



# Gully and Riverbank Erosion Mapping for the Murray-Darling Basin

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CSIRO Land and Water, Canberra  
Technical Report 3/03, March 2003

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## ***Abstract***

This report presents gully and river bank erosion predictions for the Murray-Darling Basin. The results in this report significantly improve upon those presented in the NLWRA assessment. The predicted average gully density for the MDB is 0.08 km/km<sup>2</sup>. There are approximately 89,000 km of gully in total, which on average have produced 13 million tonnes of sediment per year. In total, gullies in the MDB have eroded 1.3 billion tonnes of sediment in historical times. Over the entire MDB the new bank erosion methodology presented in this report predicts a mean annual rate of sediment production from bank erosion of 8.6 Mt/y. This is 45% of the 19 Mt/y predicted to be eroding from riverbanks in the original NLWRA assessment. Comparing the new predictions of riverbank erosion with those of gully erosion suggests that riverbanks supply 30% less sediment than gully erosion. In the NLWRA assessment the predictions were more balanced with riverbank erosion supplying 10% less. Overall the new assessment reduces the total load by almost 50%.

## ***1 Introduction***

Gully and riverbank erosion are significant land degradation processes and sources of sediment to Australian rivers. Increased sediment loads degrade downstream riverine ecosystems by increasing turbidity and nutrient loads, and by smothering bed habitat, which reduces the diversity of bedforms (Lemly, 1982; Galloway *et al.*, 1996). Erosion from stream and gully banks can generate up to 90 percent of the total sediment yield from a catchment (Olley *et al.*, 1993; Prosser and Winchester, 1996, Wallbrink *et al.*, 1998, Wasson, *et al.*, 1998). Sediment that has been eroded from gullies since European settlement is still present in many rivers and continues to impact upon river ecosystems.

This study has produced predictions of gully extent across the Murray-Darling Basin based upon extensive measurements from aerial photographs. Gully density prediction was carried out via the generation of numeric rule-based predictive models. These predictions of the location and extent of gully erosion should be useful in regional planning of erosion control. Riverbank erosion was predicted from river properties defined by the 9 second (approximately 250 m) resolution digital elevation

model for Australia, and other variables included in a simple conceptualisation of the erosion process.

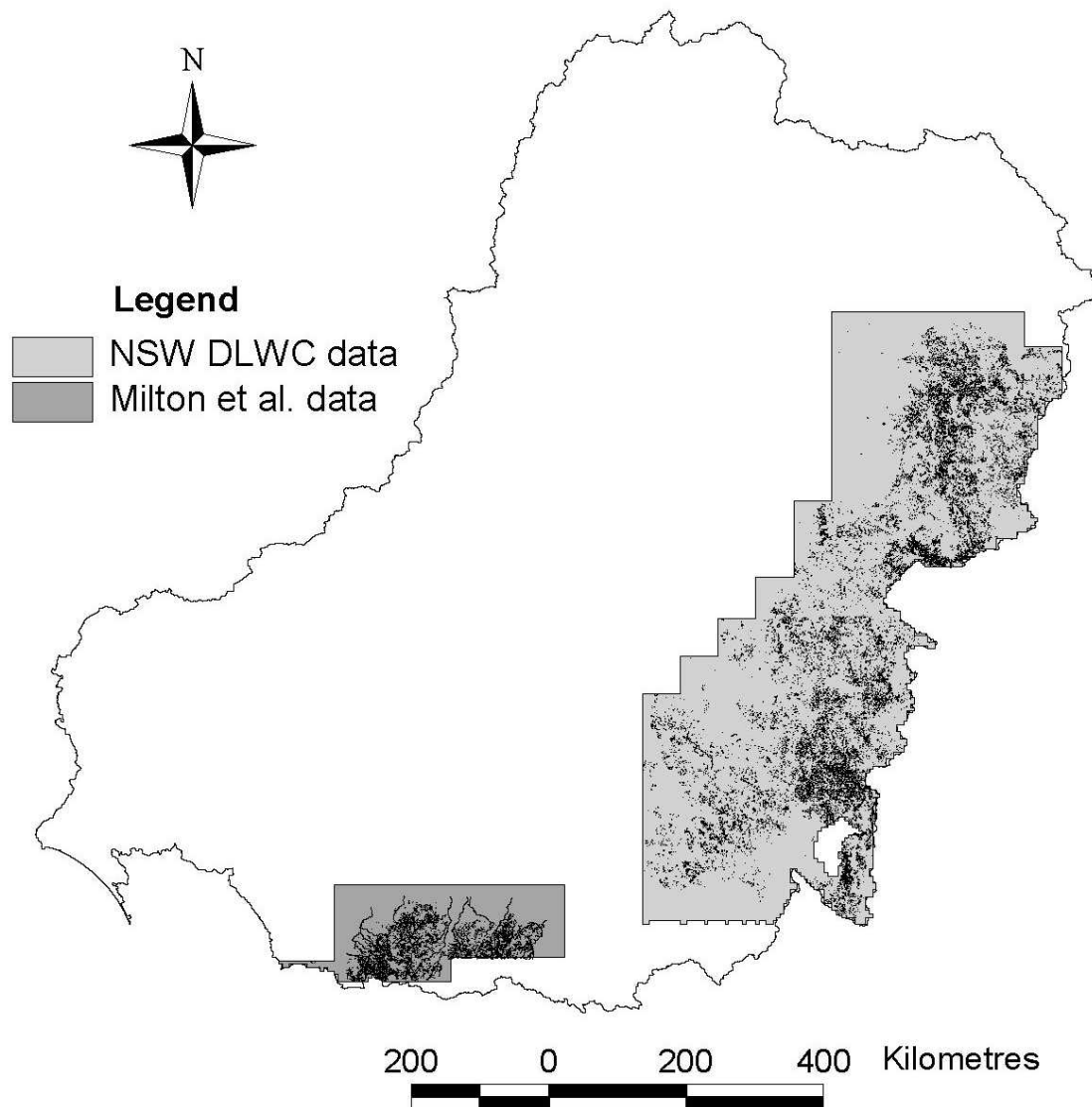
### *1.1 Gully Erosion Assessment Method*

