case 1), we assume that the objective of regional groups is to achieve the greatest decrease in suspended sediment loads in their catchment for the least investment. Investment is prioritized with respect to the outlet of their particular catchment. Second (case 2), we assume that the objective is to achieve the greatest decrease in suspended sediment loads anywhere in the basin for the least investment. Investment is prioritized with respect to all catchment outlets. Case 1 reduces sediment loads at all control locations and results in more diffuse expenditure patterns than Case 2 (Figure 8). The cost curves (Figure 9) show that this diffuse expenditure results in less reduction in sediment loads for a given level of investment.

[49] Table 4 shows the percentages of expenditure for cases 1 and 2 to achieve a 50% load reduction. The percentages of expenditure for reducing hillslope erosion and hillslope sediment delivery ratio are more or less the same. About half the expenditure should be on reducing *hsdr*, which suggests that sediment control through deposition is a desirable proposition. There is a shift of ~15% of the expenditure from gully to bank erosion for case 2. Overall, case 2 results in 25% reduction in total expenditure for the same level of sediment reduction. Such an analysis assists a body with responsibility over the entire area to differentiate requests for funds from each region according to the overall benefits rather than just the benefits to each local catchment. If regional groups are dealing with multiple funding sources, the analysis focused on their needs can help estimate a target level of investment that needs to be raised from the various sources. It is not possible to make a judgment as to which case is "best" because the value of treating all catchments or focusing attention on fewer is a societal and/or policy decision.

[50] We used the four test catchments to compare our most cost effective strategy with a formal optimization using a genetic algorithm (GA). Figure 10 shows the relative difference between the GA and scenario D for the example catchments. Scenario D produces similar results to those from the GA with relative differences within ±5% (much larger differences were obtained when compared with other scenarios) for the majority of the range of reductions. The negative relative differences suggest that scenario D sometimes performs better than the GA. We also checked this against other catchments with mixed erosion types and found similar results. The GA does not appear to perform as well in the Goulburn catchment as the others. The reason for this is unclear. Compared with the GA, scenario D is computationally far less intensive and can be applied to a larger area with many more link elements. However, the optimization procedure has potential for application to problems of more complexity that involve multiple targets or objectives. An example might be finding synergies and trade-offs between sediment and nutrient control.

4. Discussion

[51] Our study reveals some issues associated with management of sediment sources and their delivery to control locations. For example, under the most cost effective

