# Patterns of erosion and sediment transport in the Murray-Darling Basin

**RONALD DE ROSE**[1]**, IAN PROSSER**[2] **& MARTIN WEISSE**[3]

1 *CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia*
ronald.derose@csiro.au
2 *Land & Water Australia, GPO Box 2182, Canberra, ACT 2601, Australia*
3 *Institute of Geography, Schneiderberg 50, D-30167 Hanover, Germany*

**Abstract** The Murray-Darling Basin in the southeast of Australia covers approx. $1 \times 10^6$ km$^2$, equivalent to 14% of the country's total area. Accelerated erosion, primarily in upland regions, has greatly degraded river habitats over the past century. Here we describe the results from the basin-wide sediment modelling for this region using SedNet: a spatially distributed sediment routing model which predicts sediment loads, together with bed, flood plain and reservoir deposition. Comparisons are made between current (past 100 years) and natural (pre-European) conditions. The results demonstrate that the basin is one of sediment redistribution rather than net sediment export. The basin is estimated to have 18% of rivers with >100 times natural loads. Erosion of gullies and riverbanks has also resulted in 11 000 km (13% of the total) to have historical accumulation of over 0.3 m of sand and gravel averaged over the river length.

**Key words** erosion; Murray-Darling Basin, Australia; sediment budget; sediment load; spatial model

## INTRODUCTION

Extensive modification to the natural environment in many parts of Australia began with the arrival of European farmers in the early part of the 19th century. Modification of the natural environment, principally through clearance of the native Eucalypt forests, initiated a phase of accelerated erosion: the effects of which continue to the present day (Scott, 2001). Many of the ephemeral streams and creeks that previously flowed across swampy meadows and formed “a chain of ponds”, began to incise into alluvial valley fills, releasing large volumes of sediment that subsequently caused extensive sand-bed aggradation and increased suspended sediment loads. While there is evidence for declining erosion rates in recent times, erosion rates remain high in areas where poor land management practices continue (Scott, 2001).

The impacts of land degradation on river systems are an important issue for land management authorities. Targeting and prioritizing the source areas of erosion that contribute disproportionately to river loads is an efficient way of maximizing returns from investment into soil, land and river rehabilitation (Lu *et al.*, 2003). To achieve this necessitates the mapping of erosion processes and rates and the construction of a sediment budget which links river loads with upstream sources of sediment. The only practical way to assess the patterns of erosion and sediment transport across large complex areas such as the Murray-Darling Basin (Fig. 1) is a spatial modelling framework. There are often few direct measurements of sediment transport in regional catchments, and it is unrealistic to initiate sampling programmes of the processes now and expect results within decades (Prosser *et al.*, 2001a).

