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CSIRO Land and Water, Canberra
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ABSTRACT

A gully density map for the more closely settled areas of Australia has been generated, covering some 1.7 million km^2. Gully density measurements were obtained from aerial photographs and previous land degradation reports. These data were used to build a map based regression tree models of gully density. The models are based upon environmental attributes available at the continent scale. The model rules were applied across the assessment area to predict gully density in places where no measurements were available. Results show high gully density in the eastern highlands and tropical grazing lands. The rules for prediction are complex with the results being affected by many environmental variables including landuse, geology, soil texture, rainfall, indices of seasonal climate extremes and terrain-based attributes such as slope and hill slope length.

1 INTRODUCTION

Gully erosion is a significant land degradation process and a source of sediment to Australian rivers. This sediment, together with attached nutrients, has affected downstream riverine ecosystems by smothering bed habitat, reducing the diversity of bedforms and increasing turbidity and nutrient loads (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. Although gully development has slowed since about 1950 (Eyles, 1977), gullies continue to supply sediment to rivers.

This study, as a component of the National Land and Water Resources Audit (NLWRA), has produced predictions of gully extent across large areas of Australia based upon extensive measurements from aerial photographs. Gully density prediction was carried out via the generation of numeric rule-based predictive models for four regions of Australia. These predictions of the location and extent of gully erosion should be useful in regional planning of erosion control.

2 STUDY AREA

The study area (**Figure 1**) is the NLWRA River Basins Containing Intensive Agriculture (RBCIA). This area includes the Murray-Darling Basin (MDB), south-west Western Australia, Tasmania and coastal catchments from Cape York to the Eyre Peninsula.

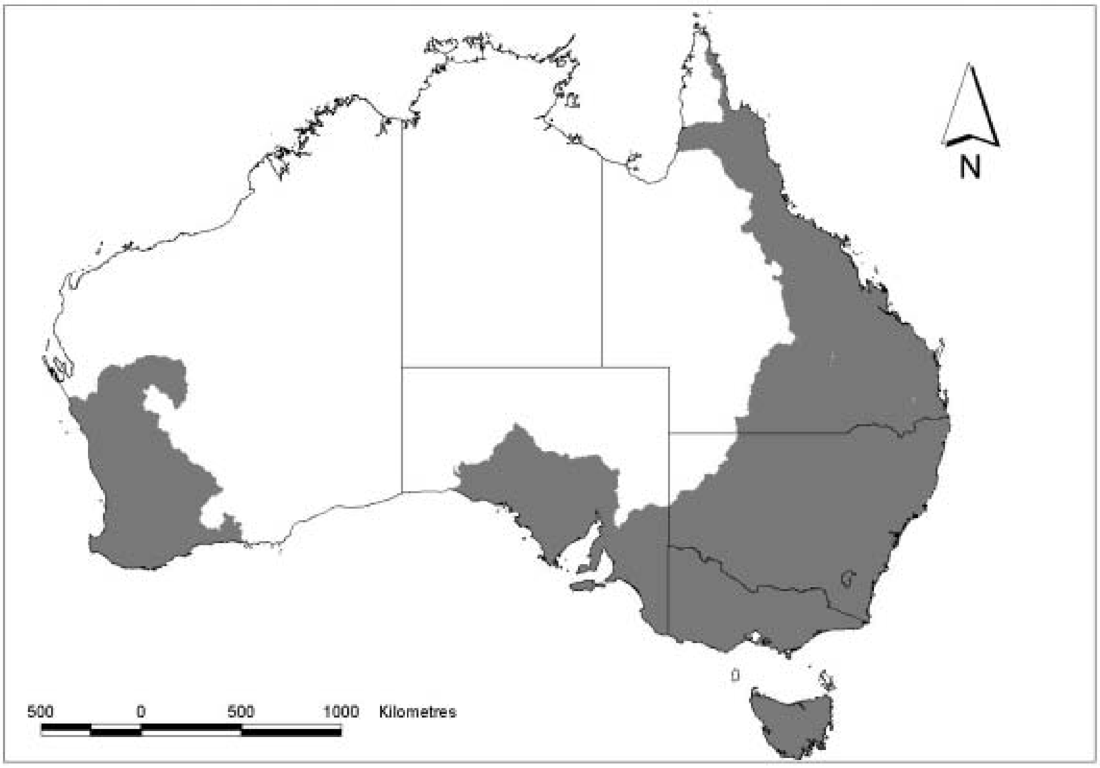


Figure 1: *The NLWRA River Basins Containing Intensive Agriculture*

3 METHODOLOGY

Three separate data sources were used to map the density of gullies across the assessment area: aerial photographs, the NSW 1988 Land Degradation Survey (Graham, 1989) and a gully density map of Victoria (DNRE, 2001).

3.1 Aerial photographs

For the NLWRA RBCIA (excluding New South Wales, the upper Murray-Darling Basin, and Victoria) gullies were traced on 428 stereo photo pairs. Photograph selection was made by first analysing the physical landscape of different areas. Lithology and rainfall distribution maps were used to ensure that a variety of landscape types were represented in the model. Availability of high quality photographs also dictated where gully density measurements were taken.

Using a stereoscope, gullies were mapped onto transparent plastic overlays. Gullies were defined on the photographs as steep walled, poorly vegetated, incised channels with a small catchment area (< 10 km^2). Each aerial photograph was also divided into terrain regions based upon land use, geology and relief. Each region was then allocated the gully density measured across the entire unit (**Figure 2**). The gullies measured from the aerial photographs were converted into gully density by dividing the sum of the total length of mapped gullies (in km) by total area of the aerial photograph (in km^2). This gave a gully density measurement of kilometres of gully length per square kilometre of area (km/km^2).