The gully density map produced in this report is a composite map of both measured and modelled gully densities within the Murray-Darling Basin (MDB). The measured data were obtained from two sources, gully mapping carried out by the New South Wales Department of Land and Water Conservation (DLWC) and a Victorian gully map produced by Lindsay Milton and others in the 1960's (Ford, *et al.*, 1993). **Figure 1** shows the areas within the MDB covered by these two data sources. Gully densities for the remainder of the MDB were modelled from these data.

### *1.2 Modelling techniques*

To estimate gully density in areas where no gully measurements had been made statistical models were constructed using the Cubist data mining tool (version 1.08; Rulequest Research, 2002). Cubist generates models that are expressed as collections of rules, where each rule has an associated multi-variate linear model. Whenever a situation matches a rule's conditions, the associated model is used to calculate a predicted value, thus a Cubist model resembles a piecewise linear regression model (except that the rules can overlap) (Rulequest Research, 2002). Models generated using Cubist estimated gully density for the MDB in terms of the known gully densities and environmental attributes available for the whole of the MDB, across which the predictions are to be made.

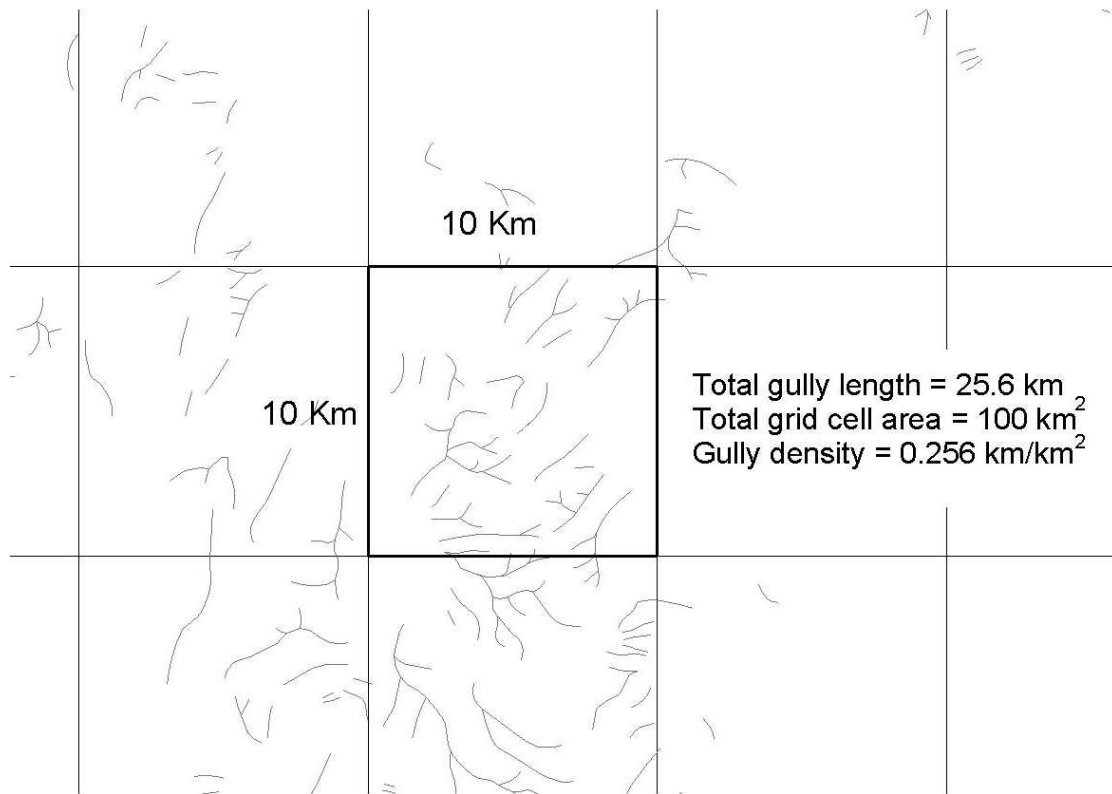
Cubist was also able to use an independent set of samples to test model accuracy, and report both summary statistics and the predictions for each validation datum. In constructing gully density models, 70% of the measured gully data were used for model building while the remaining 30% were used for model testing.