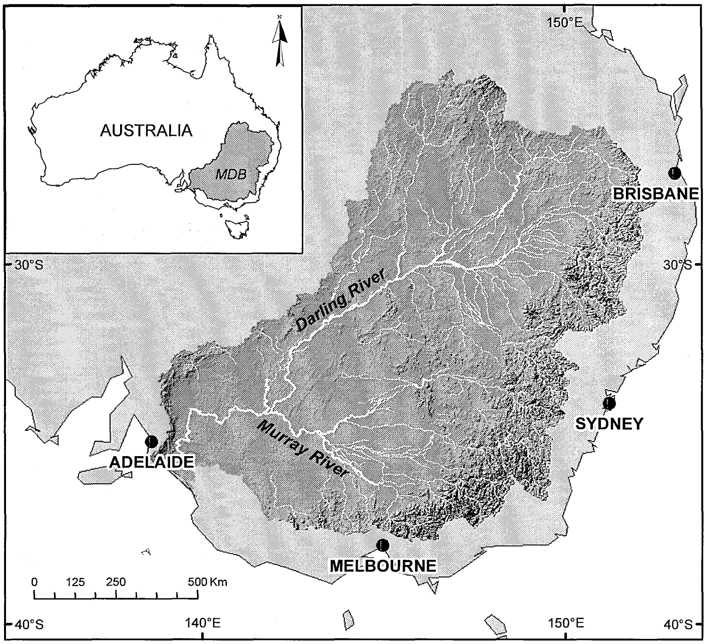

**Fig. 1** The Murray-Darling Basin and river network.

This paper summarizes results from application of a spatially distributed sediment model (SedNet) to the Murray-Darling Basin (DeRose *et al.*, 2003). SedNet couples erosion, hydrological, and sediment transport modelling to predict sediment loads and deposition throughout river networks, utilizing digital elevation models (DEM) and regional resource surveys (e.g. land use, vegetation, erosion, soil, flood plain maps). The model was first developed at national scales for the Australia NLWRA (Prosser *et al.*, 2001b), but is now routinely applied in regional scale assessments.

## STUDY AREA

The Murray-Darling Basin (MDB) is large, covering approx. 1 × $10^6$ $km^2$ or about 14% of Australia's land area (Fig. 1). The Basin contains >20 major river systems, including the three longest rivers in Australia, the Darling, Murray, and Murrumbidgee.

The MDB covers a diverse range of environments from the alpine margin of the Great Dividing Range in the east, to tropical Queensland in the north, to the central low-lying riverine plain which dominates the region, and to the sparsely vegetated arid interior in the west. Average annual rainfall shows a strong regional gradient from >1000 mm along the Great Dividing Range in the east, to as little as 180 mm in the arid west. Rainfall is highly variable and can swing from periods of above average rainfall and frequent flooding to protracted periods of drought, such as in recent years, when rainfall was well below average and many streams and rivers ceased to flow.

The natural vegetation at the time of European settlement ranged from dry and wet *sclerophyll* forest communities in the east to more open woodlands including *mallee* forests and native grasslands in the west, all of which were largely dominated by *Eucalyptus* spp. At least half of the pre-European vegetation cover has now been removed and converted for cropping, grazing, and less commonly, horticulture, viticulture or plantation forests.

Most rivers begin in the wetter and more mountainous region along the eastern and northern margins of the Basin where, although drainage networks are initially well defined, they soon flow onto the extensive riverine plain and become much more sinuous and anabranching in form. There are at least 9 major distributaries systems in the MDB where rivers split into between 2 to 5 anabranches, each diverging by up to 10–20 km, before coalescing to form the Murray and Darling Rivers. The greatest continuous length of river in the Basin extends 3750 km from the source of the Condamine, near Brisbane, to the mouth of the Murray, near Adelaide (Fig. 1). Only streams that carry sufficient flow merge with the major rivers and most smaller streams and rivers in the western arid zone dry up well before reaching the Darling River.

All major rivers are now heavily regulated due to demands on fresh water for domestic consumption, agricultural production and industry. There are many dams, reservoirs and river off-takes throughout the MDB that have reduced both mean annual discharge and flow variability throughout the river network. Outflow from the mouth of the Murray River now averages 4.9 Gl year$^{-1}$. This represents 36% of the long-term flow of 13.7 GL year$^{-1}$ estimated under natural conditions, despite there being significant inflows from coastal rivers as part of the Snowy Mountain Hydroelectric Scheme. Annual diversions have gradually climbed from 3 GL in the 1930s to 11 Gl in the early 1980s and now remains capped at this level (Murray-Darling Basin Commission).

## METHODS

The conceptual framework for the SedNet model is described by Prosser *et al.* (2001a) and details of model structure, parameterization, assumptions and limitations are given by Prosser *et al.* (2001b). A brief overview of the SedNet model follows. SedNet is a sequence of Arc-GIS routines coded in ARC Macro Language (AML) script. The model first builds a link representation of the river network from a digital elevation model (DEM), separated by tributary junctions or nodes. For the MDB, the river network was defined from a 9″ resolution (approx. 250 m) DEM producing 9900 river links averaging 12 km in length and with an upslope contributing area >50 km$^2$. Each link in the river network has an associated link watershed area averaging 100 km$^2$. The river links and associated watersheds form the basic processing elements for the model.

