Waterborne Erosion - an Australian Story

Content for the Australian Natural Resources Atlas Storyboards

Compiled by Frances Marston
Contributors
Ian Prosser, Andrew Hughes, Hua Lu and Janelle Stevenson

CSIRO Land and Water, Canberra
Technical Report 17/01, September 2001

CSIRO LAND and WATER

Waterborne erosion — an Australian story

Content for the Australian Natural Resources Atlas Storyboards

Compiled by

Frances Marston

Contributers:

Ian Prosser

Andrew Hughes

Hua Lu

Janelle Stevenson

Technical Report No. 17/01

CSIRO Land and Water, July 2001.

Contents

Waterborne Erosion – An Australian Story

Content for the Australian Natural Resources Atlas Storyboards

(A product of the National Land & Water Resources Audit)

Compiled by Frances Marston

Contributors: Ian Prosser, Andrew Hughes, Hua Lu and Janelle Stevenson

We wish to acknowledge all those who made contributions to the Project (NLWRA Theme 5.4b) including Greg Canon, John Gallant, Alan Marks, Chris Moran, Geoff Pickup, Graeme Priestley, Paul Rustomji, Anthony Scott, and Bill Young. Funding for the work was through a partnership between the National Land and Water Resources Audit and CSIRO Land and Water.

Note to reader on annotations:

The main purpose of this document is to facilitate the exchange of information that may be included as content for the Australian Natural Resources Atlas Storyboards (a web-based product of the National Land & Water Resources Audit) and to fulfil some of the reporting requirements of the Sediment Project within NLWRA Theme 5.4b). However, the Atlas will probably only reproduce a subset selection of this document.

Text *underlined and in green italics* indicates links to glossary words in Section 2.4 (Terms and expressions).

A '☞' indicates a comment describing intended web functionality. Comments are not reproduced in the print version of the document.

Hypertext links are indicated with the URL or internal link underlined and in blue – if URL unknown, a descriptive title is provided

Text which is **bold and navy** is meant to be emphasised in some way ie it flashes, sparkles, is extra bold etc on web page.

1 INTRODUCTION

1.1 Why bother telling a story about waterborne erosion?

A major issue in Australian land management is waterborne soil *erosion* and the consequent degradation of land and water resources. Because soil provides the structural support and the source of water and nutrients for plants, soil erosion results in significant reductions in productivity. Off-site, the effect of soil erosion is the degradation of water quality in streams, water storages and estuaries due to increases in sediments and associated nutrients and the consequent impacts on ecosystem health.

High concentrations of suspended sediment:

- reduce stream clarity
- inhibit respiration and feeding of stream biota
- diminish light needed for plant photosynthesis
- require treatment of water for human use

In addition an over-supply of mud or sand can cover the stream bed and cobbles and fill deep pools, making streams uninhabitable for many native fish and invertebrates. An increase in the supply of silt and clay from erosion to rivers means an increase in the supply of nutrients, for in Australian streams most nutrients are transported attached to fine mineral and organic sediment. The storage of fine sediment in a stream increases the storage of nutrients that can be released into the water, fuelling nuisance and toxic levels of algae and other primary production.

Knowledge about the **sources** and **rates** of erosion under **past and present conditions** is essential for understanding the **consequence of changes** in land use and climate on soil erosion. This is a prerequisite for **minimising the decline** of soil productivity and water quality and for **optimising the use** of resources for soil conservation and management and the sustainability of land use. ☞

1.2 Stories

- How much soil is eroded from *hillslopes* & *gullies* under various land uses and management practices? (Loss of productive capacity – ie all to do with soil loss) ☞
- How much of the soil that is eroded is transported to and reworked through rivers? (Aquatic ecosystem impacts – ie all to do with sources and transport of sediment) ☞

2 WATERBORNE EROSION – SOME THEORY BEFORE PRACTICE

Sediment and attached nutrient that are transported in streams can be derived from two types of processes: *sheetwash* and rill erosion processes on *hillslopes* and *erosion* of the streams themselves, including recently formed stream channels such as gullies. Distinction between hillslope *and gully erosion* is important for three reasons outlined below. [SoilPic 1 & 2]. ☞

1. Sediment eroded from stream banks is delivered immediately to the stream and consequently impacts on instream ecosystems. In contrast, much sediment generated from *sheetwash* and *rill* erosion is deposited on *footslopes*, *alluvial fans* and *terraces* before reaching the stream. [SoilPic 3, 4, 5 & 6]. ☞
2. Sheetwash, rill and gully erosion entail quite different management approaches. *Streambank* and gully erosion is best targeted by managing stock access to streams, protecting vegetation cover in areas prone to future gully erosion, revegetating bare banks and reducing sub-surface seepage in areas with erodible sub-soils. Sheetwash and rill erosion is best targeted by promoting consistent groundcover, maintaining soil structure, promoting nutrient uptake and using riparian buffer strips. [SoilPic 7].☞
3. Sheetwash and rill erosion can respond to short-term changes in land management, and trends are often reversible, whereas gully erosion reacts over longer time scales, and is mostly in response to the major clearing of vegetation upon introduction of modern land use. Gully erosion tends to go through a trend of rapid initial change and then gradual adjustment to a new equilibrium condition.

It is important to keep in mind that **erosion does occur as a natural process** – but accelerated rates of erosion occur as a consequence of human intervention.

2.1 Erosion processes

Erosion is the process by which the earth's surface is worn away by the action of water, wind, glaciers, waves etc. It can be natural (ie due only to the forces of nature) or accelerated (as a result of human activities) but in each case the same processes operate and the distinction is often only a matter or degree and rate.