**Figure 1** Coverage and source of gully mapping data in the Murray-Darling Basin

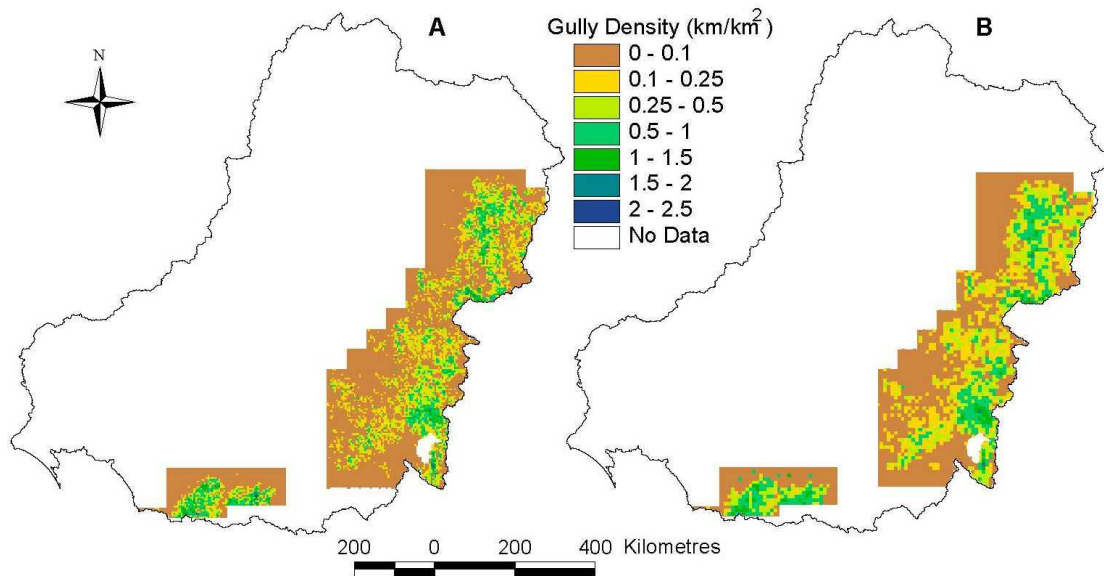
Gully density sample sets were generated by averaging the measured gully data over a grided area (**Figure 2**). For each individual grid cell the entire length of gullies was measured (in kilometres) and then divided by the total area (in kilometres<sup>2</sup>) of the grid cell. This gave a gully density measured as length of gully per unit area (km/km<sup>2</sup>). Environmental variables available for the MDB were also averaged across this grid.

This averaging procedure was performed at two grid cell resolutions: 5 km x 5 km and 10 km x 10 km (**Figure 3**). This allowed us to apply the modelling techniques at different resolutions to see which would produce the best results.



**Figure 2 Gully Density averaged over a 10 km x 10 km grid cell**

The resulting sample set was made up of 3,395 points for the 10 km resolution data and 12,428 for the 5 km resolution data, each with a calculated gully density value and the values of all predictive variables at that location.



**Figure 3 Gully density for areas of measured data averaged over a) 5 km x 5km and b) 10 km x 10 km**

The predictive variables were selected to represent the factors that could potentially control gully density. Fifteen variables were used for prediction:

- Two aggregated geology classifications derived from the 1:2,500,000 scale geology map of Australia
- Three soil characteristics derived from the Atlas of Australian Soils – solum thickness, A-horizon texture, B-horizon texture
- Six climate indices – Temperature seasonality, minimum temperature – coldest period, temperature – annual change, mean annual precipitation, lowest period moisture index, moisture index seasonality
- Contemporary landuse map produced by BRS
- Relief – slope and hill-slope length derived from the NLWRA topographic analysis of the 9" DEM.
- Annual average contemporary ground cover as determined from the normalised differential vegetation index (NDVI) derived from advanced very high resolution radiometer (AVHRR) remote sensing.

To determine which of the above variables were actually important to predict gully density, combinations of variables were tested. Examining all combinations of variables was prohibitively time consuming, so a stepwise approach was used. For the first step, each variable was used independently and the best variable identified using statistical diagnostics from Cubist outputs (correlation and relative error). This one variable was then used with each other variable, and the best second variable identified. This process was repeated until all variables were included.

Final selection of the model was based on statistical diagnostics, and visual comparisons of predicted and measured gully density maps.

### 1.3 Results of Gully Erosion Mapping

The best results, in terms of both correlation coefficients and spatially coherent patterns were consistently produced by the 10 km x 10 km model runs. Table 1 shows the best model results for the 5 km resolution and 10 km resolution model runs.

**Table 1** The best model and test data correlation coefficients for the two tested gully density resolutions

<b>Prediction Resolution</b>	<b>Modelled data correlation coefficient (r)</b>	<b>Modelled data relative error</b>	<b>Test data correlation coefficient (r)</b>	<b>Test data relative error</b>
5 km	0.73	0.55	0.71	0.59
10 km	0.84	0.45	0.74	0.57

It would appear that the spatial pattern generated by the 5 km x 5km grid averaging was too complex to model accurately using the relatively coarse scale environmental attribute data (approximately 250 m resolution grids). **Figure 3** shows the complexity of the 5 km resolution gully density pattern in comparison to the 10 km resolution data. Therefore while the 10 km resolution data is somewhat coarse it does better represent actual gully densities given the limitations in the data used to construct the models. The gully results are input into river basin modelling which uses sub-catchments of the order of 50 – 100 km<sup>2</sup> as the basic unit of calculation. The gully results are at a similar resolution to these sub-catchments.

The Cubist model used to construct the final gully density map used all fifteen predictive variables and contained 35 rules. Slope was the most predictive single variable (correlation = 0.43) with mean annual rainfall the next (correlation = 0.36). The order in which variables were selected in the regression tree model were:

- Slope
- Temperature – annual change
- A-horizon texture
- Moisture index seasonality
- Mean annual ground cover
- Temperature – seasonality
- Lowest period moisture index
- Solum thickness
- Hill slope length
- Mean annual rainfall
- Landuse
- B-horizon texture
- Minimum temperature – coldest period
- Geology1
- Geology2