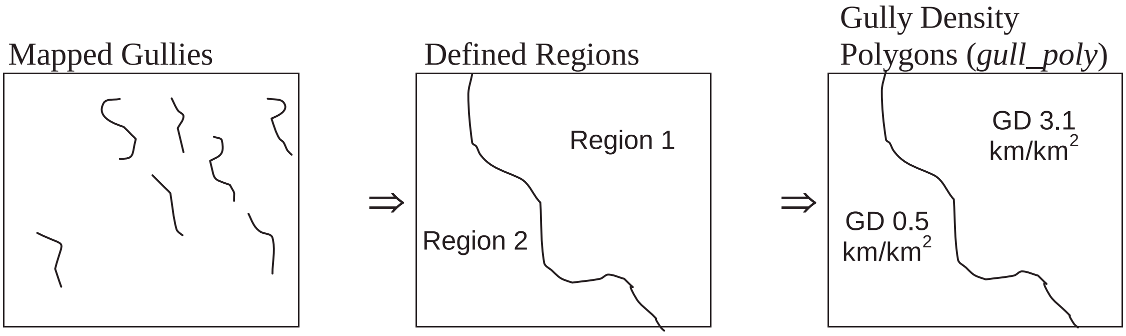
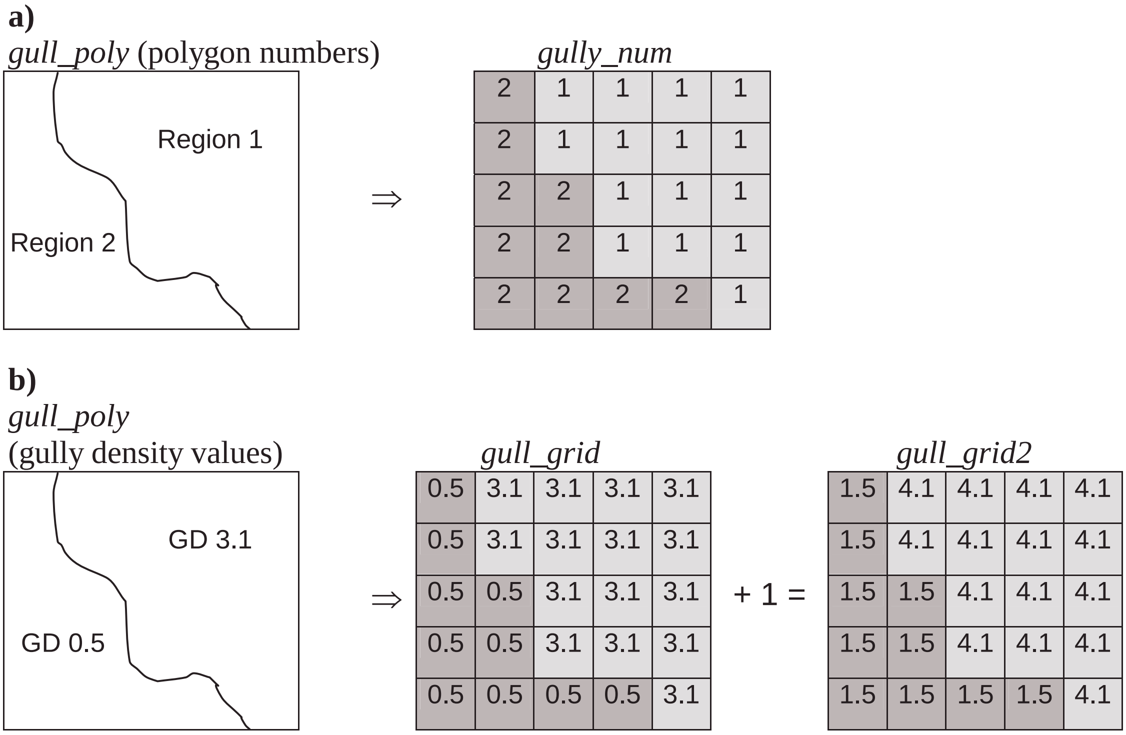


Figure 2: *Conversion of mapped gullies into gully density regions and polygons*

The gully density polygons were then converted to a format that enabled the modelling software (Cubist) to process the data. As the gully density polygons were created as ArcInfo™ polygon coverages all of the following processing was carried out using ArcInfo™ GIS software.

Firstly, the polygon coverage *gull_poly* was converted into two separate raster grids of 9 second (approximately 250 x 250 metre) resolution. The first of these grids (*gully*) contained only the identification number of each polygon, i.e., each converted polygon had a unique identification number (**Figure 3a**). The second grid (*gull_grid*) contained the actual gully density data, in kilometres of gully length per square kilometre (km/km^2), for each individual polygon (**Figure 3b**). *Gull_grid* then had a value of one added to all data cells and all NODATA cells were given a value of zero (**Figure 3b**). This was necessary because the Cubist software treats all data less than one as non-data (one can be subtracted from all data cells at the end of the modelling process). The resultant grid was a gully density grid named *gull_grid2*.



