Spatially Distributed Investment Prioritization for Sediment Control in the Murray Darling Basin

Report G to Project D10012 of Murray Darling Basin Commission: Basin-wide Mapping of Sediment and Nutrient Exports in Dryland Regions of the MDB

By Hua Lu, Chris Moran, Ronald DeRose and Greg Cannon
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CSIRO Land and Water

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Authors

Hua Lu, Chris J. Moran, Ronald DeRose and Greg Cannon
CSIRO Land and Water, PO Box 1666, Canberra, 2601, Australia.
E-mail: hua.lu@csiro.au
Phone: 61-2-6246-5923

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Executive Summary

The investment prioritization approach set out in this study suggests potential strategies identifying cost-effective interventions to control fine sediment loads across the Murray-Darling Basin. The primary aim is to develop tools that can inform judgments relating to the most cost effective means of controlling fine sediment loads. More specifically, it aims to: 1) identify priority management areas; 2) estimate sediment control expenditures at different sediment reduction levels; and 3) allocate the funds and achieve sediment reduction in a cost-effective way. It utilizes spatially-distributed information of sediment sources and transport processes derived by basin-wide sediment budget modeling using SedNet (Prosser et al. 2001; DeRose et al. 2003).

There are three major steps in this study. First, we established a number of sediment control locations to which sediment is transported. Secondly, several investment strategies were proposed and evaluated in terms of sediment control. The strategies include random selection, three forms of targeting and optimization based on a genetic algorithm. Thirdly, results of the spatially distributed soil erosion (Lu et al. 2003a; Hughes and Prosser 2003) and sediment budget study (DeRose et al. 2003) were incorporated to consider the local effects of erosion and the downstream propagation of the eroded sediment.

Four types of land management scenario were evaluated in 23 upland river basins of the MDB. The criterion of the evaluation was the monetary cost to reduce sediment loads where upland rivers discharged to lowland areas of the Basin. Costs were obtained for a range of land management options. For each scenario in each river basin a continuous function of cost and reduction in sediment load was produced. The four scenarios used were:

1. Random management, where parts of river basins and particular erosion processes were chosen at random for treatment. This is a scenario of no planning or targeting in catchment management.
2. Targeting of erosion hotspots at the source, those places in the catchment with the highest erosion rate.
3. Targeting of erosion hotspots and hillslope sediment delivery, thereby seeing where it is more effective to trap eroding soil, rather than prevent it from eroding upslope.
4. Targeting those sub-catchments and those erosion processes that contribute most to the suspended sediment loads (i.e. targeting using the contributor results from the sediment budget).

The results show that both erosion rates at the source and sediment delivery efficiency need to be considered to achieve effective targets for reducing fine sediment delivery to downstream control locations. It supports the literature that appropriate targeting policies can offer potential large cost savings relative to random management. We show that the magnitude and distribution of estimated costs can vary by several times depending on what type of erosion source or sediment delivery is targeted.
Target settings which only consider the erosion source rates can potentially result in spending more money than random management intervention. For those catchments dominated by sheet and rill erosion, reducing hillslope sediment delivery ratio (HSDR) can be more effective than reducing the sheet and rill erosion at the source level, even though the unit cost of decreasing sediment delivery ratio is more expensive than the unit cost of reduction in sheet and rill erosion. Proper targeting can reduce the cost by many times compared to the other three strategies. The reason is that although sheet and rill erosion has relatively low unit cost, its reduction at the sources becomes inefficient because of relatively small HSDR (smaller than 10% in average for the upland catchments compared to 0.4 for gully and bank erosion). The measures of trapping sediment before it enters waterways (by reducing HSDR), such as buffer strips and tree planting adjacent to streams, make more economic sense than managing thousands of hectares of uplands for sediment-reduction benefits. It highlights the difference between sediment control for on-site productivity maintenance and off-site fine sediment delivery.

For the catchments dominated by gully or bank erosion, several targeting strategies result in similar total cost although with different spending patterns at the sub-catchment element level. Random selection is the most ineffective strategy.

Sediment reduction also has other benefits, such as biodiversity and aesthetics which were not accounted for in this study. The investment prioritization study shows that through the spatial sediment budget an optimum solution of cost-effective sediment control can be determined from the map of contributing sources and the costs of restoration. This is an advantage of the budget technique. More commonly, catchments are managed for a range of objectives making an optimum solution less deterministic. In those cases, an optimum management solution can be found using techniques that can simulate quickly a large number of management scenarios from which the most effective is chosen. One of the best ways of doing this is through a modelling technique known as genetic algorithms. This technique uses the results of past simulations to improve the search for an optimal solution to a problem rather than just using random choices. This type of investment scenario work is also presented in this report.

A genetic algorithm model was built to find the optimal solution of erosion control in catchments, to solve the same problem as that posed above. The genetic algorithm found essentially the same optimum solution as that obtained from the sediment budget analysis. While the genetic algorithm was not needed for the relatively simple problem posed in this project, we have demonstrated and tested the ability to use such techniques to find optimum management solutions. We have also shown that such analyses can produce far more effective results than those obtained by more traditional targeting exercises. Thus we are now in a strong position to tackle such problems as the optimum solutions for meeting downstream targets of sediment, salt, and water yield for example while including consideration of on-site productivity.
Introduction

Australia relies heavily on the land and water resources of the Murray Darling Basin (MDB) for agricultural production. Maintaining the quality of the land and water for future generations is important for sustainable economy. It relies on a good understanding of problem and the sound management strategies. Fine sediment and attached nutrients are major sources of water quality impairments in the Murray-Darling Basin (Landmark 2001). Effective control of fine sediment loads is a critical component of natural resource management when the aim is to achieve sustainable agriculture and acceptable ecosystem integrity (Braden et al 1989). Integrated sediment control management has received considerable attention. It has led to substantial agreement among state environmental agencies, scientists, and advocacy groups that more actions need to be taken for environmental protection and preventing further decline in water quality. However, there is much less agreement about what kinds of actions represent good policy.

With a scarcity of resources, it is sensible to identify priority management areas and to target expenditure. Recent studies have demonstrated that there is economic advantage in identifying the areas that have a higher potential to deliver pollutants and prioritizing control implementation in those areas (Docjomspm et al.1990; Heatwole et al. 1987; Carpentier et al. 1998). Two basic strategies can be taken to reduce fine sediment loads to downstream waterways. One is to induce changes in the way soil erosion is managed on the field (on-site management). The second is to intercept sediment-laden runoff and filter out the sediment before it reaches targeted locations (off-site management). However, there has been little empirical evaluation of the cost-effectiveness of the two approaches in a spatially-distributed manner. Potentially, more realistic control strategies can be constructed by combining both strategies with consideration of spatial differences in landscape, climate, and land use.