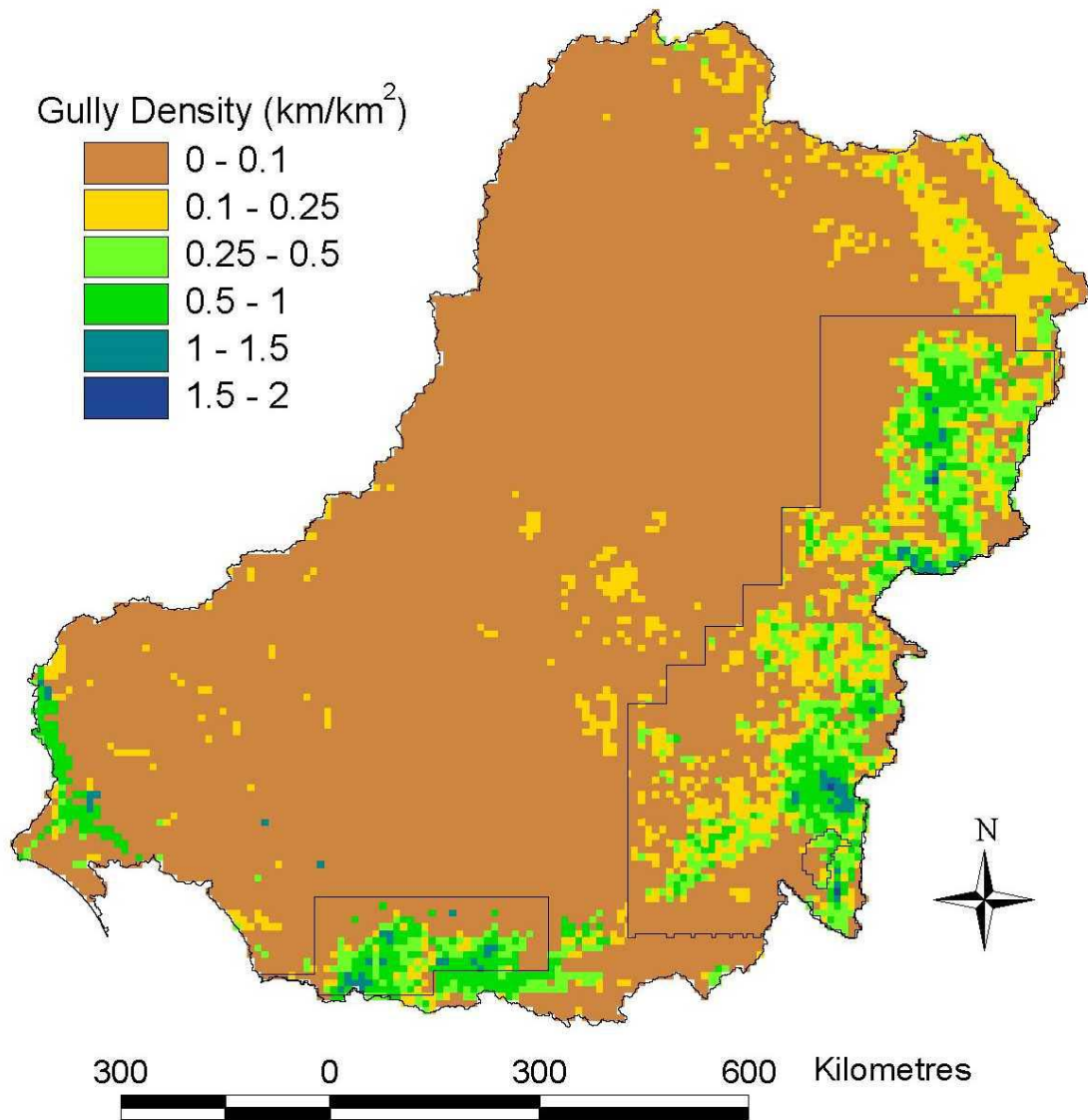
**NB:** While mean annual rainfall ranks highly as a single predictive variable it ranks lower in the regression tree because of covariance with slope.

The correlation coefficient did not improve much after the addition of about 10 variables, however, the spatial pattern produced by the model using all fifteen variables was considered to be superior to that of the models using less variables.

The final gully density results are presented in **Figure 4**. As mentioned earlier, **Figure 4** is a composite model of both the measured gully data (averaged over 10 km x 10 km) and the gully model constructed from that data. The areas of measured gully data are shown as boxes in **Figure 4**.

**Figure 4** shows the resultant gully density map in kilometres of gully length per square kilometre of area ( $\text{km}/\text{km}^2$ ). This can be converted into a soil erosion rate by

considering the volume of soil removed to form a gully and its approximate age. From available studies it was found that gullies have an average cross-sectional area of  $10\text{m}^2$ . One kilometre of gully would then produce 10,000 cubic metres (approximately 15 000 tonnes) of sediment per  $\text{km}^2$  of land. If that was eroded over a typical gully age of 100 years, the mean annual rate of erosion would be 1.5 tonnes/hectare/year.



**Figure 4** Composite gully density map for the Murray-Darling Basin (10 km x 10km grid cells).

**Figure 4** shows that some of the highest gully densities in the catchment occur on the eastern rim. Much of this area was subject to early European settlement and gullies

developed late in the 19<sup>th</sup> C. These gullies continue to contribute fine sediment and poor quality water, although gully expansion is largely complete (Eyles, 1977). The high gully densities in this area are not unexpected due to the extent of land clearance and intensive land use that have taken place. This area also consists of large areas of erodible granitic-based soils on sloping land in a climate that leads to periods of low ground cover.

Another area of moderate to high gully density is in the southern (Victorian) part of the basin. This area was also subjected to early European settlement, particularly gold mining of the 1850s. This combined with physiographic factors such as slope and climate produced a zone of particularly high gully densities.

The other area of moderate to high gully density is in the area of the Mt Lofty Ranges, South Australia. This area is similar in terrain, land use and climate to the areas of high gully erosion density in the south-eastern parts of the basin. Interestingly this area of moderate to high gully density was predicted solely by the model as there were no measured gullies in this region. Some checking against aerial photographs from this region confirms that it is an area of moderate to high gully density.