gully_num

2	1	1	1	1
2	1	1	1	1
2	2	1	1	1
2	2	1	1	1
2	2	2	2	1

gull_grid

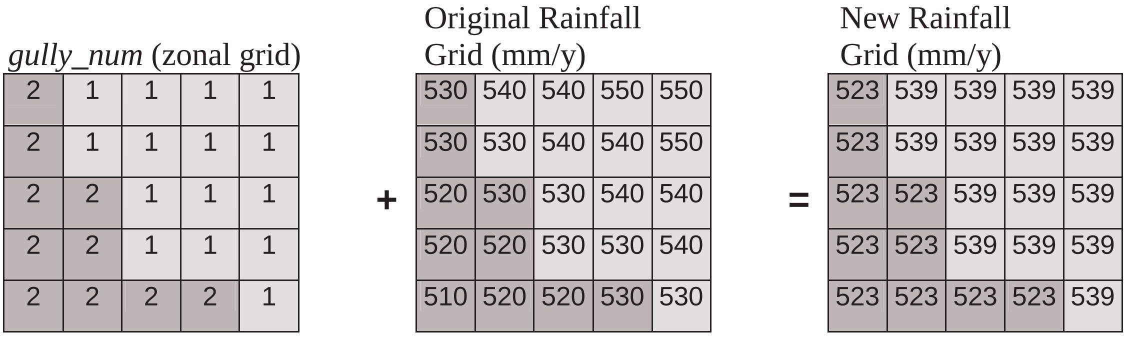
0.5	3.1	3.1	3.1	3.1
0.5	3.1	3.1	3.1	3.1
0.5	0.5	3.1	3.1	3.1
0.5	0.5	3.1	3.1	3.1
0.5	0.5	0.5	0.5	3.1

gull_grid2

1.5	4.1	4.1	4.1	4.1
1.5	4.1	4.1	4.1	4.1
1.5	1.5	4.1	4.1	4.1
1.5	1.5	4.1	4.1	4.1
1.5	1.5	1.5	1.5	4.1

Figure 3: *Conversion of defined gully density polygons to raster grids*

The next step was to determine the environmental attribute data associated with the areas (polygons) of known gully density. To do this the *gully_num* grid, created above, was used as a zonal grid. That is, each of the available environmental attributes (e.g. landuse, mean annual rainfall, geology, etc.) was summarised for each of the gully density polygons. For example, all the mean annual rainfall cells that lay within a particular polygon were averaged (mean) and that average was assigned to the polygon area and applied to new grid (**Figure 4**).



gully_num (zonal grid)

2	1	1	1	1
2	1	1	1	1
2	2	1	1	1
2	2	1	1	1
2	2	2	2	1

\+

Original Rainfall Grid (mm/y)

530	540	540	550	550
530	530	540	540	550
520	530	530	540	540
520	520	530	530	540
510	520	520	530	530

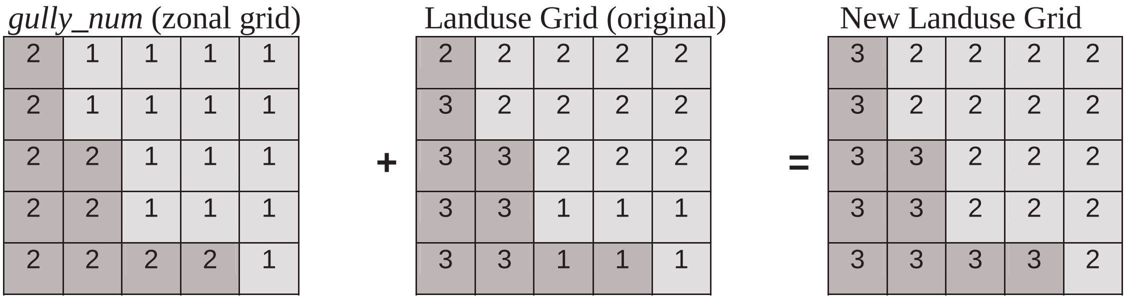
=

New Rainfall Grid (mm/y)

523	539	539	539	539
523	539	539	539	539
523	523	539	539	539
523	523	539	539	539
523	523	523	523	539

Figure 4: *An example of a conversion of a continuous environmental attribute grid (mean annual rainfall) to a zonal mean grid using the gully density polygon boundaries as the zonal mean area*

This mean average method was used for continuous data such as climatic and terrain data, however, for categorical data (e.g. landuse and geology) a zonal majority was used whereby the variable with the majority of cells within the polygon was applied to the new environmental attribute grid (**Figure 5**).



gully_num (zonal grid)

2	1	1	1	1
2	1	1	1	1
2	2	1	1	1
2	2	1	1	1
2	2	2	2	1

\+

Landuse Grid (original)

2	2	2	2	2
3	2	2	2	2
3	3	2	2	2
3	3	1	1	1
3	3	1	1	1

=

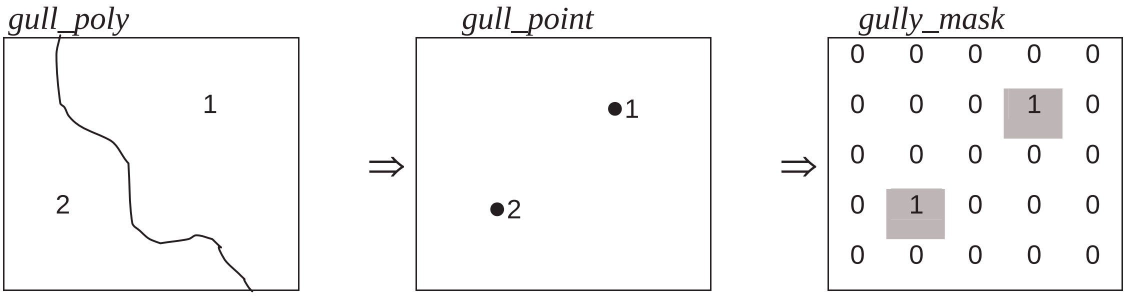
New Landuse Grid

3	2	2	2	2
3	2	2	2	2
3	3	2	2	2
3	3	2	2	2
3	3	3	3	2

Figure 5: *An example of a conversion of a categorical environmental attribute grid (landuse) to a zonal majority grid using the gully density polygon boundaries as the zonal majority area.* ***NB:*** *for the landuse grid: 1= forest; 2 = crop; 3 = grazing pasture*