2.1.1 Soil erosion proceses

Soil erosion processes (sheetwash and rill, gully, streambank, and wind erosion; mass movement; and solution) operate in conjunction to denude the earth's surface of weathered material. The first three processes (sheetwash and rill, gully, and streambank erosion) are considered in detail in this project. Wind erosion is also a significant process in dry areas but was beyond the scope of the NLWRA, and mass movement (landsliding and soil creep) and solution are minor processes in terms of accelerated erosion.

2.1.2 Components of the soil erosion process

There are three main components of the erosion process:

- Detachment
- Transport
- Deposition

Detachment of soil particles is a function of the erosive forces of raindrop impact and flowing water, the susceptibility of the soil to detach, the presence of plant cover or other roughness which reduces the magnitude of the eroding forces and management of the soil that makes it less susceptible to erosion. It occurs when the erosive forces of raindrop impact or of flowing water exceed the soil's resistance to erosion. Other detachment processes by soil organisms such as ants or burrowing animals can be significant in places.

Transport is the entrainment and movement of sediment from its original location once it has been detached from the soil. It is a function of the energy of the transporting agent, in this case flowing water. Deep and fast flows have a greater capacity to transport sediment, and fine particles are moved more easily than larger and heavier particles. *Deposition* occurs when the sediment load of a given particle type exceeds the energy available for transport or re-entrainment. This often results from a reduction in gradient, flow velocity or discharge or an increase in the hydraulic resistance of the flow induced by vegetation. Deposition results in *sedimentation*.

Sediment yield is the amount of material transported past a given point of interest (usually a measuring device in a stream or a point on a hillslope). It is the net result of erosion, transport and deposition upstream or upslope.

Sediment delivery ratio is usually described as the ratio at a particular point of gross erosion upstream or upslope to the sediment yield at that point. It is a measure of the efficiency of transport and conversely of the intensity of deposition upstream or upslope. The above definition is not strictly correct because gross erosion is rarely measured. Typically sediment yield of hillslope plots is the measure of erosion. Then, sediment delivery ratio is the reduction in sediment yield per unit area with an increase in scale from plot to hillslope, stream or river.

Soil eroded by water is transported downslope by *surface runoff*, which is the portion of rainfall that flows over the ground or in streams as opposed to infiltrating the soil or being lost to evaporation.

(Much of the above is based on Sharman & Murphy, 1991)

2.2 Describing soil erosion processes

To measure erosion and sediment transport processes for every catchment where sediment supply is of concern is an enormous and unnecessary task. Fortunately, with knowledge of the processes, surrogate factors can be measured to estimate soil erosion, sediment yields, and deposition across a diverse range of environments.

2.2.1 Sheetwash and rill erosion

The factors controling *sheetwash* and *rill* erosion are well understood from decades of soil erosion research. The most significant factors are surface cover and land use practise. Significant sheetwash erosion occurs when contact cover with the ground falls below 70%, and is particularly pronounced when cover falls below 30%. Consequently any land use that includes annual tillage and seasonal bare ground is prone to surface wash erosion. The strong effects of land use intensity on hillslope erosion are illustrated by the data in Figure 1. The graph shows a review of plot and mini catchment scale measurements of sheetwash and rill erosion in Australia.

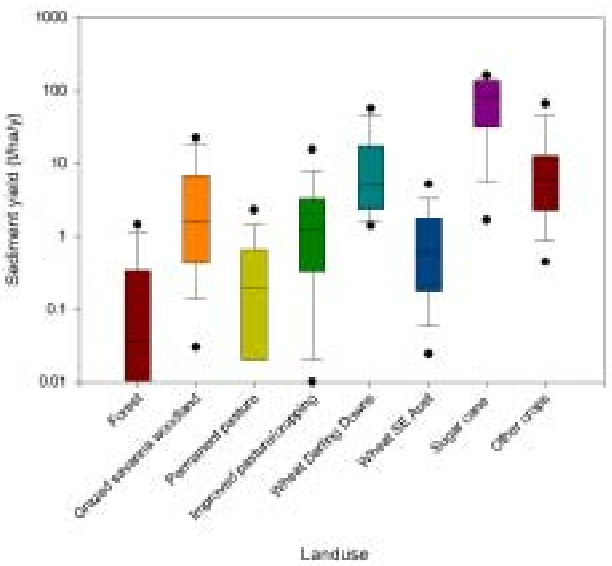


Figure 1: Sediment yields from rill and sheetwash erosion under various landuses.

Sheetwash and rill erosion is accentuated by high rainfall intensity, particularly if it occurs when the soil is bare. A large depth of rainfall over a short period of time as occurs in summer storms, is much more erosive than gentle continuous drizzle. Thus there is a tendency in Australia for sheetwash and rill erosion to increase as one moves north, where rainfall intensities are higher. The difference between sediment yields for wheat on the Darling Downs compared to SE Australia illustrates this. Steep gradients and erodible soils further accentuate erosion. Soil properties are particularly important for nutrient loss as much of the nutrient is attached to silt and clay. On poorly structured soils, silt and clay tend to be transported as individual particles rather than in larger aggregates. This increases the travel distance and the difficulty of trapping eroded sediment. ☞

A feature of sheetwash and rill erosion is the huge variability of sediment yields. Within a single landuse sediment yields vary by 100 fold depending upon rainfall, topography and management practice. Between landuses, the data suggest 10,000 fold differences between locations. Strong patterns emerge within this variation when controlling factors are considered.

In terms of sediment delivery potential to streams, the potential for the eroded sediment to actually reach the stream must be considered. Consequently, areas where hillslopes fall straight into the stream have the highest sediment delivery potential. This usually results in higher sediment delivery potential to small source streams rather than directly over the banks of major rivers and creeks.