Each river link, receives a mean annual supply of suspended (silt and clay) and bedload (sand and gravel) sediment from upstream tributaries, and from gully, hillslope, and riverbank erosion in the associated watershed area. Each river link similarly loses sediment by deposition on the flood plain (suspended) and on the bed of the channel (bedload) when the sediment transport capacity of the link is exceeded. Reservoirs and lakes trap all passing bedload while a proportion of the suspended load is trapped depending on mean annual inflow and storage capacity.

Each of the three main erosion sources are separately modelled and calibrated to local measurements where possible. Hillslope (sheetwash and rill) erosion is modelled using the RUSLE model, adjusted for seasonal variation in rainfall and cover factors (Lu *et al.*, 2001), and scaled to 50 km$^2$ by the sediment delivery ratio (SDR). The SDR represents the probability of eroded soil reaching the river network and is predicted to average 0.044 and vary mostly between 0.001 in arid regions and 0.4 in wetter regions (Lu *et al.*, 2003). As hillslope erosion generates mostly fine sediment it was considered to contribute only to the suspended load. Gully erosion was estimated using rule-based statistical extrapolation of air photo measurements of gully density (Hughes & Prosser, 2003) while river bank erosion is based on an empirical model relating a global review of meander migration rate (Rutherfurd, 2000) to stream power, extent of riparian vegetation, and flood plain width (Hughes & Prosser, 2003). Limited available data and field observations of bank texture suggest a relatively even contribution of sediment (e.g. Dietrich & Dunne, 1978) from riverbank and gully sources to the suspended and bedload of rivers. A suspended to bedload sediment contribution ratio of 40:60 was found to provide the best overall agreement between observed river loads and known extents of bedload accumulation.

A number of hydrological and channel morphological parameters (width, depth) are used to predict sediment transport and deposition. Flood plain deposition is based on the proportion of flow that goes over bank during the median flood event. Bank full discharge was considered equivalent to the 1.58 year recurrence interval flow on the annual maximum time series. The hydrological parameters were calculated from the time series of daily flows measured at hydrometric gauging stations and interpolated across the remainder of the river network by correlation with mean annual flow ($Q_a$). $Q_a$ was in turn derived by regionalization of the rainfall runoff coefficient. The model further considers regulated flow and diversion of flow along anabranching networks.

The sediment budget for natural (pre-1820) conditions assumed no significant gully erosion, the RUSLE model applied to natural vegetative cover (Lu *et al.*, 2001) and a level of riverbank erosion equivalent to 5% of current levels.

## SEDIMENT BUDGET

The sediment budget (Table 1) shows that only a small portion of the 28.7 Mt year$^{-1}$ of sediment entering the river network reaches the mouth of the Murray River. The MDB is therefore one of net sediment redistribution rather than net sediment export. Hillslope erosion is predicted to be the dominant source of suspended sediment whereas gully erosion is the dominant source of bed load. Of the sediment eroding from upland areas of the basin 46% is deposited on flood plains, 20% is trapped in reservoirs and 33% is deposited within

**Table 1** Sediment Budget for the Murray-Darling Basin.

| Sediment budget item | Predicted mean annual rate (Mt year$^{-1}$) Suspended | Bed load | Natural |
|---|---|---|---|
| Hillslope delivery | 8.4 | | 0.3 |
| Gully erosion rate | 4.6 | 7.0 | 0 |
| Riverbank erosion rate | 3.5 | 5.2 | 0.4 |
| Total sediment supply | 16.5 | 12.2 | 0.7 |
| Flood plain deposition | 13.1 | | 0.3 |
| Reservoir deposition | 3.3 | 2.6 | 0 |
| Total bed accumulation | | 9.6 | 0.3 |
| Sediment export | 0.1 | 0.0 | 0.1 |