The resultant grids in **Figures 4** and **5** produced the raw data that was entered into the model. However, the conversion from a polygon to a raster grid produced an artificially high number of sample points. That is, each 250 x 250 metre cell represented an individual sample point. Entering these multiple data points into the model would result in spurious results as it would supply the model with many consistent data points for what is effectively the same location on the landscape.

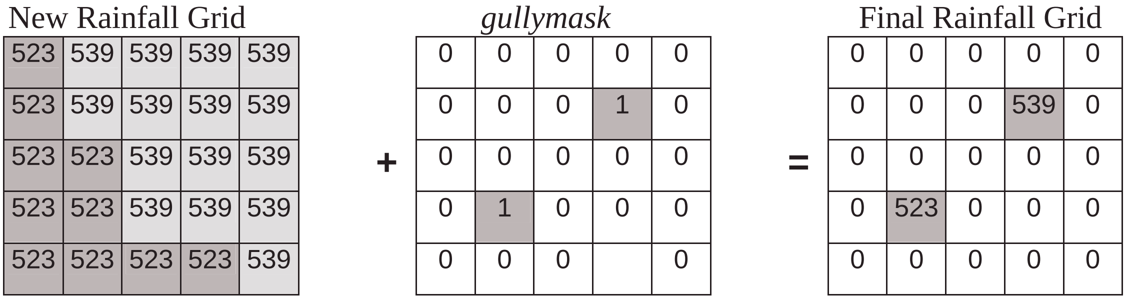
To ensure that each gully measurement was represented by a single value in the modelling a mask grid was also necessary. The polygon coverage *gull_poly* was converted into a point coverage (*gull_point*) where each polygon in the coverage was represented by a single point located approximately in the centre of each polygon. This point coverage was subsequently converted to a raster grid and all cells that contained gully density data were assigned a value of one and all cells of NODATA were assigned a value of zero. The resultant grid was a mask grid named *gully_mask* (**Figure 6**).



0	0	0	0	0
0	0	0	1	0
0	0	0	0	0
0	1	0	0	0
0	0	0	0	0

Figure 6: *The generation of a gully mask grid from the gully polygon data*

Next, using the *gully_mask* mask grid a new set of environmental attribute grids were generated that only applied data to the areas in *gullymask* that had a value of 1. All other cells were given a value of zero (**Figures 7 & 8**).



New Rainfall Grid

523	539	539	539	539
523	539	539	539	539
523	523	539	539	539
523	523	539	539	539
523	523	523	523	539

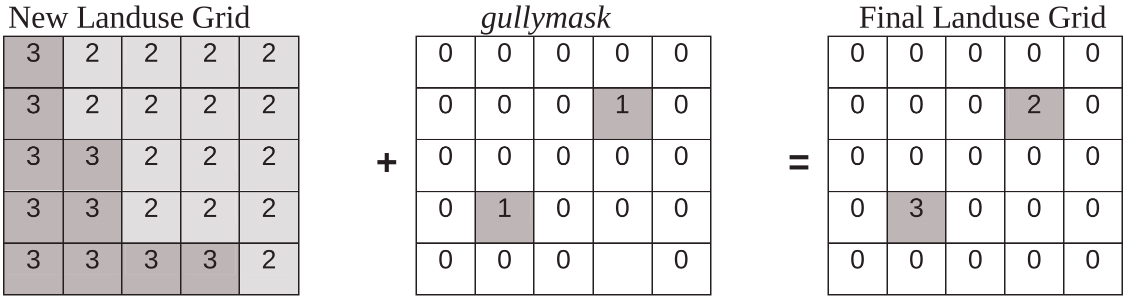
gullymask

0	0	0	0	0
0	0	0	1	0
0	0	0	0	0
0	1	0	0	0
0	0	0		0

Final Rainfall Grid

0	0	0	0	0
0	0	0	539	0
0	0	0	0	0
0	523	0	0	0
0	0	0	0	0

Figure 7: *Creation of the final continuous grid (rainfall) using the gully mask grid to reduce the number of data points to be entered into model.*