There is much literature on the cost-effective pollutant control and a growing literature on the effectiveness of interception strategies at field to small catchment scales (Shortle et al. 1998; Schwabe 2000). Several researchers implemented targeting primarily by considering sheetwash and rill erosion (Braden et al. 1989; Dickinson et al. 1990). Traditional linear, non-linear mathematical programming and multi-objective optimization have been used since 1960s (Das and Haimes 1979; Greenberg 1995). More recently, heuristic optimization, such as genetic algorithms (GAs), has been tried because of its ease of handling large data sets and searching among larger sets of possible scenarios (Srivastava et al. 2002).

Only limited efforts have been devoted to the complexities of setting spatially distributed management strategies at regional to basin-wide extents. One consequence is that current management cannot take full account of several key characteristics of sediment generation, such as differences in erosion types, spatial variation and source-to-destination processes. Several features of basin scale sediment problems complicate policy choice. One is the high degree of uncertainty about different types of soil erosion and their relations to downstream water quality. Another is the spatial variation inherent in topography, climate, soil, and vegetation cover. The spatial variation is further enhanced by management and land use patterns. Assessment of the feasibility, effectiveness and cost of technical options for sediment reduction over such a large area necessitates consideration of those spatial variations. Policies based on uniform regulatory approaches are unlikely to have significant impact in
controlling fine sediment loads because of these features of non-point pollutant sources.

Given current monitoring technology, basin-wide maps of fine sediment cannot be made with reasonable accuracy at reasonable cost. Although uncertainty is a key feature of the sediment transport problem in a large and complex catchment such as the Murray-Darling Basin, there is an increasing process understanding of the relationships between land use activities, landscape characteristics, climate and erosion sources and the movement of the spatial transport of sediment. Prosser et al. (2001) developed a spatially distributed model of mean annual sediment budgets for river basins. The model, *SedNet* (*Sediment River Network Model*), used spatial modelling of the erosion, deposition, and transport processes that move sediment and nutrients within landscapes and streams to produce regional budgets for the Murray Darling Basin. The sources of sediment considered are soil erosion by surface (hillslope) processes (Lu et al. 2003a; Lu et al. 2003b), gully erosion and riverbank erosion (Hughes and Prosser 2003). These sediment sources were routed through the river network using a simple conceptual model of the primary controls on sediment export and deposition. The results demonstrate that there is a reasonable correlation between observed and predicted specific sediment yields (DeRose et al. 2003). The sediment budget results provide a basis for prioritization for investment in reducing suspended sediment loads.

In this study, investment prioritization scenarios were proposed by designing different management strategies with different levels of sediment reduction targets at each of a number of control locations. At each control location, we define the baseline loads as the loads under current land use and management practices and the target loads as the maximum allowable loads for minimum impact on water quality. The target loads are assumed to be between baseline loads and the loads under natural conditions. Any loads smaller than or equal to target loads are acceptable, implying they have very small negative impact on the environment, e.g., water quality and river health.

We designed five different management strategies and tested twenty different levels of target loads from 0% to 95% reduction of sediment loads from the baseline. The aims were:

1. to show the cost of achieving targets;
2. to identify what target loads are achievable for a given amount of funds;
3. to form the cost curves which show how the cost changes with different target settings and different strategies overall because, for different strategies, it is expected that different costs will be encountered for the same target setting (as shown in Figure 1);
4. to reveal the most effective strategy;
5. to demonstrate the trade-off between sediment reduction and cost increase for marginal benefit, and
6. to spatially allocate the funds for sediment reduction in a cost-effective way.
Methods

Spatial Settings and terminology

The Murray-Darling Basin (MDB) is located in the south-eastern Australia and covers an area of $1.1 \times 10^6 \text{ km}^2$ or about 14% of Australia. For modelling purpose, SedNet (Prosser et al. 2001; DeRose et al. 2003) spatially divided MDB into around 10,000 sub-areas according to its topography using ESRI ArcInfo software (ESRI 2003) and 9’’ digital elevation model (DEM) derived by the Australian National University (Hutchinson et al. 2001). The sub-areas, which are called sub-catchment elements and have contributing area around 50 - 100 km$^2$, are the basic constituent elements used to compute hillslope sheet and rill erosion, hillslope sediment delivery ratio, gully erosion, and bank erosion. For clarity, in this report, we use the following terminology which was suggested by the project steering committee for all the reports produced from the project. The terms related to this report are:

**Sub-catchment element:** It is the basic constituent element of SedNet model. Normally, each has a contributing area around 50 - 100 km$^2$. There are nearly 10,000 sub-catchment elements covering MDB.

**Sub-catchment:** A group of subcatchment elements. These equate to tributary rivers of catchments. E.g., the Cotter subcatchment is a tributary of the Murrumbidgee catchment.

**Catchment:** Refers to the major upland catchment areas and associated rivers., e.g., Murrumbidgee Catchment.

**sediment control location:** This refers to the river export point for evaluations of suspended sediment contribution and sediment control options. The selecting criteria for sediment control locations are given below. In other reports produced by this project, it is sometimes called Contribution point.

**Basin:** Refers to the Murray Darling Basin as a whole, not to individual ARWC basins.
Selection of sediment control locations

The sediment budgets (DeRose et al. 2003) show that most sediments are generated and transported from the upland catchments located in the east and north part of the MDB. Further transport of sediment towards the basin outlet is limited as much of the sediment is deposited on the floodplains and in reservoirs downstream. Therefore, assessment at the MDB outlet provides little information for sediment control through management of the deteriorated upland sub-catchments. Due to these reasons, 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 erosion 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 up-stream of major reservoirs.

The selected control locations are shown in Figure 2 and the details of each selected locations are given in Table 1.

![Legend](image)

Figure 2. Fine sediment contribution estimated using *SedNet* for the major upland catchments. Critical sediment control locations are also shown.
Table 1. Locations selected for sediment control.