There is sufficient understanding of the sheetwash and rill erosion processes that a technique known as the Revised Universal Soil Loss Equation (RUSLE) has been developed to predict this kind of erosion at regional scales, on the basis of the primary driving factors. ☞

2.2.2 Gully erosion

Quite different considerations need to be made for gully and streambank erosion because of the tendency for erosion to heal over time. Gullies and *incised streams* increase the extent and size of the stream network creating large areas of bare eroding banks.

The factors which dictate sediment yield from gullies are not as well understood as for sheetwash and rill erosion. There is no equivalent of the RUSLE for gully erosion, however there is enough understanding of the processes to make regional assessments using some strategic measurements. ☞

Gullies have formed in valleys which contained no channels, or only small channels, prior to European settlement. Thus the total volume of gully represents the total amount of sediment delivered from gully erosion in historical times. There are vast differences in *gully density* from one area to another and this is the primary factor dictating the total amount of sediment yielded from gully erosion since European settlement, and is the basis of our assessment of sediment yield. Gully density can be converted to mean annual sediment load using average width, depth and age of gullies.

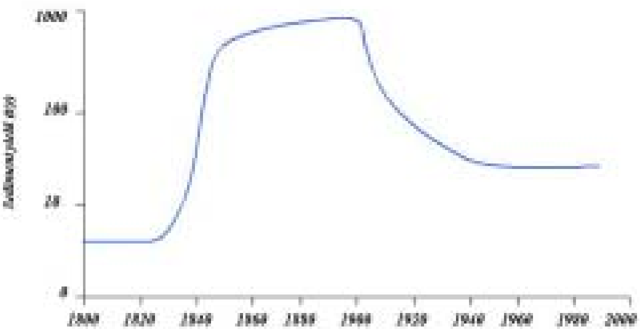


Figure 2 (based on Wasson et al. 1998)

Gullies erode deep soils that accumulate in valleys and hollows from thousands of years of upslope sheetwash erosion and *soil creep*. Once the protective vegetation cover or resistant topsoil layers are removed, gullies spread rapidly up through the valleys towards the surrounding ridges and spurs where they stop due to insufficient runoff to continue erosion. Thus gullies spread quickly once initiated but stabilise relatively quickly despite the continuing dramatic appearance of a deep bare scar on the landscape. In areas cleared long ago, such as in the late 19th century for the uplands of the

MDB, the bulk of the eroded soil was delivered to streams in the first few decades and sediment yield has since declined (Figure 2). Measurements of gully density in those areas show little net growth of the network since the 1940s. In other areas of currently intensifying land use, such as the tropical semi-arid grazing lands many gullies are still forming and continuing to expand.

Many old gullies still generate turbid water and this is most accentuated where there are highly erodible *sodic* sub-soils that are quite inhospitable for regeneration of vegetation.

2.2.3 Streambank erosion

There are many similarities between gully and streambank erosion but our understanding of the primary factors which control the rate of streambank erosion are even more limited and are the subject of current research. It is known that there has been massive widening of many of our coastal streams in historical times as a results of clearing of riparian vegetation, increased flood magnitudes and increase of flow velocities through activities such as the removal of large woody debris. This has been shown most dramatically by contrasting the Thurra and Cann rivers in East Gippsland. These are rivers draining similar catchments. The main difference is that much of the lower Cann River floodplain has been cleared while the Thurra River remains relatively pristine. Meander cutoffs on the Cann River confirm that it was similar to the Thurra River prior to European settlement. Table 1 shows a four times increase in the width of the Cann River, about a two and a half time increase in depth and a 63 times increase in bankfull discharge in historical times. These changes have supplied a vast amount of sediment downstream and have impacted the bed habitat of the lower Cann River.

Table 1: Contrasts in channel form and sediment transport between Thurra River (unaltered in historical times) and the adjacent Cann River (eroded in historical times). After Prosser *et al.* (2001); data from Brooks (1999).

Parameter	**Thurra R.**	**Cann R.**
Channel width (m)	13	66
Channel depth (m)	1.4	4
Bank height as a proportion of critical height for failure	0.29	0.9
Bankfull discharge (m^3s^{-1})	10	630
Unit stream power ($W\ m^{-2}$)	10	153
Bedload transport potential ($kg\ s^{-1}$)	0.6	325
Lateral migration rate ($m\ year^{-1}$)	0.07	4.5

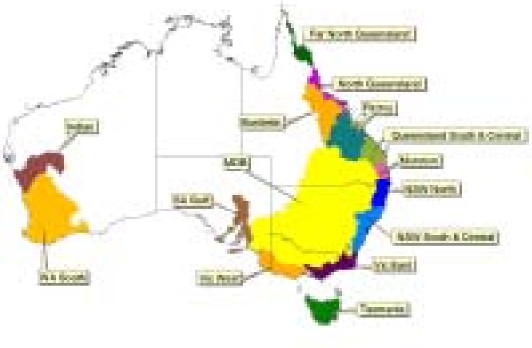
Measurements of streambank erosion from around the world show a relationship between bankfull discharge and streambank erosion rate (Rutherfurd, 2000) indicating that large rivers erode at a faster rate than smaller streams. It is understood that most current problems of bank erosion are in reaches where the native riparian vegetation has been removed. Reaches with natural riparian vegetation are more stable. It has been shown that riparian tree roots provide sufficient strength to stabilise the majority of river banks (Abernethy and Rutherfurd, 2000). These principles were used to predict bank erosion rate under current conditions.