New Landuse Grid

3	2	2	2	2
3	2	2	2	2
3	3	2	2	2
3	3	2	2	2
3	3	3	3	2

gullymask

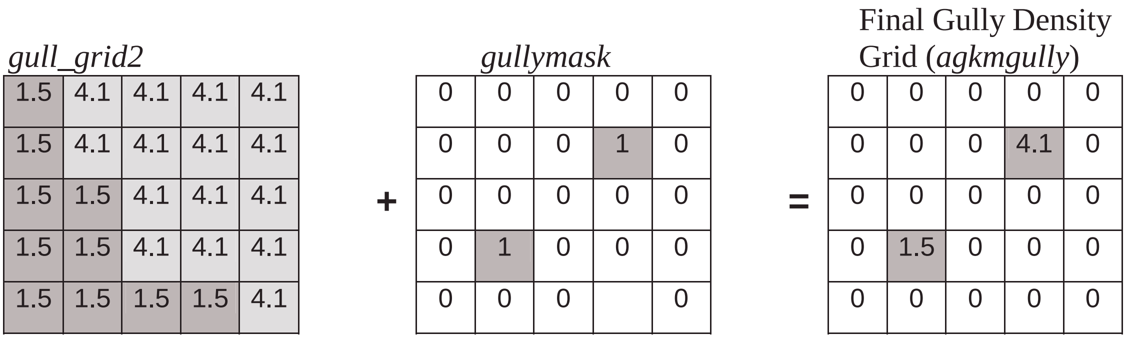
0	0	0	0	0
0	0	0	1	0
0	0	0	0	0
0	1	0	0	0
0	0	0		0

Final Landuse Grid

0	0	0	0	0
0	0	0	2	0
0	0	0	0	0
0	3	0	0	0
0	0	0	0	0

Figure 8: *Creation of the final categorical grid (landuse) using the gully mask grid to reduce the number of data points to be entered into model.*

A similar process was also applied to the gully density grid (*gull_grid2*) (**Figure 9**).



gull_grid2

1.5	4.1	4.1	4.1	4.1
1.5	4.1	4.1	4.1	4.1
1.5	1.5	4.1	4.1	4.1
1.5	1.5	4.1	4.1	4.1
1.5	1.5	1.5	1.5	4.1

\+

gullymask

0	0	0	0	0
0	0	0	1	0
0	0	0	0	0
0	1	0	0	0
0	0	0		0

=

Final Gully Density Grid (*agkmgully*)

0	0	0	0	0
0	0	0	4.1	0
0	0	0	0	0
0	1.5	0	0	0
0	0	0	0	0

Figure 9: *Creation of the final gully density grid using the gully mask grid to reduce the number of data points to be entered into model.*

The final data preparation step was to covert all the final ArcInfo™ grids into binary floating point files. UNIX shell scripts were then prepared to facilitate the conversion of the floating point files into a format that the Cubist software would accept. From the steps described above the resulting tabulated data that was used in Cubist were structured as shown below:

No.	**Gully Density (km/km^2)**	**Landuse**	**Mean Rainfall (mm)**	**Var x**	**Var y**
1	4.1	2	539	…	…
2	1.5	3	523	…	…

The Cubist regression tree software used for the modelling is a tool for generating rule-based predictive models from data. We used Cubist to predict gully density in terms of the known environmental attribute values (e.g. land use and mean annual rainfall). Cubist did this by building a model containing one or more rules, where each rule is made up of a combination of conditions and an associated linear expression. If a case satisfies all the conditions of a rule, then the linear expression is appropriate for predicting the target value. A Cubist model thus resembles a piecewise linear regression model (except that the rules can overlap) (Rulequest, 2001).

UNIX shell scripts were prepared to automatically test various combinations of environmental attributes. The combination of variables that gave the best correlation coefficient as well as produced the most spatially coherent patterns was used. Gully density maps for each prediction region were generated by converting the resultant rule-based text files into ArcInfo™ AML scripts.

Initially a single model for the entire assessment area (excluding NSW and upper MDB and Victoria) was generated, however, the results from this were poor so regions of geographical contiguity were defined and models constructed for each region. The three regions are: West Australia; South Australia and Tasmania; and coastal Queensland (**Figure 10**).