<table>
<thead>
<tr>
<th>AWRC Basin Name</th>
<th>AWRC-No</th>
<th>Latitude (deg min)</th>
<th>Longitude (deg min)</th>
<th>Location description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warrego River</td>
<td>23</td>
<td>146 7</td>
<td>26 45</td>
<td>Below confluence with Angellala Creek</td>
</tr>
<tr>
<td>Border River (1)</td>
<td>17</td>
<td>149 0</td>
<td>28 3</td>
<td>Moonie River, below confluence with Thomby Creek</td>
</tr>
<tr>
<td>Border River (2)</td>
<td>17</td>
<td>150 2</td>
<td>28 35</td>
<td>Macintyre River, at confluence with Boobora watercourse</td>
</tr>
<tr>
<td>Border River (3)</td>
<td>17</td>
<td>149 48</td>
<td>28 29</td>
<td>Weir River</td>
</tr>
<tr>
<td>Border River (4)</td>
<td>17</td>
<td>149 37</td>
<td>28 24</td>
<td>Weir River</td>
</tr>
<tr>
<td>Border River (5)</td>
<td>17</td>
<td>149 47</td>
<td>28 47</td>
<td>Croppa Creek</td>
</tr>
<tr>
<td>Condamine-Gulgoa River (1)</td>
<td>22</td>
<td>148 34</td>
<td>27 48</td>
<td>Maranoa River</td>
</tr>
<tr>
<td>Condamine-Gulgoa River (2)</td>
<td>22</td>
<td>148 35</td>
<td>28 7</td>
<td>Balonne River</td>
</tr>
<tr>
<td>Paroo River</td>
<td>24</td>
<td>144 51</td>
<td>28 26</td>
<td>Below confluence with Werai Creek</td>
</tr>
<tr>
<td>Gwydir River</td>
<td>18</td>
<td>150 27</td>
<td>29 41</td>
<td>Below confluence with Horton River</td>
</tr>
<tr>
<td>Macquarie-Bogan River (1)</td>
<td>21</td>
<td>147 10</td>
<td>31 30</td>
<td>Bogan River, below confluence with Albert-Priest Channel</td>
</tr>
<tr>
<td>Macquarie-Bogan River (2)</td>
<td>21</td>
<td>148 3</td>
<td>31 46</td>
<td>Ewenmar Creek, below Millpulling Creek</td>
</tr>
<tr>
<td>Lachlan River</td>
<td>12</td>
<td>146 56</td>
<td>33 9</td>
<td>Below confluence of Humbug and Wallamundry Creeks</td>
</tr>
<tr>
<td>Lachlan River</td>
<td>12</td>
<td>147 26</td>
<td>33 8</td>
<td>Goobang Creek</td>
</tr>
<tr>
<td>Murrumbidgee River (1)</td>
<td>10</td>
<td>146 31</td>
<td>35 33</td>
<td>Murrumbidgee River</td>
</tr>
<tr>
<td>Murrumbidgee River (2)</td>
<td>10</td>
<td>145 56</td>
<td>35 19</td>
<td>Billabong Creek</td>
</tr>
<tr>
<td>Goulburn River</td>
<td>5</td>
<td>145 4</td>
<td>36 11</td>
<td>Above confluence with Murray River</td>
</tr>
<tr>
<td>Broken River</td>
<td>4</td>
<td>145 28</td>
<td>36 11</td>
<td>Lower Nine Mile Creek</td>
</tr>
<tr>
<td>Campaspe River</td>
<td>6</td>
<td>144 52</td>
<td>36 13</td>
<td>Above confluence with Murray River</td>
</tr>
<tr>
<td>Owens, Kiewa, and Upper</td>
<td>3, 2, 1</td>
<td>146 8</td>
<td>36 1</td>
<td>On Murray River below confluence with Owens River</td>
</tr>
<tr>
<td>Murray Rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loddon River</td>
<td>7</td>
<td>143 44</td>
<td>35 26</td>
<td>Little Murray River above confluence with Murray River</td>
</tr>
<tr>
<td>Namoi River</td>
<td>19</td>
<td>149 37</td>
<td>30 14</td>
<td>Below confluence with Bohena Creek</td>
</tr>
<tr>
<td>Castlereagh River</td>
<td>20</td>
<td>147 58</td>
<td>30 17</td>
<td>Below confluence with Nedgera Creek</td>
</tr>
</tbody>
</table>
**Fine Sediment Yield Calculation**

The fine sediment yield at a single sediment control location \( k \) is calculated by SedNet (Prosser et al. 2001; DeRose et al. 2003) using the following equation:

\[
Y_k = \sum_{i=1}^{N} \left[ (E_i \times \text{hs}d_r_i) + G_i \times 0.4 + B_i \times 0.4 \right] \times \text{rs}d_r_i
\]

where \( Y_k \) is the total fine sediment contributed to the location \( k \) [t/year], \( E_i \) is the total sheet and rill erosion rate at sub-catchment element \( i \) [t/year], \( \text{hs}d_r_i \) is the hillslope sediment delivery ratio for sub-catchment element \( i \), \( G_i \) is the total gully erosion rate at sub-catchment element \( i \) [t/year], \( B_i \) is the total bank erosion rate at sub-catchment element \( i \), \( \text{rs}d_r_i \) is the large scale (river) sediment delivery ratio, and \( N \) is the number of sub-catchment elements contributing to the location \( k \).

Following consultation with the project steering committee, it was felt that there was no basis to consider any differential weighting of the control locations at this stage. Therefore, equal weighting is used in this study. The total sediment yield to multiple locations can be calculated as:

\[
Y = \sum_{k} Y_k
\]

where \( Y \) is the total sediment loads from all pre-specified control locations. The independence of the selected locations allows us to carry out the analysis independently from location to location. However, multiple weighting can be easily included in the future to differentiate the relative importance of each location.

**Management Focus at Different Scale**

There are scaling and computational issues in large scale investment prioritization of sediment control. Scaling has been an active topic in catchment modelling for decades. Accordingly, there should be different management focuses at different scales. As shown in the Figure 3, as areal extent decreases, the management focus becomes more specific in relation to management practices of controlling sediment. At regional scale, the primary management focus is to set up strategic targets and allocation of funds. At small catchment level, where there is adequate information about land use, specific management practices, costs, and net return of the individual properties, the cost-effective Best Management Practices (BMP) placement individual fields becomes the primary issue. Data availability is a serious limitation when it is attempted at basin scale. Placing specific BMPs, such as types of tillage, certain crop rotation, and exact locations of tree planting to field level across the basin using the information based on large scale sediment budget can be potentially misleading because there can be inadequate representation of local descriptors which are often critical for small scale management decisions.
Apart from data availability, computational intractability is another limiting factor in large scale modelling. The number of ways to allocate BMPs throughout the basin is exponential with regard to the number of elements considered. Possible elements include major catchments, sub-catchments, sub-catchment elements, or 250 m by 250 m cells. For example, the search space for 50 elements and 10 non-mutually exclusive BMPs encompasses \(2^{10^{50}}\) possible placement scenarios. Slight increase in the number of elements or BMPs can easily make the scenario evaluation computational intractable.

**Input Data Structure**

The input data is a table with the following 11 columns. It is the part of the output of SedNet (Prosser et al. 2001; DeRose et al. 2003).