2.3 Predicting erosion

Measurement of soil erosion is time consuming and constrained by severe data limitations. There are large gaps in erosion mesurement in terms of regions and particular environmental conditions assessed. The only way to cover these gaps and provide a regionally comprehensive assessment is to use the data and that gathered elsewhere to predict erosion based upon more widely measured surrogate factors such as climate, land use, soil properties and topography. The stories and predictions presented in these pages about soil loss and sediment movement are the outputs of **sophisticated modelling routines** based upon intensive assessment of available data. They describe findings **generated** within a spatial modelling framework on a **continental scale** for an area defined as Australian river basins containing intensive agriculture (ARBIA).

This area encompasses locations of intensive land use in Australia and their surrounding catchments to make a largely contiguous area. Geographically, it is the catchments of the Australian east coast (extending from Cape York to the Eyre Peninsula), Tasmania, the south west of Western Australia, and the Ord Basin. For this project the Ord Basin and Western Plateau drainage divisions were excluded due to lack of information. Complete catchments are used to put intensive land use in the context of the catchments in which it is located. The assessment area consequently includes much non-intensive land use such as forestry and rangelands. Much of the sheetwash and rill erosion work was undertaken across the whole continent as data covered that whole area.

The assessment area has been divided into regions to assist the storytelling process. ☞



Map 1: For the modelling exercise the assessment area was divided into regions (based on river basins) for which much of the data is presented. This provided a useful reporting mechanism.

Maps have been prepared for: ☞

- Current levels of continental soil loss from sheetwash and rill erosion ☞
- Natural levels of continental soil loss from sheetwash and rill erosion ☞
- Difference between current and natural levels of continental soil erosion ☞

- Continental soil erodibility ☞
- Continental rainfall erosivity ☞
- Continental ground cover ☞
- Continental soil erosion from gully erosion ☞

2.3.1 Modelling sheetwash and rill erosion

The controls on hillslope erosion by *sheetwash* and *rill erosion* are well understood and there are several models which incorporate these factors. Our modelling is based on the Revised Universal Soil Loss Equation (*RUSLE*) using time series of remote sensing imagery and daily rainfall combined with updated spatial data for soil, land use and topography.

The RUSLE calculates mean annual soil loss (tonnes/ha/yr) as a product of six factors: rainfall erosivity, soil erodibility, hillslope length, hillslope gradient, ground cover and land use practice.

The factors included in the RUSLE vary strongly across the Australian continent, providing a method for estimating the spatial patterns of erosion using consistent information for each factor. Due to the lack of spatial data for contour cultivation and bank systems, an assessment of the land use practice factor is excluded. This has the effect of not predicting reductions in soil loss due to use of minimum tillage and other conservation practises in intensive land use areas. This limitation is taken into account when discussing then results.

Mean annual values for rainfall erosivity and ground cover are often used to calculate mean annual hillslope erosion. This neglects important seasonal patterns of rainfall erosivity and cover. Problematic to the standard annual application of the RUSLE is the pronounced wet-dry precipitation regime in Australia's tropics and Mediterranean climate areas. To adequately represent the erosive potential of rainfall for each temporally distinct period, the study applied the RUSLE model on a monthly averaged basis, calculating appropriate erosivity and cover factors for each month. Twenty years (1980-1999) of daily rainfall data mapped across Australia and 13 years (1981-1994) of satellite vegetation data were used for this purpose. Incorporation of seasonal effects reduces predicted mean annual soil loss in Australia's tropics by a factor of 1.5.

The predictions of sheetwash erosion under present land use need to be put in context of erosion under natural vegetation cover. We predicted natural erosion using the same procedure, with a cover factor for native vegetation and keeping the other factors of soil erodibility, rainfall erosivity and topography as for the present day.

The cover factor for native vegetation was obtained assessing areas of reserve where native vegetation cover is retained in each of Australia's native vegetation zones. In the reserves, the RUSLE C factor was determined from remote sensing data as part of the assessment of current soil loss. The native vegetation cover of these reserve areas was extrapolated across the river basins containing intensive agriculture using an empirical decision tree model based on climatic topographic, and geological factors. The cover management factor for areas not contained within the assessment area remained unchanged.

The acceleration of current mean annual soil loss above natural rates was predicted as the ratio of the current to pre-European mean annual soil loss predictions.

For a full technical description of the modelling procedure see Technical Document PDF. ☞

2.3.2 Modelling gully erosion

Three separate data sources were used to map the density of gullies throughout the river basins containing intensive agriculture. For NSW, the data from the NSW 1988 land degradation survey were used (Graham, 1989). These are measurements of gully density (kilometre of gully length per km^2 of land) from aerial photographs across NSW. The measurements were taken on a regular grid of 5 to 10 km spacing across NSW. At each point an erea of 1 km^2 was measured. We found that this area was small compared to the spacing of gullies. There was thus 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.

For Victoria, an existing polygon map of gully density was provided by DNRE based upon mapping by Lindsay Milton and others (Ford *et al.*, 1993). This is also at fairly coarse scale consisting of 33 polygons across the state.

No existing data were available for the rest of the assessment area so gullies were traced on more than 428 stereo pairs of aerial photographs sampled from the other States. These data were digitised and used to build a decision tree model of gully density. The decision tree model estimated gully density for the entire assessment area in terms of the known gully densities (measured from the aerial photographs) and environmental attributes available at the continental scale. For example, the model was able to determine that areas with granitic lithology, moderate hillslope gradient and moderate to high rainfall are likely to have higher gully densities than an area of similar geology and rainfall but lower hillslope gradients. Numerous environmental attributes were used to determine which environmental attributes had the greatest predictive ability in terms of gully density. Attributes used included land use, geology, soil texture, rainfall and indices of seasonal climate extremes. Because of the inability to detect gullies in forested areas from aerial photographs and the fact that gullies are less likely to occur in forested areas, a gully density value of zero was applied to all areas with forest cover.