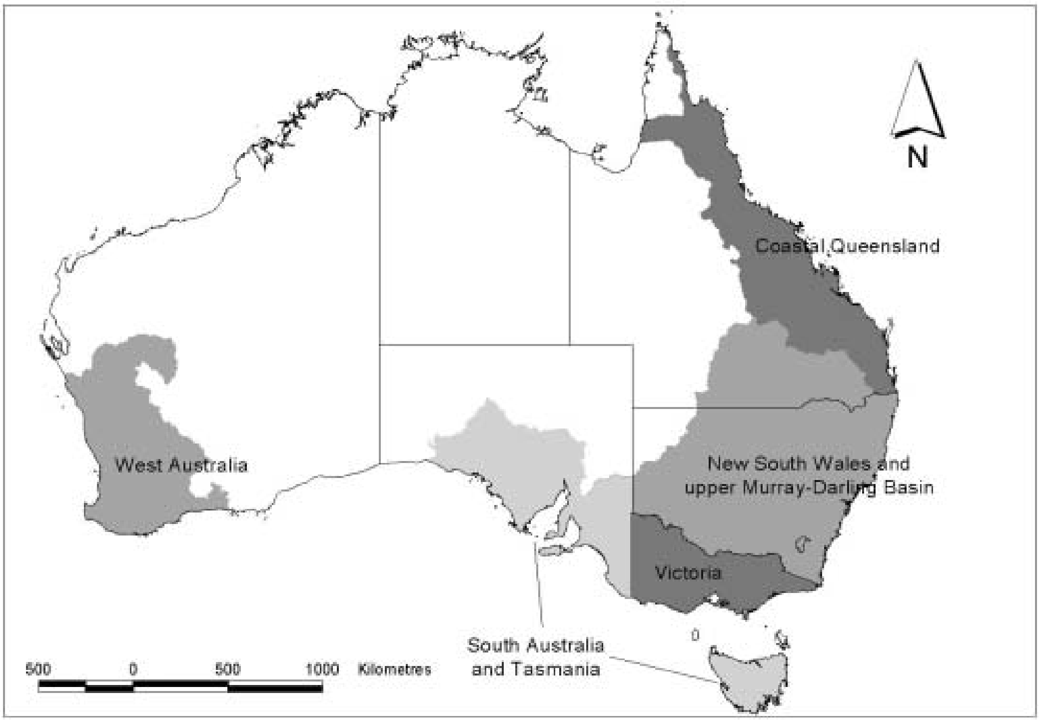


Figure 10: *Gully density prediction regions*

Seventy percent of the measured gully density points were used to create each model. The remaining 30% were used to test model accuracy. **Table 1** indicates the relationships for the model and test data for each of the prediction regions.

Table 1: *Model and Test data correlation coefficients for the gully density prediction regions.*

Prediction Region	Modelled Data	Test Data
NSW and upper MDB	0.94	0.83
Coastal Queensland	0.81	0.43
South Australia and Tasmania	0.89	0.84
West Australia	0.73	0.43

The data in **Table 1** indicates that the best models were for NSW and upper MDB; and for South Australia and Tasmania. In comparison, the predictions for Coastal Queensland and West Australia are poor. Such poor results may be attributed to several factors including the scarcity of aerial photographs (particularly for West Australia) and the "over mapping" of gully density polygons (which was the case for parts of the Coastal Queensland region). "Over mapping", in this instance, means the over complexity assigned to the terrain polygons during the aerial photograph analysis step. Very complex terrain polygons can produce poor results because the inability of the model to resolve the differences in scale of very detailed terrain polygons with relatively coarse scale (9second) input environmental variables.

On the basis of the test correlation coefficients, the gully density predictions for the West Australia and Coastal Queensland regions are not as reliable as those for the NSW/upper MDB and South Australia/Tasmania regions. However, manual aerial photograph verification of areas of high predicted gully density was carried out and the results gave us confidence that the models reasonably predicted areas of high gully density.

In general the test results are indicative of the difficulty in modelling a natural process with high variability using a limited database. Taking this into account it should noted that the resulting gully density map is not without inaccuracies and for some areas has not been confirmed by aerial photograph or field verification. However, it does provide a broad illustration of gully extent on a continent scale.

Table 2 shows the environmental variables that produced the best model results for each prediction region. The environmental variables used to predict gully density for each of the regions varied considerably. Landuse is the only variable that was used by all four models with soil texture, temperature (seasonality) and relief being the next most common variables used to predict gully density. This inconsistency in the variables used by each model again illustrates the difficulty in modelling a complex natural process from such a limited information base. Of greater encouragement is the observation that each of the environmental variables used have plausible cause and effect links to gully formation.

Table 2: *Environmental variables used by each regional model*

Environmental variables	Prediction Region			
	NSW and upper MDB	Coastal Queensland	SA and Tasmania	West Australia
Soil texture (A horizon)	✓	✓	✓	
Soil texture (B horizon)	✓		✓	✓
Solum thickness	✓		✓	
Soil type			✓	✓
Temperature – seasonality		✓	✓	✓
Min temp – coldest period	✓			
Temperature – annual change	✓	✓		
Annual precipitation		✓	✓	
Moisture Index seasonality	✓		✓	
Geology/age class	✓	✓		
Hill slope length		✓	✓	
Land use	✓	✓	✓	✓
Ground cover range	✓			
Relief		✓	✓	✓
Slope (percent)			✓	✓

3.2 Land Degradation Survey of New South Wales (1988)

For NSW and the upper MDB, data from the 1988 Land Degradation Survey of NSW were used (Graham, 1989). These are measurements of gully density from aerial photographs across NSW. The measurements were taken on a regular grid of 5 to 10 km spacing across NSW, resulting in over 13000 sample points. At each sample point an area of 1 km^2 was examined. We found that this area was very small compared to the spacing of gullies. Thus there was much variation in the data even within a small region as some sample points were on top of hills, where gullies do not form, and at the other extreme were sample points at valley junctions which contained small networks of gully. Consequently the data only represented coherent and predictable patterns of erosion if averaged over a large area. We found that the best results were achieved by averaging the data across 40 x 40 km cells and then applying the data to the same modelling technique described in **Section 2.1**. No gully density measurements were acquired for the Queensland part of the MDB, however because of physiographic similarities with areas within NSW, the NSW model was also applied to this area.

3.3 Victoria

For Victoria, several gully density maps were explored. The first map extended the NSW 40 x 40 km model to the whole of Victoria. The second used data from the aerial photograph-based model method described earlier. The third source was a polygon map of gully density, provided by DNRE, which was based upon mapping by Lindsay Milton and others (Ford, *et al*., 1993). This is at fairly coarse scale consisting of 33 polygons across the state, however, as it was based entirely on intensive aerial photograph interpolation it was assumed to provide the best spatial distribution of gully density and therefore this data was used.

4 RESULTS AND DISCUSSION

Figure 11 shows the resultant gully density map in kilometres of gully length per one square kilometre of area (km/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 limited studies it was found that the average sized gully is approximately five metres wide and two metres deep. One kilometre of gully would then produce 10,000 cubic metres (approximately 15 000 tonnes) of sediment per km^2 of land. If that was eroded over an average gully age of 100 years, the mean annual rate of erosion would be 1.5 tonnes/hectare/year.