**Table 2. Input data structure.**

<table>
<thead>
<tr>
<th>Sub_No</th>
<th>Area</th>
<th>(\bar{E}_i)</th>
<th>(E_i)</th>
<th>(\bar{hsdr}_i)</th>
<th>(hsdr_i)</th>
<th>(\bar{G}_i)</th>
<th>(G_i)</th>
<th>(\bar{B}_i)</th>
<th>(B_i)</th>
<th>(rsdr_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33</td>
<td>2.5</td>
<td>1.2</td>
<td>0.05</td>
<td>0.0</td>
<td>2.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>0.5</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.8</td>
<td>0.0</td>
<td>2.7</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>N</td>
<td>51</td>
<td>1.5</td>
<td>0.5</td>
<td>0.2</td>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
<td>3.9</td>
<td>0.0</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 3. Management focuses at different scale.
In the Table 2, Sub_No is the number of sub-catchment elements which contribute sediment to a downstream sediment control location \( k \). Area donates Sub-catchment element area, \( E_i \) donates current hillslope erosion rate [t/year] at sub-catchment element \( i \), \( \bar{E}_i \) is natural hillslope erosion rate [t/year] at sub-catchment element \( i \), \( \hsdr_i \) is current hillslope sediment delivery at sub-catchment element \( i \), \( \bar{\hsdr}_i \) is natural hillslope sediment delivery ratio at sub-catchment element \( i \), \( G_i \) is current gully erosion rate [t/year] at sub-catchment element \( i \), \( \bar{G}_i \) is natural gully erosion rate [t/year] at sub-catchment element \( i \), \( B_i \) is current bank erosion rate [t/year] at sub-catchment element \( i \), \( \bar{B}_i \) is natural bank erosion rate [t/year] at sub-catchment element \( i \), \( rsdr_i \) is large scale (river) sediment delivery ratio. In previous reports describing SedNet outputs this is referred to as the Contributor. We assume that \( rsdr_i \) remains constant for each sub-catchment element during construction of investment prioritization scenarios. This assumption means that we focus the management intervention within each sub-catchment element rather than at larger scales.

**Cost Functions**

In general, the cost function can be written as: 
\[
C_E = f_E(E, \bar{E}, E) ,
\]
\[
C_{\hsdr} = f_{\hsdr}(\hsdr, \bar{\hsdr}, \hsdr) ,
\]
\[
C_G = f_G(G, \bar{G}, G) ,
\]
\[
C_B = f_B(B, \bar{B}, B) ,
\]
for hillslope sheet and rill erosion, hillslope sediment delivery ratio, gully erosion, and bank erosion, respectively, where \( \bar{\cdot} \) and \( _{\cdot} \) represent their current (upper bound) and the natural conditions (lower bounds) and \( E, \hsdr, G, B \) without upper and lower bars are the targeted rates of hillslope sheet and rill erosion, hillslope sediment delivery ratio, gully erosion, and bank erosion, respectively, after some management interventions.

For a simple and linear case, we have estimated the unit cost of sediment reduction as \( s_E \) [t/ha/year], \( s_{\hsdr} \) (per 1% reduction of \( \hsdr \)), \( s_G \) and \( s_B \). (See Appendix I for detail). For a given sub-catchment element, the costs involved to reduce sediment can be written as:

\[
C_E = (E_{old} - E_{new}) * s_E \tag{3}
\]
\[
C_{\hsdr} = (\hsdr_{old} - \hsdr_{new}) * s_{\hsdr} * 100 / \hsdr_{old} \tag{4}
\]
\[
C_G = (G_{old} - G_{new}) * s_G \tag{5}
\]
\[
C_B = (B_{old} - B_{new}) * s_B \tag{6}
\]

The total cost for a sub-catchment element can then be estimated as \( C_E + C_{\hsdr} + C_G + C_B \). Accumulating the cost for all sub-catchment elements results the total cost required for certain amount of sediment reduction at control locations.

More realistically, the unit costs are not necessarily constant but depend on other biophysical variables (e.g., vegetation cover, slope, soil) and possibly social and economical variables (e.g. ease of access to necessary facilities and local community willingness to participate). Also, the cost functions could be nonlinear. For a convex function where unit cost increases when the sediment reduction increases, possible
functional forms of unit function could be:

\[ s_X = a \exp \left[ b \left( \frac{X_{\text{new}} - X_{\text{old}}}{X - X} \right)^n \right] \]

(7) or

\[ s_X = a \left( \frac{X_{\text{old}} - X_{\text{new}}}{X - X} \right)^n \]

where \( X \) represents one of the erosion types (sheet and rill, gully or bank erosion) or hillslope sediment delivery ratio, \( a, b \) and \( n \) are parameters which need to be determined by available cost data. An increase in parameter \( n \), for example, results in a more concave shape of the unit cost function. The actual unit cost functions could be determined by:

1. regression using existing cost data, or
2. fuzzy logic using other economic and environmental measures.

Further research and data collection are needed for the implementation of above methods to estimate spatially-distributed cost.

**Investment Prioritization Scenarios**

In this study, the objective of investment prioritization is to reduce the total sediment load at the downstream control location \( k \) by a certain percentage \( \alpha \) (range from 0%-100%). We set up three strategies (random selection, Target A and Target B) to mimic the types of approaches that are currently being implemented or under consideration. A fourth strategy (Target C) uses the new information from the SedNet budgets which relates the sediment delivery at a control location to the spatial distribution of the sediment sources – the so-called contributor. A fifth strategy is illustrated as a proof-of-concept of a spatial optimization procedure. It is implemented here as a test against the analytical optimal solution (Target C) to demonstrate its potential for use in situations where the optimum approach cannot be formulated analytically, e.g., trading off between on-site productivity losses and downstream impacts or trading off sediment and nutrient control (again with potential on-site and off-site tensions). We hypothesize that each strategy will achieve the reduction in fine sediment delivery to the control location at different cost per increment of sediment reduction and may exhibit a different functional form across the range of \( \alpha \) from 0% to 100%.

The strategy that produces the lowest cost consistently across a range of reduction percentage \( \alpha \) would be the best strategy for investment prioritization to control sediment transport to the control locations.

**Random Selection**

Steps:

1. Initialize cost to zero.
2. Randomly pick up one value from any values of \( E_i, hsdr_i, G_i \), and \( B_i \) (this is equivalent to randomly selecting a sub-catchment element and an
erosion source or control option, the latter being hsdr). Reduce the chosen value by a certain percent \( \beta \) (say 1%), e.g. \( X_{\text{new}} = X_{\text{old}} \times \beta \), where \( X \) represents one of the erosion types (sheet and rill, gully or bank erosion) or hillslope sediment delivery ratio.

(3) Estimate \( Y_k = \sum_{i=1}^{N} (E_i \times \text{hsdr}_i + G_i \times 0.4 + B_i \times 0.4) \times \text{rsdr}_i \) and accumulate the cost.

(4) Repeat 2) to 3) until

\[
y_k \leq (1 - \alpha) \sum_{i=1}^{N} (E_i \times \overline{\text{hsdr}}_i + \overline{G}_i \times 0.4 + \overline{B}_i \times 0.4) \times \overline{\text{rsdr}}_i
\]

**Targeting A**

Strategy Target A only considers the sediment generation at its source. The effects of sediment delivery efficiency at both sub-catchment element level and large-scale (river) level are not considered. This strategy mimics so-called hot spot control of sediment sources. Unlike more conventional hot spot control strategies we prioritize across all sediment sources not just hillslope erosion.

Steps:

1. Initialize cost to zero.

2. Select the largest value from one of the columns \( E_i, G_i, \) and \( B_i \). Start from the column with the lowest unit cost. Reduce the value by a certain percent \( \beta \) (say 1%), e.g. \( X_{\text{new}} = X_{\text{old}} \times \beta \), where \( X \) represents one of the erosion types (sheet and rill, gully or bank erosion). The last selected column is hillslope sediment delivery ratio as it has the highest unit cost (see Appendix I).