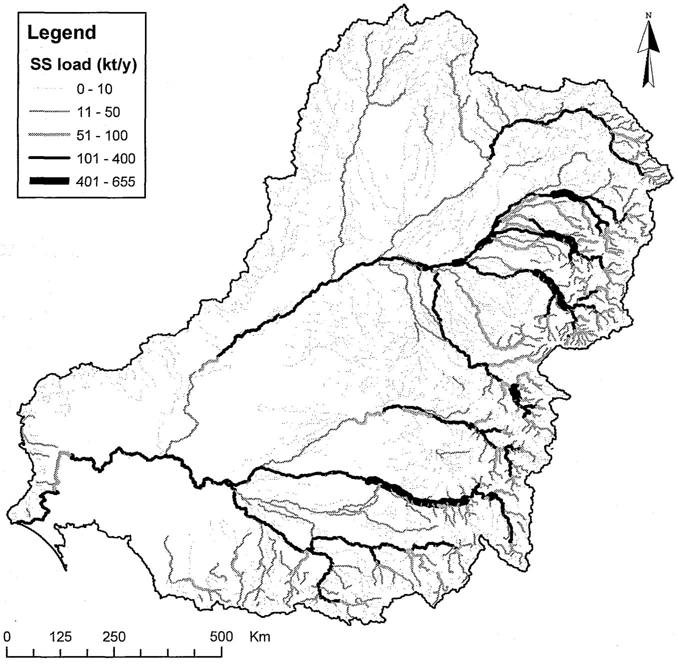

**Fig. 2** Suspended sediment loads (SS) across the MDB.

channels as sand slugs. Under natural conditions, only 3% of the present day amount of sediment is predicted to enter the river network, but as no reservoirs and much higher flows existed prior to regulation, then rates of sediment export from the basin as a whole would appear to have been similar to the present day.

River suspended sediment (SS) loads vary considerably across the Basin (Fig. 2). In general they are greatest, typically exceeding 100 and occasionally 400 kt year$^{-1}$, along the main reaches of rivers draining the eastern and southern basin margins. In these regions specific SS yields are equivalent to 10–50 t km$^{-2}$ year$^{-1}$ and thus low by international standards. Yields decline with distance downstream and are predicted to be below 1 t km$^{-2}$ year$^{-1}$ for much of the lowland river network. Regions of the river network with highest loads, together with upland areas having extensive soil erosion, are those most impacted by increases in SS relative to natural conditions. Overall, 63% and 18% of the river network is predicted to have SS loads above 20 and 100 times natural rates.

The sediment budget model also predicts extensive sand accumulation as a result of accelerated gully and river bank erosion. In all, some 20% of the river network is affected by sand deposition and 13% is predicted to have sand accumulation over 0.3 m in thickness where significant impacts on fresh water habitat can be expected. The river reaches most affected by sand accumulation are those lying below regions of extensive gully and bank erosion and where there is a decrease in sediment transport capacity owing to decrease in channel slope. Consequently most sand slugs are predicted to occur where there is a transition from the higher energy streams of upland areas to the lower energy of the more sinuous lower gradient rivers of the lowlands. This pattern is generally consistent with field observations of the sites of sand slug deposition in regional catchments.

## MODEL EVALUATION

Each of the erosion process sub-models contain significant localized error due to limited spatial resolution of data sources. This, together with model assumptions where many of the parameters are treated as global constants (e.g. bank full discharge = 1.58 year recurrence flow, coarse to fine sediment production ratio of 0.6:0.4) means that there is potentially significant spatial error in predicted loads.

The performance of the present model results can be determined by comparison with measured loads from river quality sampling sites and the results of radionuclide ($^{137}$Cs/$^{210}$Pb) tracer studies which determine the relative proportion of river sediment derived from subsoil (gully and riverbank) and hillslope sources (Wallbrink *et al.*, 1998). Figure 3 shows that despite the uncertainties in source terms there is reasonable agreement between predicted and observed specific SS yields for a number of sites within major southern tributaries of the Murray River. Sites with upslope basin areas of >3000 km$^2$ have a relative error of 0.30 while those for smaller basin areas have a greater error of 0.82, suggesting a decrease in model accuracy with decreasing scale. Care is therefore needed in the interpretation of predicted loads for the smaller rivers and streams.