Three separate models were generated from the data, based upon geographic areas: West Australia; South Australia and Tasmania; and coastal Queensland. A model for the northern part of Australia (including parts of the Northern Territory and north Western Australia) was attempted, however, an inadequate number of high quality aerial photographs prohibited the generation of accurate results.

For a full technical description of the modelling procedure see Technical Document PDF. ☞

2.3.3 Modelling streambank erosion

All streams with a catchment area greater than 50 km^2 and a length greater than 5 km were mapped over the assessment area using the national 9" *digital elevation model*. The proportion of each stream that has cleared native riparian vegetation was determined by intersection of the streams with a coverage of native vegetation in 1995 obtained from the Australian Land Cover Change project at a resolution of 100 m (http://www.brs.gov.au:80/land&water/landcov/alcc_results.html). This is the best available data but it is only a crude measure of riparian condition as 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 hills. Erosion was assumed to only occur on sections of river with cleared riparian vegetation. The mean annual rate of bank erosion was calculated by:

$$BE = 0.008 Q_b^{0.4}$$

(modified from Rutherfurd, 2000) where BE is bank erosion rate in m/y; and Q_b is bankfull discharge, estimated from gauging records across the assessment area. Bankfull discharge was assumed to be equal to a flow of *recurrence interval* of 1.6 y. Multiplying the bank erosion rate by the length of cleared bank and an assumed average bank height of 3 m and bulk density of 1.5 t/m^3 gives the mean annual supply of sediment from bank erosion to each *stream link* in t/y.

For a full technical description of the modelling procedure see Technical Document PDF. ☞

2.3.4 Modelling sediment transport in rivers

Much of the sediment moving on hillslopes is deposited before reaching the stream, often on footslopes or in *riparian* lands. We obtained the most satisfactory results of river sediment transport by assuming that only 5-10% of sheetwash and rill erosion was delivered to streams; that is a hillslope sediment delivery ratio of 5-10%. This accords broadly with observations of hillslope and small catchment sediment yields. Sediment from gully and streambank erosion is delivered more efficiently, but little of the sediment that has reached streams over historical times has been yielded to the coast. It is a widely held observation that much of the sediment is stored along the way on floodplains or on the stream bed. When substantial sediment is deposited on the stream bed it can have an impact on aquatic ecosystems. Floodplain deposition in billabongs and other features may also be detrimental, however, it has the benefits of protecting downstream reaches and the coast from receiving that sediment. This is a benefit when current rates of sediment supply are accelerated above natural rates.

Individual stream links have widely varying potential for deposition because of strong differences in the energy of flow and the extent of floodplains. The crucial aspect of modelling sediment transport through rivers is to predict the patterns of deposition through the river network in addition to the supply of sediment to the rivers.

The sediment sources described in Section 2.2 deliver both coarse and fine grained sediment to streams. These are treated separately within the river network because of their different transport processes and different impacts on rivers. Fine sediment is transported in suspension in the river flow. When flood flows overtop the banks they spread onto the floodplain and a proportion of suspended sediment goes with that overbank flow. Floodplain flows are relatively shallow and slow flowing. In many cases the flow is retained on the floodplain for several days. Under these conditions much of the suspended sediment has time to settle out of the flow and be deposited on the floodplain. The amount of sediment that settles on the floodplain was predicted as a function of the mean sediment concentration and the ratio of floodplain area to overbank discharge.

Flows within the stream are generally too fast for there to be any net accumulation of suspended sediment from year to year and the within channel sediment is delivered quickly downstream. Rivers have a capacity to transport vast quantities of suspended sediment particularly during floods and the concentration of sediment in Australian rivers, and rivers in general, is limited by the supply of the sediment to the river; that is, if the amount of sediment supplied is doubled then the river will be able to carry the extra load and the sediment concentration will be doubled.

Coarse sediment is transported along the bed of the stream by rolling and relatively short hops into the flow. Under very fast, deep flow their may be brief periods of suspension. The sediment moves much slower than the flow and generally moves 10s to 100s of metres during an individual flood, accumulating on the bed of the stream between floods. The capacity of streams to transport coarse sediment is quite limited and accelerated sediment supply can exceed the capacity of the stream to convey sediment downstream. Under such conditions there is net accumulation of excess sediment on the bed of the stream, covering the natural substrate. The total amount accumulated over historical times is the amount of coarse sediment supplied less the total capacity to transport coarse sediment downstream. The capacity to transport coarse sediment is a function of the river slope and its discharge regime. Accumulation of coarse sand and fine gravel has been extensive in historical times.

A mean annual sediment budget was constructed through each river network for the river basins containing intensive agriculture. Separate budgets were constructed for coarse and fine sediment. The sediment budget accounts for the supply of sediment to each stream link and deposition within the link. The remaining sediment is yielded to the next link downstream. The sediment budget was conducted sequentially from the top of each catchment to the mouth. Coarse sediment is derived from gully erosion, streambank erosion and sediment yield from tributaries. Supply of coarse sediment directly from hillslopes to rivers was assumed to be negligible. Fine sediment is derived from sheetwash and rill erosion, gully erosion, streambank erosion and tributary sediment supply. Streambank and gully erosion were predicted to yield an equal proportion of fine and coarse sediment. This conforms with observations and produced realistic sediment budgets for each component. Fine sediment dominates the sediment yield as one moves through the river network because of its faster transport, and lower residence time in the river network.