3. Estimate \( Y_k = \sum_{i=1}^{N} (E_i \times \text{hsdr}_i + G_i \times 0.4 + B_i \times 0.4) \times \text{rsdr}_i \) and accumulate the cost.

4. Repeat 2) to 3) until

\[
y_k \leq (1 - \alpha) \sum_{i=1}^{N} (E_i \times \overline{\text{hsdr}}_i + \overline{G}_i \times 0.4 + \overline{B}_i \times 0.4) \times \overline{\text{rsdr}}_i
\]

**Targeting B**

Strategy Target B considers both the sediment sources and delivery capability at sub-catchment element level. The effects of large scale (river) deliver efficiency are not considered. This mimics hot spot targeting where the delivery capacity of the sub-catchment element is taken into account in the strategy.
Steps:

(1) Initialize cost to zero.

(2) For each erosion type, normalize the unit cost by their delivery efficiency. Namely, \( s_E = \text{avg\_hsdr} \), \( s_G = 0.4 \) and \( s_B = 0.4 \), where avg\_hsdr is average value of hillslope sediment delivery ratio for all the sub-catchment elements contribute to sediment control location \( k \).

(3) Select the largest value from one of the columns \( E_i \), \( G_i \), and \( B_i \). Start from the column with the lowest normalized unit cost. Reduce the value by a certain percent \( \beta \) (say 1%), e.g. \( X_{\text{new}} = X_{\text{old}} \times \beta \), where \( X \) represents one of the erosion types (sheet and rill, gully or bank erosion). The last selected column is hillslope sediment delivery ratio as it has the highest unit cost (see Appendix I).

(4) Estimate \( Y_k = \sum_{i=1}^{N} (E_i \times \text{hsdr}_i + G_i \times 0.4 + B_i \times 0.4) \times \text{rsdr}_i \) and accumulate the cost.

(5) Repeat 2) to 4) until

\[
Y_k \leq (1 - \alpha) \sum_{i=1}^{N} (E_i \times \text{hsdr}_i + G_i \times 0.4 + B_i \times 0.4) \times \text{rsdr}_i
\]

**Targeting C**

Strategy **Target C** not only considers the sediment sources and delivery capability at sub-catchment element level, but also considers the large scale (river) delivery efficiency. Therefore, this strategy includes all components of the budget. In particular, it introduces the contributor information which has previously not been available. This strategy effectively represents an analytical solution of the optimum source control for cost-effective reduction in downstream delivery of fine sediment.

Steps:

(1) Initialize cost to zero.

(2) For each sub-catchment element, calculate the cost of reducing \( E_i \), \( \text{hsdr}_i \), \( G_i \), and \( B_i \) by a certain percent \( \beta \) (say 1%), e.g. \( X_{\text{new}} = X_{\text{old}} \times \beta \). Estimate \( dY_k = Y_{k,\text{old}} - Y_{k,\text{new}} \), where \( Y_k = \sum_{i=1}^{N} (E_i \times \text{hsdr}_i + G_i \times 0.4 + B_i \times 0.4) \times \text{rsdr}_i \) for each reduction. Calculate sediment delivery efficiency \( e_i \) by dividing the cost by \( dY_k \) for different types of reduction and sub-catchment elements.

(3) Sort \( e_i \) in ascending order and implement the reduction only for the most efficient one, which is the one with the smallest \( e_i \).

(4) Repeat 2) to 3) and accumulate cost until
\[ Y_i \leq (1-\alpha) \sum_{i=1}^{N} (E_i \times hsd_{i} + G_i \times 0.4 + B_i \times 0.4) \times rsdr_{i} \]

**Constraints**

All the strategies described above share some common constraints. The constraints are:

1. \[ Y_i \geq \sum_{i=1}^{N} (E_i \times hsd_{i} + G_i \times 0.4 + B_i \times 0.4) \times rsdr_{i} \], which means that, at each sediment control location, sediment yield cannot be reduced to be smaller than its natural rate.

2. \[ X_i \leq X_i \leq \overline{X}_i \], \( \forall i \), which means that, at each sub-catchment element, erosion reduction is only allowed to happen between its minimum rate \( X_i \) (assumed here to be that under natural conditions) and its current rate \( \overline{X}_i \) for any type of erosion (sheet and rill, gully and bank) and hillslope sediment delivery ratio. In this study, we made a strong assumption that the minimum HSDRs for all the sub-catchment elements are zero.

**Optimization Using a Genetic Algorithm**

Apart from the targeting strategies described above, the most rigid strategy to achieve the lowest cost for a certain amount of sediment reduction at each control location can be written as an optimization problem:

\[
\min \sum_{i=1}^{N} (C_{E,i} + C_{hsdr,i} + C_{G,i} + C_{B,i})
\]

\[\text{S.t.} \sum_{i=1}^{N} (E_i \times hsd_{i} + G_i \times 0.4 + B_i \times 0.4) \times rsdr_{i} \leq (1-\alpha) \sum_{i=1}^{N} (E_i \times hsd_{i} + G_i \times 0.4 + B_i \times 0.4) \times rsdr_{i} \]

\[ \sum_{i=1}^{N} (E_i \times hsd_{i} + G_i \times 0.4 + B_i \times 0.4) \times rsdr_{i} \geq \sum_{i=1}^{N} (E_i \times hsd_{i} + G_i \times 0.4 + B_i \times 0.4) \times rsdr_{i} \]

\[ E_i \in [E_i, \overline{E}_i], \ \forall i \]

\[ hsd_{i} \in [hsd_{i}, \ hsd_{i}], \ \forall i \]

\[ G_i \in [G_i, \overline{G}_i], \ \forall i \]

\[ B_i \in [B_i, \overline{B}_i], \ \forall i \]

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 of sub-catchment element, gully erosion and bank erosion, respectively for sub-catchment element \( i \). Other variables are the same as previously defined. A well-established genetic algorithm (Koziel and Michalewicz 1998) was used to solve above optimization problem.
Results

Our results are separated into three categories, *viz.*:

1. Proof-of-concept of spatial optimization versus targeting;
2. Comparison of effectiveness of forms of targeting and random selection strategies across the MDB;
3. Spatial visualization of the best strategy from (2).

As stated above, we hypothesized that *Target C* should be an analytical expression of the optimal approach for reducing fine sediment delivery to a specified location through control of sediment sources and alteration of hillslope sediment delivery ratio. We tested this by implementing all five strategies for each of three control locations, *viz.*, Goulburn, Murrumbidgee and Namoi catchments. The units to which we applied the control strategies were the sub-catchment elements (~50-100 km^2) as defined for the SedNet modeling of sediment budgets across the Basin. The unit over which the comparisons/optimizations were performed were the sub-catchment elements of each of the catchments, e.g., for Goulburn we report the irrigation drains, Broken River, Seven Creeks, Pranjip Creek, Canal, Major Creek, Sunday Creek, Home/Spring Creek, Upper Goulburn, Yea River, and Acheron River. We implemented nineteen levels of sediment reduction at each control location (\(\alpha = 0.05, 0.1, 0.15, 0.2, 0.25, \ldots, 0.95\)). Different cost curves were obtained for each strategy. Appendix II shows the cost curves for the sub-nodes within Goulburn, Murrumbidgee and Namoi catchments for five different strategies outlined above. Averaged sediment contributions of three sediment sources are also shown for each of the sub-catchments. We found that *Target C* produces very similar results to optimization using GA, whilst *Target C* is computationally far less intensive. However, the optimization procedure has potential for application to problems of more complexity, e.g., trading off between on-site productivity and off-site sediment delivery, and between on-site nutrient generation vs off-site delivery.