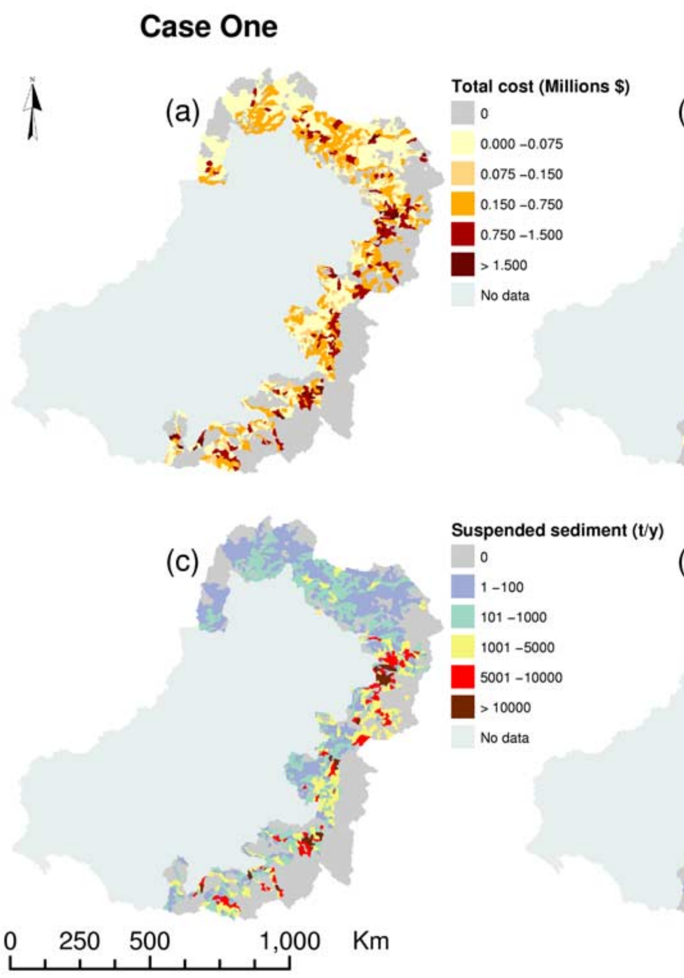

Figure 8. Spatially distributed investment prioritization across the MDB. (left) Prioritizing across all control locations (see Figure 2) and (right) treating each control location independently. (a and b) Total expenditure and (c and d) reduction in suspended sediment contribution.

scenario, there is greater expenditure in hillslope sediment delivery ratio (*hsdr*) than reducing rates of sheet and rill erosion (Figure 7). This reflects that trapping of sediment before it enters waterways requires less cost outlay than managing large areas of uplands. If the result that greater expenditure in control of *hsdr* is interpreted as a preferred strategy, it is predicated on the assumption that achieving downstream suspended sediment targets is more important than preserving the soil on-site for productivity reasons. Alternatively, we might interpret these data as providing a guide as to how much additional profit the lost soil would have to provide to make an argument for controlling source rates. This could be included in the analysis by reducing the cost of the latter. A second consideration in deciding whether augmentation of *hsdr* is preferred is the effectiveness of the measures we have simulated. Under average conditions, control measures for *hsdr* e.g., riparian or hillside buffer strips, are likely to be effective [*Castelle et al.*, 1994]. In environments dominated by extreme events with large suspended sediment loads, it is important that the capacity of the control technique is sufficient (appropriate buffer width and suitable vegetation [*O'Laughlin and Belt*, 1995]).

[52] The use of a spatial sediment budget (sources, transport and storages) and explicit mapping of the contribution of sediment to control locations provides a rational basis for investment prioritization. In previous work using a

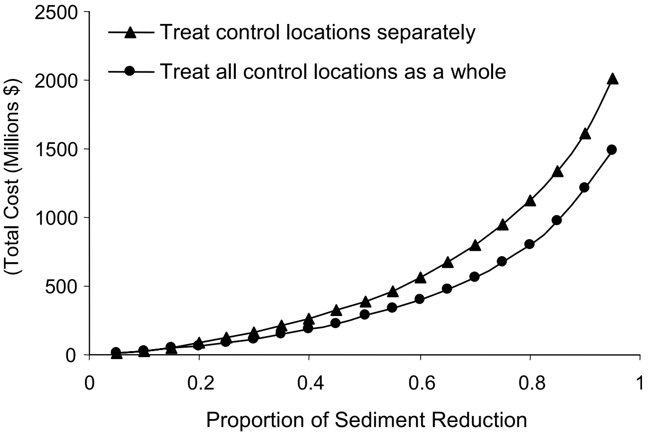

Figure 9. The cost curves for the MDB using both cases presented in Figure 8.

Table 4. Percentages of Expenditure for Treating the 23 Sediment Control Locations Separately (Case 1) and Together (Case 2) for 50% Load Reduction

	Hillslope Sheetwash and Rill Erosion	hsdr	Gully Erosion	River Bank Erosion
Case 1	0.7	54.4	16.3	28.5
Case 2	0.8	56.7	1.5	41.0

sediment network model, *Gianessi and Peskin* [1981] only included large rivers and ignored many smaller streams and water bodies such as reservoirs and lakes. Their sediment sources were estimated based on administrative elements such as agricultural production areas instead of hydrological catchments. Their model did not consider the deposition processes and they speculated that consequently this could result in substantial overestimation of the amount of sediment reaching waterways. Compared with *Gianessi and Peskin* [1981], we recognize the major sources of sediment and the processes of deposition between the sources and the target measurement locations. We have demonstrated that investment can be more efficiently prioritized than if only part of the sediment budget is represented. It is a justifiable extrapolation that mapping of the strength of sources of other diffuse pollutants, e.g., nutrients, will be similarly constrained as the basis of investment prioritization and policy simulation. It is preferable and tractable to map the connections between the sources and the target delivery locations. If such connections are not made, simulation and policy experimentation may be conducted in situations where the initial error (whose magnitude remains unknown) is greater than the differences between treatments. Failure to take into account the connection between source and target location and its spatial distribution will lead to unknown and possibly large errors.