Deposition within reservoirs was considered in addition to floodplain deposition of suspended sediment and instream deposition of coarse sediment. The trap efficiency of reservoirs was calculated from the widely used Brune rule (Brune, 1953) based upon the ratio of mean annual flow to reservoir storage capacity. Most of the larger reservoirs in Australia trap 90% or more of incoming sediment, and thus strongly modify sediment delivery downstream.

For a full technical description of the modelling procedure see Technical Document PDF. ☞

2.4 Terms and expressions

Alluvial Fan

Material deposited by a stream where it emerges from the constriction of a valley to a plain.

(From Whittow, 1986)

Assessment Area

The river basins containing intensive agriculture form the basis of the assessment area for this and several other NLWRA projects dealing with agriculture and catchment processes. It encompasses locations of intensive land use in Australia and their surrounding catchments to make a largely contiguous area. Geographically, it is the catchments of the Australian east coast (extending from Cape York to the Eyre Peninsula), Tasmania, the south west of Western Australia, and the Ord Basin. For this project the Ord Basin and Western Plateau drainage division were excluded due to lack of information. Complete catchments are used to put intensive land use in the context of the catchments in which it is located. The assessment area consequently includes much non-intensive land use such as forestry and rangelands.

Detachment

Detachment of soil particles is a function of the erosive forces of raindrop impact and flowing water, the susceptibility of the soil to detach, the presence of plant cover or other roughness which reduces the magnitude of the eroding forces and management of the soil that makes it less susceptible to erosion. It occurs when the erosive forces of raindrop impact or of flowing water exceed the soil's resistance to erosion. Other detachment processes by soil organisms such as ants or burrowing animals can be significant in places.

Digital Elevation Model (DEM)

A geographic grid of an area where the contents of each grid cell represents the height of the terrain in that cell. Consists of X, Y and Z coordinates.

Erosion

Erosion is the continuing geomorphological process involved in landscape development as a smoothing or levelling of the earth's surface by removal of weathered material.

It can be natural (ie due only to the forces of nature) or accelerated (as a result of human activities) but in each case the same processes operate and the distinction is often only a matter or degree and rate.

(Based on Sharman & Murphy, 1991)

Footslope

The lower part of a slope above the gentler gradient of a valley floor or plain.

(From Whittow, 1986)

Geomorphological Processes

Processes which comprise the physical and chemical interactions between the Earth's surface and the natural forces (gravity, ice, water, wind, waves, etc) acting upon it to produce landforms.

Gully Density

The linear extent of gully, measured as kilometres of gully per km^2 of land.

Gully Erosion

The removal of soil by running water which results in the formation of deep channels – *gullies* – which tend to form in upland areas, have steep sides which often have headward eroding scarps, and usually convey ephemeral runoff to relatively small drainage areas. Gullies are at least 50 cm deep. Gullies erode unchanneled valleys and dips and eventually become vegetated and infill, distinguishing them from permanent streams.

(Sharman & Murphy, 1991)

Headcuts

A sharp ephemeral waterfall cut into soil at the head of a gully or incised stream. Over time the headcut migrates headward by scour and toppling of the soil.

Hillslope

All the land surface above a stream or channel edge.

Incised Streams

Permanent streams which have deepened and widened by several metres as a result of vegetation removal or increased forces of flow to produce streams with high, bare vertical banks with headcuts incised into floodplains. They resemble large gullies.

Recurrence Interval

The flow expected to occur on average every 1.6 y based upon analysis of peak flows in each year of gauging record.

Revised Universal Soil Loss Equation (RUSLE)

Like the USLE, the RUSLE calculates mean annual erosion (tonnes/ha/yr) as a product of the six factors: rainfall erosivity, soil erodibility, hillslope length, hillslope gradient, ground cover and land use practice. However because the original slope steepness factor of the USLE overestimates erosion from slopes steeper than 9%, the RUSLE applies a different slope steepness equation in determining the hillslope gradient factor.

Related term: Universal soil loss equation (USLE).

Rill Erosion

Similar to sheetwash erosion except that the concentrated wash process causes the formation of tiny channels or rills, a few centimetres to 50 cm deep, which usually only carry water during storms and are removed by tillage.

Sediment

Solid material (predominantly particles and grains of rock) that have been transported by water and deposited or settled out of suspension.

Sediment Delivery Ratio (SDR)

Sediment delivery ratio is usually described as the ratio at a particular point of gross erosion upstream or upslope to the sediment yield at that point. It is a measure of the efficiency of transport and conversely of the intensity of deposition upstream or upslope. The above definition is not strictly correct because gross erosion is rarely measured. Typically sediment yield of hillslope plots is the measure of erosion. Then, sediment delivery ratio is the reduction in sediment yield per unit area with an increase in scale from plot to hillslope, stream or river

Sediment Transport

Transport is the entrainment and movement of sediment from its original location once it has been detached from the soil. It is a function of the energy of the transporting agent, in this case flowing water. Deep and fast flows have a greater capacity to transport sediment, and fine particles are moved more easily than larger and heavier particles. *Deposition* occurs when the sediment load of a given particle type exceeds the energy available for transport or re-entrainment. This often results from a reduction in gradient, flow velocity or discharge or an increase in the hydraulic resistance the flow induced by vegetation. Deposition results in *sedimentation*.

Sediment Yield

The amount of material transported past a given point of interest (usually a measuring device in a stream or a point on a hillslope). It is the net result of erosion, transport and deposition upstream or upslope.