Our whole-of-Basin analysis was carried out for all the control locations shown in Figure 1. The unit of sediment control in this case was the sub-catchment elements referred to above. Therefore, we present results for the major catchments of the MDB (again as indicated by the location of control locations). We implemented nineteen levels of sediment reduction at each control location (\(\alpha = 0.05, 0.1, 0.15, 0.2, 0.25, \ldots, 0.95\)) for the strategies of *Random* and *Target A to C*. Appendix III shows the cost curves thereby derived. Averaged contributions of three erosion types are also shown. Without considering the delivery efficiency, targeting (such as *Target A* and *B*) is not necessarily better than *random selection*. It can even sometimes be more expensive.

For the catchments dominated by sheet and rill erosion, reducing hillslope sediment delivery ratio can be more effective than reducing the sheet and rill erosion at the source level, even though the unit cost of sediment delivery ratio is more expensive than the unit cost of reduction in sheet and rill erosion. An important consideration is the effectiveness of HSDR measures under extreme events. Many SDR control techniques, *e.g.*, riparian buffer strips or hillside strips, are effective under a variety of storm events. However, in environments dominated by large events with large fine sediment loads, it is important that the capacity of the control technique is sufficient. This is critical as the message that accelerating on-site erosion is acceptable as long as there are buffer strips at the bottom of hillslopes can be
misleading. For those areas dominated by sheet and rill erosion, Target C can reduce the cost by many times compared to the other three strategies Random selection, Target A and B as shown in Figure 4.

![Figure 4. Cost – sediment reduction curve for a sub-catchment where the dominant erosion type is hillslope sheet and rill erosion.](image)

For the catchments dominated by gully or bank erosion, the costs of Target A, B and C are not largely different compared to that of random selection for the same level of sediment reduction (Figure 5). However the spending pattern differs at sub-catchment element level. This is because of the assumption in the budget modeling that gullies are 100% connected to the stream network. This means that a gully or bank sediment source hot spot always delivers its load at a similar rate. In reality, not all gullies will be equal sources of sediment and not all gullies deliver directly to the streams. This is an area requiring further work, particularly as the extent to which
gullies are repairing naturally remains uncertain. Assuming that river bank erosion contributes directly remains sound. However, our analysis does not take into account the variability in efficacy of expenditure given the great variation in river bank structure and condition. As expected, for those catchments dominated by gully and bank erosion, random selection is the most ineffective means to control sediment.

For the catchments with mixed erosion types (with sheet and rill erosion as one type), Target A is often the most ineffective way of controlling sediment delivery to the control locations and it can be even worse than random selection, shown in Figure 6. By considering sediment delivery efficiency within sub-catchment elements, Target B performs better. Target C is the best strategy because even though sheet and rill erosion has relatively low unit cost, reduction in sheet and rill erosion at their sources becomes inefficient overall due to the relatively small hillslope sediment delivery ratio (comparing to 0.4 for gully and bank erosion). This highlights the difference between sediment control for on-site productivity maintenance and off-site fine sediment delivery.

![Figure 6. Cost – sediment reduction curve for a sub-catchment with mixed erosion types.](image)

Given that our aim was to develop techniques for reducing delivery of fine sediment from sediment source to downstream control locations, the hypothesis that Target C is an optimization technique is supported by our results. There are a very large number of possible map representations of the application of Target C. We choose here to represent the amount of reduction in each of the sediment sources (and HSDR) for $\alpha = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 0.9$. The total expenditure in each sub-catchment at each of these $\alpha$ values is also presented (see Appendix III).

Figure 7 (DeRose et al. 2003) shows the relative area contribution of total fine sediment yields and from the three main erosion processes in the Murrumbidgee and Balonne catchments, respectively. The black lines represent the relative area contribution made by the different sub-catchment elements (which was estimated by ranking sub-catchment elements in order of decreasing suspended sediment contribution and then comparing the cumulative total contribution against the cumulative percentage total area occupied). The Murrumbidgee catchment, in which bank erosion dominates, has a strong convex relative area contribution curve. It
suggests that much of the fine sediment loads at the outlet point is produced in a small percentage of the total catchment area. Shown in the maps (Figures A.7 to A.15) in Appendix III, even for a large amount of sediment reduction (say $\alpha = 0.6$), actions in only a small proportion of the sub-catchment elements are required for rehabilitation. On the other hand, the Balonne catchment, in which fine sediment yields were dominated by hillslope sheet and rill erosion, has a less convex relative area contribution curve. It requires a greater proportion of sub-catchment elements to be targeted to achieve the same level of sediment reduction (see Figures A.7 to A.15 in Appendix III). This demonstrates the merit and feasibility of prioritizing specific sub-areas for erosion control using targeting (as shown in this study, Target C).

Figure 8 shows the cost-sediment reduction curve for the whole MDB by adding the cost for all control locations listed in Table 1 and Figure 2. It shows that the total cost increases almost linearly from 5% ($\alpha = 0.05$) to 50% ($\alpha = 0.50$) sediment reduction to those control locations listed in Table 1 and shown in Figure 2. From $\alpha = 0.50$, the slope of the cost curve becomes steeper and suggests trade-off point for marginal benefit.

Figure 7. SedNet estimations of relative area contributions of suspended sediment in the Murrumbidgee and Balonne catchments respectively. The relative proportions of suspended sediment contribution from each of the main erosion processes are also shown. (After DeRose et al. (2003).
Conclusions

Our key findings are:

(1) Target C and optimization using GA are the most cost-effective strategies for all conditions. Computationally, Target C is fast and can be operationally applied to the basin wide scale.

(2) Without considering the delivery efficiency, targeting (such as Target A and B) does not necessarily do a good job compared to random selection. It can even sometimes be more expensive than random selection.

(3) For those catchments dominated by sheet and rill erosion, reducing hillslope sediment delivery ratio can be more effective than reducing the sheet and rill erosion at the source level, even though the unit cost of sediment delivery ratio is more expensive than the unit cost of reduction in sheet and rill erosion. Target C and optimization using GA can reduce the cost by many times compared to the other three strategies. The measures of trapping sediment before it enters waterways (primarily reduce HSDR), such as buffer strips and tree planting adjacent to streams (Hairsine 1996; Karssies and Prosser 1999) make more economic sense also has other benefits, such as biodiversity, aesthetic, etc, which were not accounted for in this study.