[53] *Dickinson et al.* [1990] examined four scenarios for targeting erosion control at small scale considering one type of sediment source. They concluded that all scenarios will be more effective than random management. Such a general conclusion should be treated with caution. Our budget approach shows that it is possible that some forms of prioritization, if based on a false premise, can lead to greater expenditure than random management.

[54] It is widely reported that the cost effectiveness of investment prioritization increases as catchment area increases. A common explanation is that increasing the area increases the heterogeneity which results in cost savings because there are more options for investment. Conversely, as area is reduced the optimum resource allocation is more costly because more constraints are introduced. Our analyses of the four catchments within the basin followed this expectation, i.e., when we looked at subnodes within the catchment the cost was greater for all levels of reduction. However, the difference in area of the individual catchments was not a good indicator of the magnitude of the difference in costs. This is because the internal heterogeneity is not primarily related to the size of the catchment rather it is related to the sediment source, transport and deposition characteristics. Heterogeneity cannot be inferred from catchment area. For three of our four test catchments the curvature of the accumulative sediment delivery function was consistent with the degree of change in cost effectiveness. The Goulburn catchment was different because it has only minor hillslope erosion (Figure 4) which is the most costly form to control. Therefore in some cases we need to know the detailed nature of the heterogeneity to complement the characterization from the accumulative area curves. By carrying the analysis beyond the sediment budget and through a resource allocation prioritization exercise these details are incorporated into the results. It was necessary to couple the spatial sediment budget results to the investment prioritization analysis to achieve this.

[55] The sediment budget allows us to compute directly a solution for allocation of resources which is comparable to a formal heuristic approach, our optimization with GA formulation. The decision as to which control measure is chosen is based on cost. Commonly, catchments are managed for a range of objectives. Therefore the optimum approach cannot often be formulated intuitively or exactly (as we did with our scenario D). Such a solution can be found using optimization techniques that can search through a large number of management scenarios from which the most effective is chosen. With some improvement, our optimization using GA procedure has the potential for use in such situations, e.g., trading off between on-site productivity losses and downstream impacts or trading off sediment and nutrient control.

[56] There are several aspects of the estimation of cost which are worthy of further study. The estimation of unit costs used here is similar to the direct compliance costs approach [*Ribaudo and Shortle*, 2001], in which only the resources directly devoted to sediment control are considered. Other costs include: changes in the farmer's choices of what to produce, the selection of production processes and inputs as a result of trying to reduce compliance costs, input and output price changes resulting from changes in market conditions, and social costs of monitoring, enforcement and administration [*Ribaudo and Shortle*, 2001]. In a recent survey of previous studies on agricultural pollution control, *Horan and Shortle* [2001] highlighted that private control on costs and cost uncertainty were rarely considered, especially at the spatial scale comparable to that of our study. This is primarily because information needed to

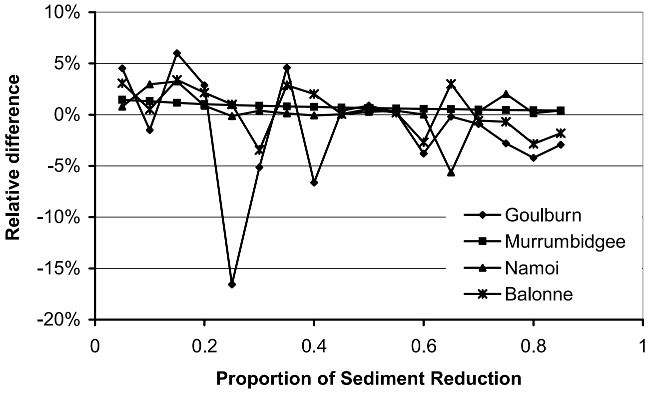

Figure 10. Relative difference between the total costs using the full sediment budget (scenario D) and the genetic algorithm optimization. The relative difference is calculated as $100\ (\mathrm{Cost}_{\mathrm{Scenario\ D}} - \mathrm{Cost}_{\mathrm{GA}})/\mathrm{Cost}_{\mathrm{Scenario\ D}}$. The catchments are the same as those shown in Figure 1.

establish empirical cost relationships is often only available for small areas. Potentially, the cost component in this study could be enhanced by coupling or otherwise integrating results from an explicit economic model [*Ribaudo and Shortle*, 2001].