There is little gully erosion predicted over the central and north-western parts of the basin. Much of this region is far from areas of measured gully erosion and the modelling is thus an extrapolation. We have confidence in the results because they compare favourably with the 1988 reconnaissance-scale survey of land degradation in New South Wales (Graham, 1989) which did map those areas. This mapping, at a coarser resolution, and our modelling both show very little gully erosion where rainfall and slope decreased. Therefore any errors in the extrapolation have little consequence for our sediment budgets. There is no gully erosion mapping for Queensland but much of that region has similar environmental conditions to northern and western New South Wales so the modelling is not being used to make long extrapolations, giving some confidence in the results.

Overall, the average gully density for the MDB is 0.08 km/km<sup>2</sup>. There are approximately 89,000 km of gully in total, which on average have produced 13 million tonnes of sediment per year. In total, gullies in the MDB have eroded 1.3

billion tonnes of sediment in historical times. The gully density predicted in this report is less than that predicted by the NLWRA gully density model (0.13 km/km<sup>2</sup>). We attribute this result to the use of higher quality input data and the consequent generation of more accurate spatial models.

#### *1.4 Time Sequence of Gully Erosion*

The river sediment budget model (SedNet) produces mean annual river loads from a mass balance of mean annual rates of sediment input and deposition. As described above, the basic measurement of gully density is converted into a mean annual rate of sediment supply by dividing the total volume of gullies by their age. This produces the time averaged rate of sediment supply. If we interpret those results as representing the current state of sediment transport in the basin we are implicitly assuming that there are no strong temporal patterns in the development of gullies over historical times. That is, we assume that the time-averaged sediment yield from gullies is a reasonable approximation of the current sediment yield, considering the degree of uncertainty in the other aspects of the modelling. For the NLWRA, a constant value of gully age of 100 y was used across the assessment area. Here we consider whether an improved representation of time in the gully modelling is justified.

Early work on the historical development of gully erosion focussed on the Southern Tablelands of New South Wales, mainly to the south of Canberra (Eyles, 1977; Prosser and Winchester, 1996). This work showed that the majority of present gullies were initiated soon after settlement of the region and associated clearing of forests and degradation of valley-floor vegetation. The historical documentary and field evidence shows that most gullies formed between 1850 and 1900. Aerial photography first became available in the 1940's. Comparison of gully extent on those photographs with the current photographs showed very little change in gully extent in the last 50 years. This history of gully development has been used to suggest that gully sediment yields were very high from 1850 to 1900, declining in time since that date. The current rate of erosion remains uncertain, however. It should also be noted though that the vast bulk of sediment yielded from gullies is derived from the sidewalls rather

than the gully head (Blong *et al.*, 1982) so that stability of gully extent since the 1940's does not necessarily imply a reduction in sediment yield.

A similar history of gully erosion has been found for the Victorian part of the MDB, where gold mining, beginning around the 1850's was an additional cause of widespread gully development. For the Southern Tablelands of New South Wales and Victoria there is clear evidence that the sediment yields of gullies should be averaged over 150 y rather than 100 y. We have undertaken high resolution SedNet predictions in the Goulburn-Broken catchment of Victoria and compared these to results of water quality monitoring at 11 stations across the catchment. The monitoring results provide a good estimate of current sediment yield, and the monitored sites cover a wide range of gullied and un-gullied sub-catchments. There is a strong association of high area specific sediment yield (t/ha/y) recorded at the monitoring stations and the total extent of gully erosion upstream. All stations with high sediment yields come from sub-catchments with moderate to high gully densities. This suggests that gullies still yield considerable sediment today, despite the drier than average conditions over the monitoring period and the age of the gullies. The SedNet model predicts that across the Goulburn-Broken catchment, gullies are responsible for 60% of the total sediment yield. The current sediment yield is systematically over-predicted, in comparison with gauging stations, if the mean annual yield from gullies is estimated using an age of 100 y. Predictions are close to observations if a gully age of 150 is used. The results suggest that specifying gully age may improve the results but that no further inclusion of temporal patterns is warranted, given the uncertainty over these patterns as outlined below.

More recent work on the history of erosion has expanded the geographical scope of the studies beyond the Southern Tablelands and into other regions, although still focussed in the south eastern part of the basin. This has shown that the majority of gully erosion, and riverbank erosion, does not always occur immediately after initial agricultural settlement. In Tarcutta Creek, a tributary of the middle Murrumbidgee catchment, Page and Yarden (1998) found that gullies and stream banks expanded as late as the 1980's. We have found anecdotal evidence for widespread gully initiation in the nearby Tumut River catchment in the 1960's. A detailed study of a highly eroded sub-catchment of the Lachlan River (Bush, 2001) found that one third of the

gully length formed between 1944 and the present day. Work on a grazed savannah catchment in Queensland found that while there were extensive gullies present in 1960 they doubled in length between then and the present day, despite no further land clearing (Post, unpublished data). The reasons for the differences between these regions and the Southern Tablelands of New South Wales are not yet clear and until further information is available it is hard to justify moving away from a time averaged gully sediment yield to gully growth as a function of time.