(4) For the catchments dominated by gully or bank erosion, Target A, B and C result in similar total cost although with different spending patterns at the sub-catchment element level. As expected, random selection is the most ineffective strategy.
For the catchments with mixed erosion types (with sheet and rill erosion as one type), Target A is often the least effective way of controlling sediment delivery to the control locations and it can be even worse than random selection. By considering sediment delivery efficiency within each sub-catchment element, Target B performs better. Target C and optimization using GA remain the best performers among all five strategies. The reason is that although sheet and rill erosion has relatively low unit cost, reduction in sheet and rill erosion at their sources becomes inefficient overall due to the relatively small hillslope sediment delivery ratio (compared to 0.4 for gully and bank erosion).

The investment prioritization scenarios we proposed and presented in this study show that erosion rates at the sources and sediment delivery efficiency are key considerations for setting and achieving effective targets for reducing the fine sediment delivery to downstream locations. Target setting which only considers the erosion source rates can potentially result in spending more money than random management intervention.

**Caveats on Application of Results**

This study has developed and demonstrated techniques for prioritizing actions to control downstream delivery of fine sediment. We do not recommend implementing our results operationally at this stage because of the following issues:

1. The uncertainty involved in estimating unit costs for each erosion type and sediment delivery ratio. A lot of work needs to be done to better estimate the unit costs and to tailor actions and costs to particular circumstances. Our cost structures are a simplified guide only. One interesting prospect is to consider how such results might be used to help guide a market in provision of the services required to control sediment sources.

2. The uncertainties involved in the large scale sediment budget.

We believe the scenario results presented provide insights into the complexity of controlling sediment delivery over large spatial extents in catchments experiencing different types of erosion and sediment transport due to the differences in climatic and environmental conditions. The approach we designed for tackling the investment prioritization scenarios can be a very effective tool for analyzing those complexities in a spatially distributed form. The methods can be made operationally useful as the above issues associated with cost and sediment budget uncertainties are resolved. The GA optimization approach also presents good prospect for dealing with even more complex trade-offs. However, work is required to develop faster algorithms and software implementation to deal with such large data and parameter space optimizations.

It is critical that the results presented in this study should not be taken as suggestions for management action at field to small catchment scales. The sediment budgets that underpin this analysis are of the same resolution, input data quality and therefore output certainty as the whole-of-basin budgets. Analysis of management intervention strategies to be considered for implementation must be supported by
budgets based on higher resolution and superior data quality inputs. Such an analysis is beyond the scope of this project.

Important limitations of the present study are the static perspective, lumped management interventions, and the exclusion of broader-issue-based multiple objective consideration. The static aspect assumes immediate response by ignoring the time lag between management interventions and actual reaction at the control location. Studies also show that interventions at the right time provide improved cost-effectiveness e.g., sediment generation and transport often show a strong seasonality. For simplification, we ignore the effects of time delay in response and optimal timing to control sediment. The proposed approach does not directly link to specific management practices, such as tree planting, conservation tillage, and vegetative buffer filter. This is because of scale considerations, computational limitation and management data availability. While it is acknowledged that decision-making generally attempts to reconcile and identify 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 fine sediment control at specific locations. Within a broader multi-criteria analysis framework, some of the “economically optimal” outcomes may be further constrained or rejected for social or political reasons or for other realities. In this respect, however, by combining economic efficiency analyses and biophysical information (DeRose et al 2003), the investment prioritization presented in this study provides useful guidance relating to tradeoffs.

Acknowledgements

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References


Appendix I:  Unit Cost Estimations

**Gullies**

Calculation is for conventional fencing, tree planting and watering. Assumes complete protection and reduction of erosion to 0.

Cost ($/t) = \frac{k}{g}

where \( g \) = average gully erosion rate in t km\(^{-1}\) yr\(^{-1}\) and \( k \) = riparian cost in $ km\(^{-1}\) of gully

\[
g = \bar{w} \times \bar{d} \times 1000 \times \frac{DBD}{t}
\]

where \( \bar{w} \) = mean gully width = 5 m, \( \bar{d} \) = mean gully depth = 2 m, 1000 = 1 km, \( DBD \) = mean dry bulk density = 1.5 t m\(^{-3}\), \( t \) = period of gully development = 100 years

\( k = (a \times l) + (p \times n \times h) + c \)

where \( a \) = cost of conventional fencing per m = $6.50, \( l \) = fence length per km of gully = 2000 m, \( p \) = cost of plant = $5.50, \( n \) = plant density required per ha = 550, \( h \) = area in ha planted per km of gully = 1.5 ha (includes 5 m riparian margin each side), and \( c \) = cost of watering per km of gully = $3000

**River bank**

Calculation is for conventional fencing, tree planting and watering. Assumes complete protection and reduction to natural rate (equivalent to 98% riparian cover).

Cost ($/t) = \frac{k}{b}

where \( b \) = average bank erosion rate above natural in t km\(^{-1}\)yr\(^{-1}\) and \( k \) = riparian cost in $ km\(^{-1}\) of gully

\[
b = \sum_{i=1}^{n} (BE_i - BEN_i) / l_i (1 - PR_i)
\]

where \( BE_i \) = average current bank erosion rate in t yr\(^{-1}\) for stream link \( i \), \( BEN_i \) = average natural bank erosion rate in t yr\(^{-1}\) for stream link \( i \), \( l_i \) = length of stream link \( i \) in km, \( PR_i \) = proportion of riparian vegetation and \( n \) = stream links with current bank erosion > natural. For the Murrumbidgee catchment \( b = 537 \) t km\(^{-1}\).

\( k = (a \times l) + (p \times n \times h) + c \)

where \( a \) = cost of conventional fencing per m = $6.50, \( l \) = fence length per km of river = 2000 m, \( p \) = cost of plant = $5.50, \( n \) = plant density required per ha = 550, \( h \) = area in ha planted per km of river = 2 ha (includes 10 m riparian margin each side), and \( c \) = cost of watering per km of river = $3000

**Hillslope**

Calculation is for implementation of cell grazing. Assumes well managed cell grazing with no overgrazing, even in drought years and also assumes complete reduction of erosion to the natural rate:

Cost ($/t) = \frac{m}{z}
where \( z \) = average hillslope erosion rate above natural in t/ha/yr and \( m \) = cost of implementing cell grazing in $ ha\(^{-1}\), and

\[
z = \left( \sum_{i=1}^{n} \left( HSLP_i - NHSLP_i \right) / area_i \right) / n
\]

where \( HSLP \) = current hillslope erosion rate of watershed \( i \) in t yr\(^{-1}\), \( NHSLP \) = natural hillslope erosion rate of watershed \( i \) in t yr\(^{-1}\), \( area_i \) = area of watershed of \( i \) ha and \( n \) = number of watersheds with above a threshold erosion rate. The threshold effectively excludes watersheds with low rates of erosion (eg., forested areas). For the Murrumbidgee a threshold value of 0.3 t ha\(^{-1}\) yr\(^{-1}\) was used resulting in \( z = 3.3 \) t ha\(^{-1}\) yr\(^{-1}\).

\[
m = e \times 2 \times \sqrt{s \times 10000} / s
\]

where \( e \) = cost of electric fencing per m = $4.0, \( s \) = average size of paddock = 10 ha

We may need to in future consider fertilizer and pasture seed costs, as for cell grazing to be warranted, it is a more intensive land use. I have also assumed 100% effectiveness, but it will probably in reality be somewhat less due to incomplete ground cover during drought years.