Some of the highest gully densities occur in the eastern highlands (Figure 2). Much of this area was subject to early European settlement and gullies developed late in the

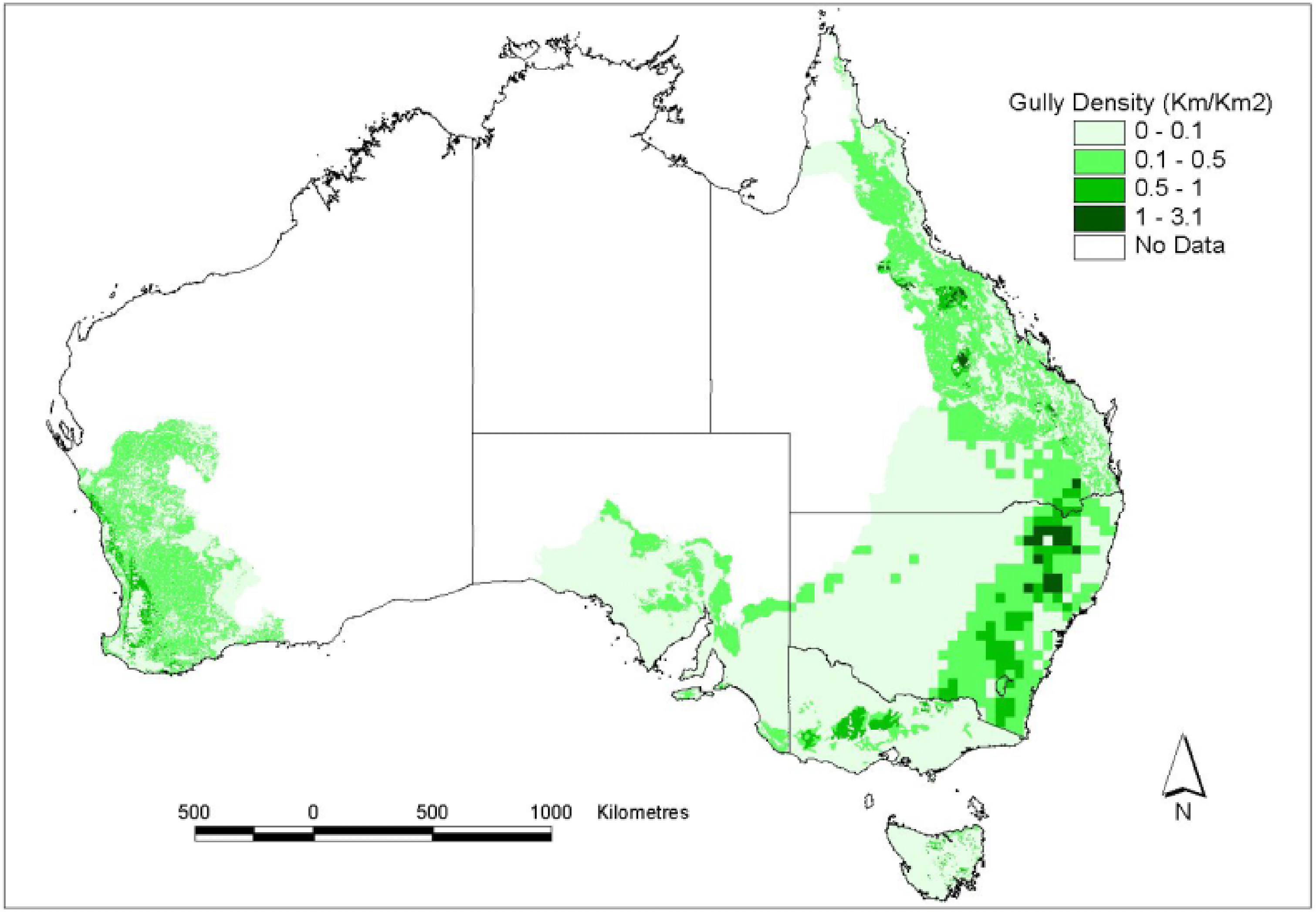


Figure 11: *Gully density map of the study assessment area (kilometres of gully length per square kilometre)*

19th C. These gullies continue to contribute fine sediment and poor quality water, although gully expansion is largely complete (Eyles, 1977). This contrasts with the situation on the north Queensland grazing lands where gullies have developed more recently and are continuing to expand and therefore are supplying significantly more sediment at present. Only low to moderate gully erosion is predicted in the West Australia region but this is a significant process when the current and natural low rates of surface wash erosion rates in this region are taken into account (Lu *et al*., 2001).

The highest gully density predicted is approximately 3.1 km/km^2 in the Nogoa River sub-catchment of the Fitzroy River basin. Initially, this was an area predicted to be of high gully density but where no measurements were made. Subsequent checking of photographs confirmed the model results. Similarly high values of gully density are possible for isolated patches of NSW/upper MDB and Victoria but were not detected because of averaging over large areas.

Some areas of historical gully erosion are not represented in the map because gullies could not be detected under forest cover. This applies mainly to alluvial gold mining in central Victoria and tin mining in Tasmania which have resulted in pockets of high gully density.