## **2 Introduction to Riverbank Erosion**

Riverbank erosion is the most uncertain of the sediment source terms in the river budget modelling. It is known that degradation of riparian vegetation and other impacts on our rivers have resulted in greatly increased rates of riverbank erosion, to the extent that this erosion process cannot be ignored as a sediment source in regional assessments. There remains, however, very little data on the rates of river bank erosion and the environmental factors controlling those rates. The only large-scale quantitative rule of which we are aware is the simple empirical rule for meander migration and bank erosion proposed by Rutherford (2000) following a review of global literature:

$$BE = 0.016Q_{1.58}^{0.60} \quad (1)$$

where  $BE$  is the bank erosion rate in metres of recession per year, and  $Q_{1.58}$  is the discharge ( $\text{m}^3/\text{s}$ ) of the 1.58 y recurrence interval flood event, assumed to represent bankfull discharge. The bank rule essentially scales the rate of bank erosion to the size of the river as both size and discharge increase with catchment area. This rule was applied across Australia as part of the river sediment budgets for the NLWRA. The results revealed two limitations. First, many of the highest predicted rates of bank erosion were in high discharge rivers that were largely undisturbed with resultant low rates of bank erosion. Brooks (1999) has shown that natural rates of bank erosion can be very low in Australian rivers with intact riparian vegetation and that erosion is greatly accelerated with removal of riparian vegetation (see also Abernethy and Rutherford, 2000; Prosser et al. 2001). Second, the overall rate of erosion was too high when averaged over historical times, contributing more sediment

to rivers than recorded by river monitoring data. Equation (1) was modified for inclusion in SedNet to incorporate these three effects:

$$BE_x = 0.008(1 - PR_x)(Q_{1..58})^{0.60} \quad (2)$$

where  $PR_x$  is the proportion of bank with intact native riparian vegetation. Riparian vegetation was mapped across the NLWRA assessment area, including the MDB, by intersection of the river network with a grid of native vegetation cover detected by remote sensing in 1995. This was obtained from the Australian Land Cover Change project at a resolution of 100 m (BRS, 2000). This is the best available data but is still a crude measure of riparian condition. The 100 m resolution fails to identify narrow bands of remnant riparian vegetation in cleared areas but it also fails to identify narrow valleys of cleared land penetrating otherwise uncleared land.

For sediment budgets, the erosion rate needs to be expressed in terms of tonnes per year of sediment eroded along the length ( $L_x$ , m) of each river link  $x$ . We did this by assuming a mean bank height of 3 m, and a sediment bulk density of 1.5 t/m<sup>3</sup>. Thus

$$BC_x = 18(1 - PR)(Q_{1..58})^{0.6} L_x \quad (3)$$

where  $BC_x$  is the input from bank erosion in each link (t/y).

The results of bank erosion mapping for the MDB, using equation (2) are shown in **Figure 5**. These are the results included in the NLWRA assessment. Geomorphic studies of our lowland rivers show that they have experienced very little historical erosion (Rutherford, 2000), and in some areas there is greater concern over channel contraction rather than erosion. This observed pattern is not reflected in the results of **Figure 5**, because Equation 2 predicts an ever increasing rate of bank erosion as a river increases in size and discharge downstream. This is particularly evident along the Darling River where very high rates of erosion are predicted along cleared river banks.

### 2.1 MDB Assessment of Riverbank Erosion

The main processes of riverbank erosion are mass failure of the banks (slumping) and scour of the banks by the hydraulic forces of flow. Mass failure results in local

movement of sediment and changes to bank form but only results in significant sediment yield if the slumped soil is removed by river flow, often leading to further slumping of steepened banks. Thus, fluvial scour can be viewed as the most significant process. The rate of fluvial scour has been related to stream velocity, boundary shear stress and stream power. These are all functions of discharge and slope. In his review of global bank erosion data, Rutherford (2000) found a significant relationship with stream power ( $P = \rho g Q S$ , where  $\rho$  is the density of water,  $g$  is the acceleration due to gravity and  $S$  is the river bed slope) but this was not as good a relationship as that for bankfull discharge. This was partly because channel slope was not specified for some data sets. In this project we have explored whether the observed pattern of low bank erosion in the lowland streams of the MDB could be better predicted from stream power than bankfull discharge.

A second limitation of the original NLWRA results is that they do not consider whether the river banks are composed of erodible materials or not. Many rivers have such high energy (and high stream power) that erodible alluvial materials have not accumulated. These rivers have beds and banks composed largely of rock and erode very slowly, as a function of the weathering and abrasion rate of the rock. For our purposes, the erosion rate of rock is so small to be negligible. Valley floors are narrow where alluvial materials do not accumulate and the banks are composed of bedrock, then as the valley floor widens downstream an increasing proportion of the banks are composed of alluvial materials rather than bedrock. We mapped floodplain width, for the purposes of predicting floodplain deposition, as part of the NLWRA sediment budgets (Pickup and Marks, 2001). This can be used as a surrogate for valley width. Limited field surveys in the Murrumbidgee catchment, conducted as part of an associated project, show that where floodplain width is zero the banks are almost completely composed of rock; where the floodplain is 300 m wide or less, there is 20% exposure of rock; where floodplains are 300-500 m wide there is 8% of rock exposure; and where valleys are more than 500 m wide there is negligible exposure of rock and the banks are composed of erodible materials. These observations can be expressed as an exponential relationship describing an increasing proportion of erodible bank as a function of floodplain width.

Including stream power and the proportion of erodible banks into a new bank erosion rule for the MDB gave:

$$BE_x = 0.00002\rho g Q_x S_x (1 - PR_x) (1 - e^{-0.008F_x}) \quad (4)$$

where  $Q_x$  is mean annual flow in Ml/y and  $F_x$  is the floodplain width in m. Other terms are as defined above.