[57] Several issues of significance remain to be dealt with. We have not dealt with temporal variation in either exploitation of opportunities for targeting or the success and time course of response to management actions once taken. The imperfect uptake of management by recalcitrant landholders (or landholders who see insufficient incentive in participating) is not examined. While it is acknowledged that decision making generally attempts to identify and reconcile multiple objectives dealing with social, political, environmental, ecological and economic issues, the cost effectiveness analysis proposed in this study only addresses a narrowly simplified objective concerned with suspended sediment control at specific locations. Within a broader multicriteria analysis framework, some of the "economically optimal" outcomes may be further constrained or rejected for social or political reasons or for other realities. By combining economic efficiency analyses and biophysical information, the investment prioritization presented in this study provides useful guidance relating to tradeoffs and thereby further aids to the development of environmental policies for agricultural pollution control [*Horan and Shortle*, 2001].

[58] The results presented here should not be taken as suggestions for management action at field to small catchment scales. The whole-basin sediment budgets that underpin this analysis are of insufficient resolution, input data quality and therefore output certainty for implementation of specific management interventions. The basin-wide data are suitable for differentiating relative investment across broad regions to support policy decisions on allocation of resources, for example. We suggest that for decisions regarding on-ground action, these prioritization techniques can be applied locally if they are supported by budgets based on higher resolution and superior data quality inputs and more detailed information on management practices.

5. Conclusion

[59] We used a spatial budget of annual suspended sediment loads as the basis for studying the costs of various strategies to reduce downstream loads. We proposed a range of investment prioritization scenarios which successively included more of the information in the budget. This enabled us to demonstrate that a spatially distributed sediment budget approach provided a rational basis to determine a least cost strategy for sediment control. We showed 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 were shown to be more costly than considering the linkages between sources and downstream loads. In some cases, focusing only on source rates can be more expensive than random allocation of funds.

[60] We used the cost curves from the most cost-effective scenario to compare the effects of catchment area and heterogeneity of the contributing sediment source. Of four test catchments, of considerable area (~20,000–54,000 km^2), we found that all catchments showed a response to breakup by area, i.e., it was more efficient to invest without breakup, as expected. The largest catchment showed the least response and the smallest the greatest response. The order of response was more consistent with the heterogeneity of the contributing sediment sources. This was characterized by the curvature of a function describing the relationship between the proportion of sediment delivered to a control location and the area of the contributing sources. This function was only available through the spatial sediment budget exercise.

[61] **Acknowledgments.** This study was partially funded by the Murray Darling Basin Commission (MDBC) under project D10012. This work was supported and guided by a Steering Committee, and Lisa Robbins, Scott Keyworth and Sharon Davis of the MDBC. We thank Greg Cannon and Tristram Miller for their technical assistance and B. Croke, ANU, for hydrological regionalization for the sediment budgets. Data for cost estimation were kindly supplied by Goulburn-Broken Catchment Management Authority, Australia. We also would like to thank Elisabeth Bui in CSIRO Land and Water for fruitful discussions. We are grateful for the constructive input from the anonymous referees.

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R. DeRose, CSIRO Land and Water, Canberra, ACT 2601, Australia.

H. Lu, Institute of Theoretical Geophysics, University of Cambridge, Cambridge CB3 OWA, UK.

C. J. Moran, Centre for Water in the Minerals Industry, University of Queensland, Brisbane, Queensland 4072, Australia. (chris.moran@uq.edu.au)

I. P. Prosser, Land and Water Australia, Canberra, ACT 2601, Australia.