The NSW and upper MDB region contains significant proportions of the moderate to high gully densities (> 1 km/km^2). This is not unexpected due to the extent of land clearance and intensive land use that have taken place. In addition their large areas of erodible granitic based soils on sloping land and in a climate that leads to periods of low ground cover. The vast majority of the gully erosion in this region is focussed on the eastern rim of the basin where it presents a substantial impact on rivers (NLWRA, 2001b). Other regions with significant areas of high gully erosion are the Burdekin and Fitzroy basins, and the NSW coast. High densities were not recorded in Victoria because of the large scale averaging but are present in central Victoria and the Dundas Tablelands of western Victoria. Areas of high gully density tend to be on granitic or sandstone rock types in areas of variable climate which produce seasonally low ground cover, and in rolling terrain of pastoral or mixed pastoral and cereal cropping land uses. Tasmania and northern Queensland have little or no areas of high gully erosion. This results from a number of factors including permanently good vegetation cover, naturally well developed stream networks or broad valleys which do not concentrate flow.

Overall, the average gully density for river basins within the assessment area is 0.13 km /km^2. There are approximately 325 000 km of gully in total, which on average have produced 44 million tonnes of sediment per year. In total, gullies have eroded 4.4 billion tonnes of sediment in historical times. In most cases gullies are directly connected to streams and rivers so that the vast majority of the eroded sediment has been delivered to the river network. The predicted mass of gully erosion is of comparable magnitude to stream bank erosion (33 Mt/y) and sediment delivery from sheetwash and rill erosion (50 Mt/y) (NLWRA, 2001a). Gully and stream bank erosion, however, supply most of the coarse sediment that is transported into rivers.

5 CONCLUSIONS

This study has illustrated that spatial modelling techniques can be successfully used to predict gully erosion extent at the continent scale. Because of the large degree of variability that occurs in natural processes such as gully erosion, accurate results require intensive mapping. Despite this the resultant gully density map illustrates the broad spatial patterns of gully erosion and demonstrates that gully erosion is a significant process on a national scale. The results should provide a useful tool in regional planning for erosion control and river restoration and in assessment of the extent of river degradation. In areas of high significance more intensive mapping of gully extent and evaluation of current sediment yields and impacts is warranted.

6 FURTHER WORK

Although much data went into the generation of each of the regional gully density models, prediction accuracy is low (particularly for the West Australia and Coastal Queensland regions) and analysis of further aerial photographs may assist in producing better results. With additional input data it may also be possible to generate a single model for the whole of Australia instead of producing regional models that use inconsistent variables. Input gully data quality, in respect to terrain polygon over mapping, is another factor that could be improved in places.

Further verification of the results, in the form of field or aerial photograph analysis is required to validate the results and improve the model where necessary.

The assessment approach produced a map of current gully extent. Gully erosion typically occurs as a protracted pulse of activity. Initially sediment yields are high as the gully forms, but then they decline, leaving a fully developed gully as evidence of the total erosion. A time series of aerial photography in key regions could be used to assess where gullies are still expanding and where they have reached completion.

7 ACKNOWLEDGMENTS

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8 REFERENCES

DNRE (2001). Victoria Department of Natural Resources and Environment website, http://www.nre.vic.gov.au

Eyles, R.J. (1977). "Changes in drainage networks since 1820, Southern Tablelands, NSW", Australian Geographer, 13, 377-387.

Ford, G.W., Martin, J.J., Rengasamy, P., Boucher, S.C., Ellington, A. (1993). "Soil Sodicity in Victoria", Australian Journal of Soil Research, 31, 869-909.

Galloway, J. N, Howarth, R. W., Michaels, A. F., Nixon, S. W., Prospero, J. M., and Dentener, F. (1996) "Nitrogen and phosphorus budgets of the North Atlantic Ocean and its watershed." Biogeochemistry, 35, 3-25.

Graham, O.P. (1989). "Land degradation survey of NSW 1987-88: Methodology". SCS Technical Report No. 7 Soil Conservation Service of New South Wales.

Lemly, A. D. (1982) "Modification of benthic insect communities in polluted streams: combined effects of sedimentation and nutrient enrichment", Hydrobiologia, 87, 229-245.

NLWRA (2001a) "Agricultural productivity and sustainability" National Land and Water Resources Audit, Canberra, in press.

NLWRA (2001b) "Ecosystem Health 2000". National Land and Water Resources Audit (in press), Canberra.

Lu, H., Gallant, J., Prosser, I.P., Moran, C., and Priestley, G. (2001), "Prediction of sheet and rill erosion over the Australian continent, incorporating monthly soil loss distribution." CSIRO Land and Water Technical Report 13/01, CSIRO Land and Water, Canberra, Australia.

Olley, J.M., Murray, A.S., Mackenzie, D.M., Edwards, K. (1983) "Identifying sediment sources in a gullied catchment using natural and anthropogenic radioactivity." Water Resources Research, 29, 1037-1043.

Prosser, I.P., Winchester, S.J. (1996) "History and processes of gully initiation and development in Australia." Zeitschrift für Geomorphologie Supplement Band, 105, 91-109.

Rulequest (2001). "Data mining with Cubist", http://www.rulequest.com/cubist-info.html

Wallbrink, P.J., Murray, A.S., Olley, J.M., Olive, L.J. (1998) "Determining sources and transit times of suspended sediment in the Murrumbidgee River, New South Wales, Australia, using fallout ^{137}Cs and ^{210}Pb. Water Resources Research, 34, 879-887.

Wasson R.J, Mazari R.K, Starr B, Clifton G. (1998). "The recent history of erosion and sedimentation on the Southern tablelands of southeastern Australia: sediment flux dominated by channel incision." Geomorphology, 24, 291-308.