## 2.2 Bank Erosion Results

**Figure 6** maps the result of Equation (4) across the MDB using the same inputs for riparian vegetation and discharge prediction as in **Figure 5**. Riverbed slopes were derived from the AUSLIG 9" DEM. The map shows substantial reduction in bank erosion rates in the lowland rivers, conforming better to geomorphological knowledge of the region. Of particular difference is removal of the very high bank erosion rates predicted for the Darling River, which is a large river with poor riparian vegetation. It is, however, a very low energy river with very low slope, hence there is limited ability of flows to scour the banks. Some of the upper valleys of the MDB are reduced in erosion rate, in comparison to the NLWRA results, as a result of incorporating bedrock exposure into the analysis, while others have increased as a result of having steep slopes and therefore high stream power relative to their discharge. It should be noted that bankfull discharge, used in the original rule, is a linear function of mean annual flow so the influence on the results of discharge variations across the MDB remains unchanged. The differences between the two assessments are illustrated in **Figure 7**.

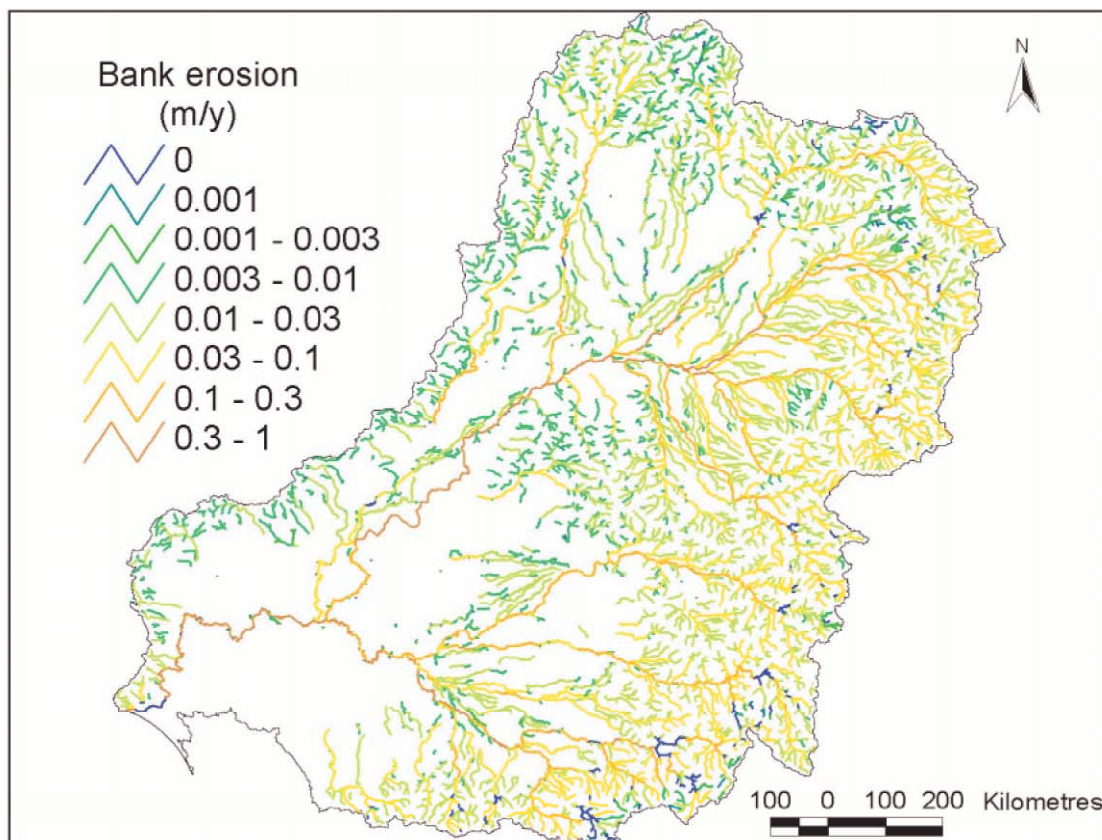
Over the entire MDB the new results predict a mean annual rate of sediment production from bank erosion of 8.6 Mt/y. This is 45% of the 19 Mt/y predicted to be eroding from riverbanks in the original NLWRA assessment. The vast majority of that change has been in the drier western part of the basin where all terms of the river sediment budgets are most uncertain and where there is little data on erosion rates. Across the basin the mean annual rate of erosion is between 1 and 2 cm/y, although it will not be distributed evenly in time. The vast majority of bank erosion occurs during large infrequent flood events. The highest rates of erosion predicted are

approximately 40 cm/y equating to 40 m of river widening over the last 100 y. This degree of widening is supported by historical records.