At the lower end of the river system, regular measurement of turbidity (Mackay *et al.*, 1998) indicates that the Murray has a lower average turbidity (30 NTU) than the Darling (109 NTU) above the confluence of the two rivers. This contrasts with average annual SS concentrations of 35 and 12 mg l$^{-1}$, respectively, based on predicted SS yields and discharge at the same locations. Given that river loads appear reasonably well represented for tributaries of the Murray River (Fig. 3) then this difference tends to imply under prediction of loads in the Darling River. Radionuclide studies in the Namoi River, a tributary of the Darling, suggest that >70% of transported sediment is derived from predominantly bank erosion sources (Olley & Scott, 2002) and this contrasts with a much lower model estimate of approx. 30%. This, together with estimates of river loads based on turbidity measurements (Olley & Scott, 2002) which are about four times those predicted by SedNet, point to significant underestimation of the levels of river bank erosion for some basin areas and this has led to under prediction of river loads for the Darling River. Furthermore, Olley & Caitcheon (2000) suggest that, on the basis of major element chemistry, most of the sediment presently transported in the Darling-Barwon River is derived from weathered granite and

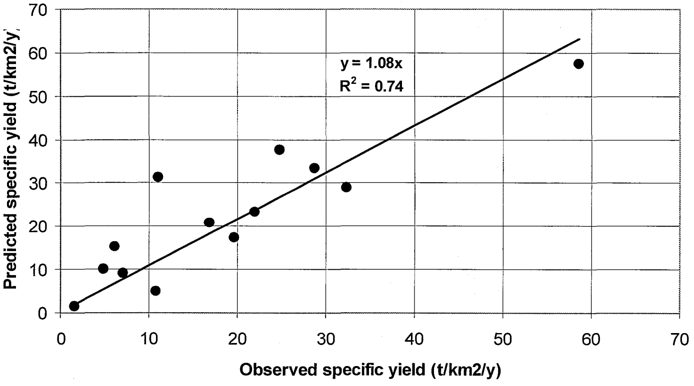

**Fig. 3** Comparison of predicted and observed specific SS loads.

sedimentary bedrock in lowland areas rather than originating from contemporary erosion of intensely farmed basalt terrain in upland areas.

## MODEL DEVELOPMENT

The present sediment budget and basin-wide estimates of SS loads provide a synoptic overview of erosion and sediment transport throughout the MDB. When compared with measured loads, the present results also provide an examination as to where potential deficiencies in the model occur. Currently there are few measurements of river bank erosion in Australian rivers and this means that significant localized under or overestimation in river loads will occur due to a lack of effective model calibration or parameterization. Similarly, as routing of suspended sediment through river networks depends on channel geometry and the frequency of bank full discharge and overbank flooding, then poor spatial representation of these parameters will also lead to significant localized error in prediction of river loads. There is growing evidence that the statistically derived 1.58-year recurrence interval flow provides poor spatial representation of, and may in fact underestimate, bank full discharge for many Australian basins. Lower than actual bank full discharge may have led to overestimation of the levels of flood plain deposition and is therefore also a likely cause for under prediction of river loads along lower reaches of the Darling River.

The present sediment budget is considered a major improvement over previous studies and is the best that can be achieved using currently available data sources and knowledge. While it provides us with a reasonable picture of the spatial patterns of sediment source areas, deposition and river loads, it has also highlighted where future development work is needed before the model can be applied at much smaller regional scales. Future research and model development of SedNet aims to provide better spatial representation of rates of river bank erosion and to provide a much more rigorous understanding of channel geometry and how this affects bank full discharge and routing of sediment through river networks.

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