**HSDR**

Calculation for HSDR channel component only. Assumes riparian revegetation of the channel network \(< 50 \) km\(^2\) in upslope area. Increased channel roughness is assumed to deposit more sediment in the channel.

Cost ($ per % of HSDR) = \( q / u \)

Where: \( q \) = cost for riparian zone establishment of the \(< 50 \) km\(^2\) channel network and \( u \) = total % reduction in HSDR

\[q = le \times k\]

where: \( le \) = average total length of channel network \(< 50 \) km\(^2\) upstream area and \( k \) = riparian establishment cost per km stream length (as per bank erosion above). For Murrumbidgee catchment total upstream channel network was assessed to be 30 km for a typical watershed based on the 250k national river network.

\[u = -1 \times 100 \times (1 - f_{ratio}) \times r \times (1 - HSDR) / HSDR\]

where: 100 = percentage conversion, -1 = makes result positive, \( f_{ratio} \) = Roughness ratio = \((n_f)^{0.6} / (n_p)^{0.6}\) = 1.274, \( n_f \) and \( n_p \) are mannings n for forest and pasture vegetation respectively, \( r \) = proportion of sediment retention \((1-HSDR)\) that the channel network contributes to, \( HSDR \) = the mean hillslope sediment delivery ratio of non forested watersheds. \( HSDR \) = 0.09 and \( r \) = 0.20 in the case of the Murrumbidgee catchment.
Table A.1. Unit cost table

<table>
<thead>
<tr>
<th></th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gully (per tonne)</td>
<td>130</td>
</tr>
<tr>
<td>Riverbank (per tonne)</td>
<td>34</td>
</tr>
<tr>
<td>Hillslope (per tonne)</td>
<td>80</td>
</tr>
<tr>
<td>HSDR (per % of current HSDR)</td>
<td>9900</td>
</tr>
</tbody>
</table>

References for data: All data for riparian costs kindly supplied by Goulburn-Broken Catchment Management Authority.
Appendix II:

Figure A.1. Cost-sediment reduction curves for the sub-nodes within Goulburn, Murrumbidgee and Namoi catchments.
MURRUMBIDGEE (2)

Cost (Million $)

Proportion of Sediment Reduction

- Random
- Target A
- Target B
- Target C
- GA Opt.

MAINTAIN

HOULAGHANS

GOODRADIGBEE

ADJUNGBILLY

TUMUT River

TARCUTTA

$3.0 \times 10^1$
$2.5 \times 10^1$
$2.0 \times 10^1$
$1.5 \times 10^1$
$1.0 \times 10^1$
$0.5 \times 10^1$
$0.0 \times 10^1$

$7.0 \times 10^0$
$6.0 \times 10^0$
$5.0 \times 10^0$
$4.0 \times 10^0$
$3.0 \times 10^0$
$2.0 \times 10^0$
$1.0 \times 10^0$
$0.0 \times 10^0$

$6.0 \times 10^1$
$5.0 \times 10^1$
$4.0 \times 10^1$
$3.0 \times 10^1$
$2.0 \times 10^1$
$1.0 \times 10^1$
$0.0 \times 10^1$

$6.0 \times 10^1$
$5.0 \times 10^1$
$4.0 \times 10^1$
$3.0 \times 10^1$
$2.0 \times 10^1$
$1.0 \times 10^1$
$0.0 \times 10^1$

$6.0 \times 10^1$
$5.0 \times 10^1$
$4.0 \times 10^1$
$3.0 \times 10^1$
$2.0 \times 10^1$
$1.0 \times 10^1$
$0.0 \times 10^1$
NAMOI (2)

- Random
- Target A
- Target B
- Target C
- GA Opt.

**RANGIRA Cr**

**BOHENA Cr**

**MAULES Cr**

**MOOKI RIVER**

Cost (Million $) vs. Proportion of Sediment Reduction
Figure A.2. Area averaged sediment distributions in three erosion types for the sub-nodes within Goulburn catchment shown that gully and bank erosion dominates. Avg_her, avg_gully, and avg_bank stand for averaged hillslope erosion rate, averaged gully erosion rate, and averaged bully erosion rate, respectively.

Figure A.3. Area averaged sediment distributions in erosion type for the sub-nodes within Murrumbidge catchment shown some of the sub-catchments are dominated by single type of erosion and others have mixed erosion types in terms of sediment contribution. Avg_her, avg_gully, and avg_bank stand for averaged hillslope erosion rate, averaged gully erosion rate, and averaged bully erosion rate, respectively.

Figure A.4. Area averaged sediment distributions in erosion type for the sub-nodes within Namoi catchment shown majority of the sub-catchments are dominated by sheet and rill erosion with mediate intensity of gully erosion and little bank erosion in terms of sediment contribution.
Avg_her, avg_gully, and avg_bank stand for averaged hillslope erosion rate, averaged gully erosion rate, and averaged bully erosion rate, respectively.
Appendix III:

Figure A.5. Cost-sediment reduction curves for the major control locations within MDB.
MDB (4)

LODDON

BROKEN

UPPER MURRAY

GOULBURN

CAMPASPE

Proportion of Sediment Reduction

Cost (Million $)
Figure A.6. Area averaged sediment distributions in erosion type for the major sediment control locations shown that sheet and rill erosion dominates in the north and gully and bank erosion dominates in the south in terms of sediment contributing to the control locations. It is also shown that the average sediment contributors are high in the north-east up-catchments such as Macinty, Croppa, Gwydir and Namoi rivers but relatively low for the up-land catchments in the north of MDB. Medium to high sediment deliveries are found for the up-land catchments in the south and south-east of MDB. Avg_her, avg_gully, and avg_bank stand for averaged hillslope erosion rate, averaged gully erosion rate, and averaged bank erosion rate, respectively.
Figure A.7. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 10% of fine sediment reduction at control locations.
Figure A. 8. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 20% of fine sediment reduction at control locations.
Figure A. 9. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 30% of fine sediment reduction at control locations.
Figure A. 10. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 40% of fine sediment reduction at control locations.
Figure A. 11. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 50% of fine sediment reduction at control locations.
Figure A. 12. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 60% of fine sediment reduction at control locations.
Figure A. 13. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 70% of fine sediment reduction at control locations.
Figure A.14. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 80% of fine sediment reduction at control locations.
Figure A.15. Total cost, reductions of hillslope sheet and rill erosion, sediment delivery ratio, gully erosion and bank erosion for 90% of fine sediment reduction at control locations.