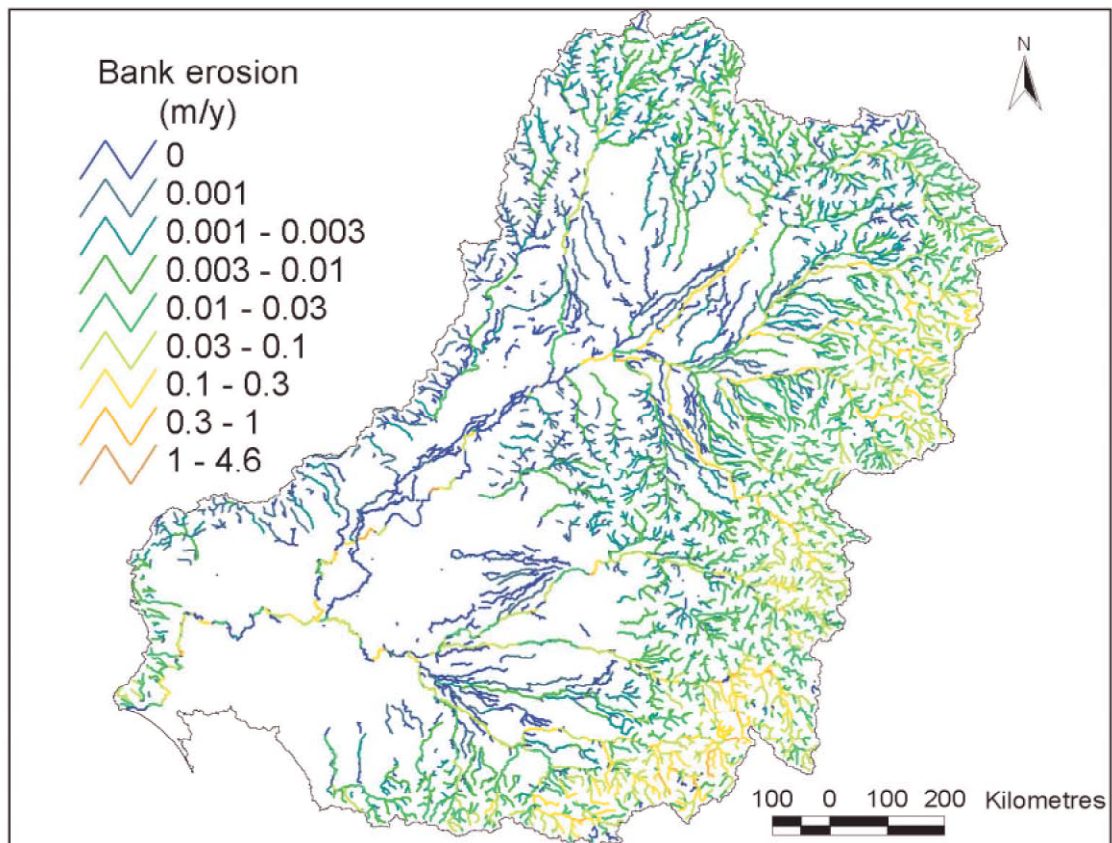
### 3 Conclusion

This report presents gully and river bank erosion predictions for the Murray-Darling Basin. The results in this report significantly improve upon those presented in the NLWRA assessment.

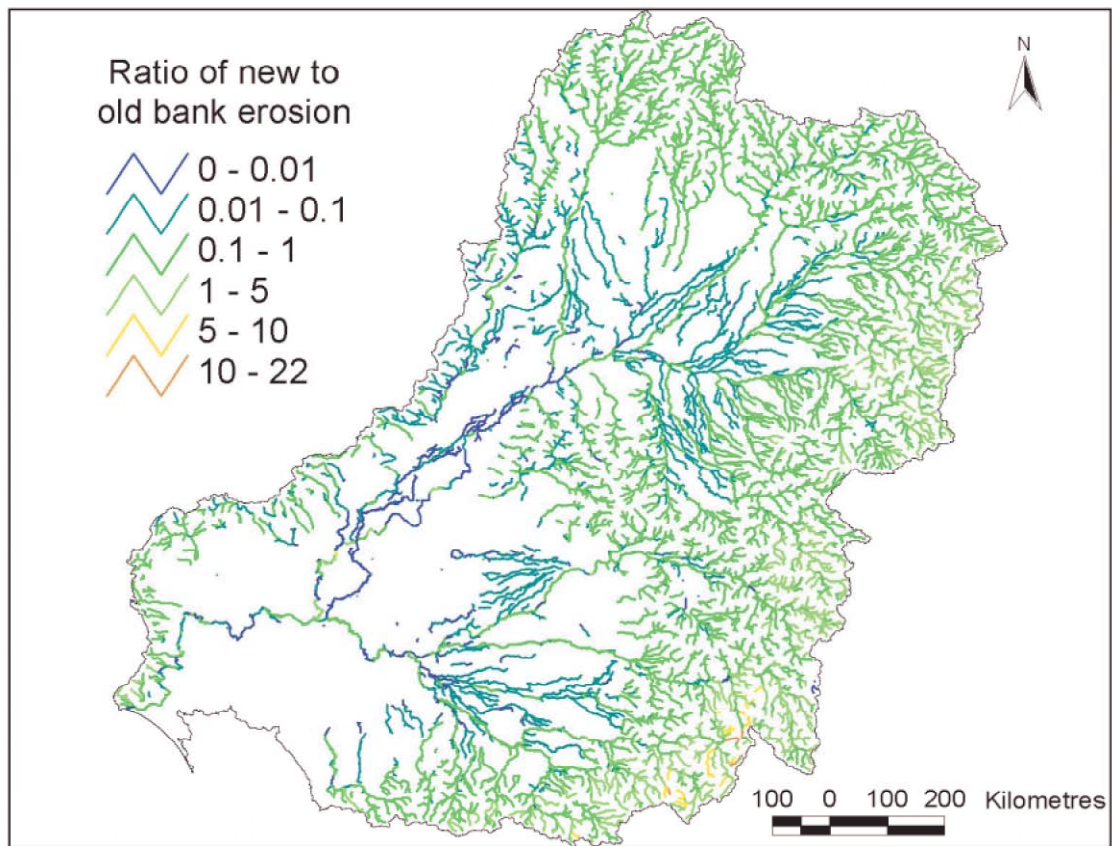
Comparing the new predictions of riverbank erosion with those of gully erosion suggests that riverbanks supply 30% less sediment than gully erosion. In the NLWRA assessment the predictions were more balanced with riverbank erosion supplying 10% less. Overall the new assessment reduces the total load by almost 50%.



**Figure 5. Original bank erosion prediction used for the NLWRA, based upon bankfull discharge and riparian vegetation.**



**Figure 6. Mean annual rate of bank erosion predicted as a function of discharge, riverbed slope, riparian vegetation and valley width using Equation (4).**



**Figure 7. Ratio of the new bank erosion predictions of Figure 6 with the NLWRA results of Figure 5.**

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