Sheetwash or Surface Wash Erosion

The removal of a relatively uniform layer of soil by raindrop splash and/or by diffuse surface runoff during intense storms. On land where soil is not protected by a surface cover, soil is lost from most of the land surface by sheetwash erosion.

(Based on Sharman & Murphy, 1991)

Soil Creep

(Sometimes) imperceptible slow but continuous movement or displacement of soil or subsoil, evidenced by leaning trees and fences and bowed walls.

Streambank Erosion

The removal of soil from streambanks by the direct action of water in the channel. Typically it occurs under high flow conditions by scour and mass failure processes, and particularly by undercutting of the toe of the bank.

Sodic Soil

Typically sodic soils are considered unstable and, as a consequence, have high erodibility and often present problems for soil conservation strategies. This is because the exchangeable sodium percentage (ESP), which is a measure of the cation exchange capacity occupied by sodium ions, of the fine earth soil material is 6 or greater.

Stream Link

The division of a river into lengths of stream between tributary junctions.

Surface Runoff

Most soil eroded by water is transported downslope by *surface runoff*, which is the portion of rainfall that becomes surface flow.

Terrace

A flat or gently inclined land surface bounded by a steeper ascending slope on its inner margin and a steeper descending slope on its outer margin.

(From Whittow, 1986)

Universal Soil Loss Equation (USLE)

The USLE calculates mean annual erosion (Y, tonnes/ha/y) as a product of six factors: rainfall erosivity factor (R), soil erodibility factor (K), hillslope length factor (L), hillslope gradient factor (S), ground cover factor (C) and land use practice factor (P):

$Y = RKLSCP$

The precise form of each factor is based on soil loss measurements on hillslope plots, mainly in the USA.

Related term: Revised universal soil loss equation (RUSLE).

3 THE EROSION STORY

Managing the on-site impacts of soil erosion requires a comprehensive understanding of the major erosion processes of sheetwash and rill erosion, gully erosion and streambank erosion.

Modelling these provides predictions about overall patterns of soil erosion and associated conditions.

3.1 The sheetwash and rill erosion picture

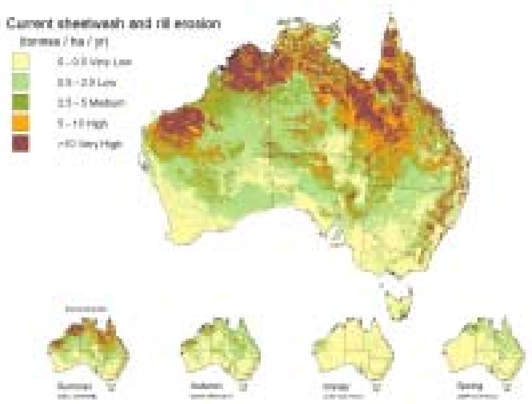
The assessment of erosion from sheetwash and rills is based upon combining the influence of several environmental and land use factors which determine the broad regional patterns of erosion. The most significant of these, as required for the RUSLE model, are:

- soil erodibility
- rainfall erosivity
- land cover
- slope gradient
- slope length

These factors are used to determine regional patterns of erosion, based upon an extensive database of erosion plot studies and national geographical information on soils, topography, and remote sensing. Each of the geographical layers has a degree of uncertainty at any particular place as a result of resolution and measurement limitations but they produce coherent large scale patterns because of the huge variation in factors across large areas. Because of the limitations of accuracy and resolution, the results should not be used at any finer scale than sub-catchments of 25 km^2 or so. To accurately assess soil erosion from any individual paddock or farm, measurements need to be made on the farm of the local soil properties, land use and topography.

Continental snapshot of erosion

Modelling produced a geo-referenced annual averaged soil erosion map and its monthly distributions.



Map 2

The predictions show broadscale patterns of annual soil erosion under contemporary landuse (potential hillslope erosion) with the northern part of the continent having higher erosion potential than the south. There is also a zone of high potential soil erosion on the western slopes of NSW. These patterns reflect seasonal effects. In the north, summer has the most erosive rain, when it can coincide with relatively little ground cover and produce high erosion potential. In southern Australia the opposite occurs, with winter being the most erosive season but where rains falls on well vegetated land. This produces the quite strong north-south gradient shown in the map and the tendency for summer soil erosion shown in Figure 3 below.

The results are described as representing soil erosion potential for two reasons. First, no assessment could be made of the reduction in soil erosion under some cropping land uses as a result of conservation practices such as minimum tillage and stubble retention. Second, in parts of southern Australia, the naturally high soil erosion potential on steeper slopes has resulted in soils with significant stone and rock cover, which reduces the actual rate of erosion. Again there was no data available to model this phenomenon.

Monthly Total Erosion (millions tonnes/year)

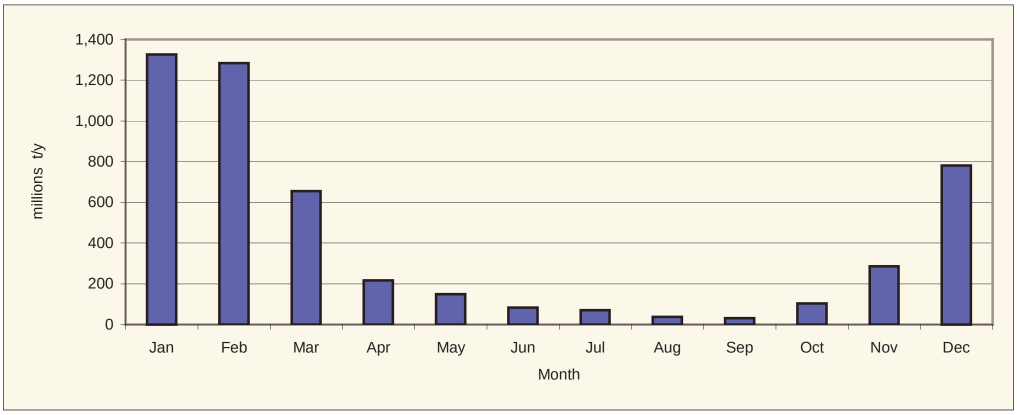


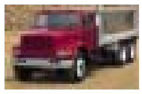
Figure 3: Continental Erosion

The following observations can be made by examining the modelled predictions:

- Potentially 1.5 billion tonnes of soil is moved annually on hillslopes.
- The average soil erosion rate is 2.2 tonnes/ha/year.
- 62% of the continent experiences low erosion, only 1% faces high erosion and 37% of the continent experiences medium hillslope erosion potential using the boundaries defined in Table 2.
- Overall, 10% of the area is eroded at a rate greater than the continent average rate. This shows the value in targeting erosion control to particular problem areas.
- Under any given rainfall regime, the map shows that the reduction of protective ground cover increases the risk of high rates of erosion.

Table 2: Erosion Rates

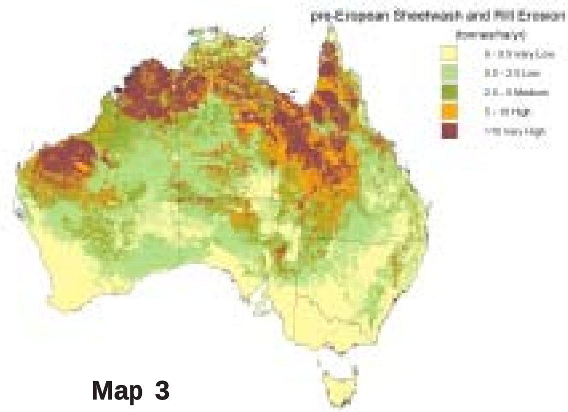
Erosion Rate	Tonnes/ha/year
Low	< 0.5
Medium	0.51 – 9.9
High	> 10



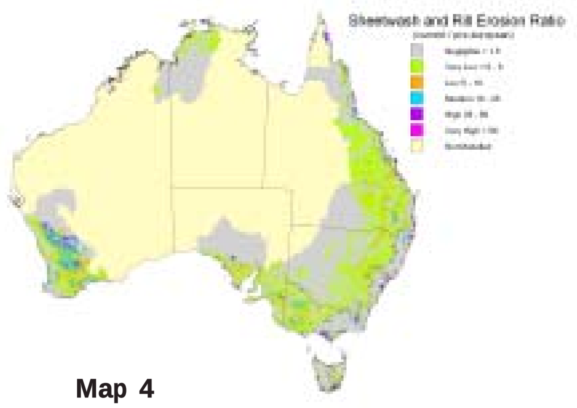
Having trouble visualising the quantities of soil under consideration?

The average 6-wheel tip truck carries about 12 tonnes. Each truck load would remove a bit less than one millimetre of soil from the MCG (which is 20,000m^2 or 2 ha) at a rate of 6 t/ha/y. Less than a millimetre would be hard to detect each year but maintained over 30 y of continuing soil erosion makes 27 mm of soil. Remembering that this is the most fertile part of the soil in which most of the roots live, the impact on management would be significant.

To understand current issues of land degradation it is necessary to compare the predictions of current soil erosion potential to that of pre-European settlement conditions under native vegetation cover, for some areas may have naturally high erosion rates.



Map 3



Map 4

The map of pre-European soil erosion produces the same broad pattern of relatively high soil erosion potential in northern Australia and much lower rates in southern Australia (Map 3). The gross pattern of contemporary soil erosion potential reflects the natural distribution of soil erosion across the continent. Within each climatic zone there are areas of significantly accelerated contemporary erosion potential shown by the ratio of contemporary to natural erosion potential (Map 4). These are areas where cover has been reduced at least seasonally. For example, although the overall erosion rate is low in the wheat belt of WA it is still many times higher than the naturally very low rate. Similar results are found for the cereal crop belt from Victoria through to Queensland and the extensive grazing lands and tropical crop lands of north Queensland.

Croplands

The most intensive crop land uses have the greatest potential to result in accelerated erosion (Table 3). Sugar cane and tropical fruit crops are of particular concern in this regard as they are located in areas of high rainfall erosivity and if undertaken on sloping land, soil erosion can only be stopped by retaining good cover at all times. Cereal and legume crops in southern Australia are less susceptible to accelerated erosion because of low rainfall during times of low cover. The potential for soil erosion highlights the importance of soil conservation procedures under these land uses. Considerable effort has been invested in minimum tillage, stubble retention, and contour banking in croplands. These practices are widely, but not universally adopted, and have greatly reduced soil erosion rates in crop lands. The sugar cane industry reports adoption of minimum tillage, green cane harvesting and trash blanketing in 80% of cases. This has reduced soil erosion rates on sloping land from the order of 100t/ha/y to 5-10 t/ha/y. Tillage is still necessary when planting a new crop, when there is risk of accelerated soil erosion. Riparian filter strips offer the greatest potential as a last line of defence under these circumstances, protecting streams from sediment and attached nutrients. Attention has only recently been given to riparian management and this is the area of greatest potential for improvement in crop land use. Filter strips of <5 m width can be effective at protecting against erosion rates of < 20 t/ha.

While the potential for accelerated erosion in crop lands is of concern the total area covered is far less than by grazing lands, which contribute a greater amount to the total soil erosion predicted throughout the river basins containing intensive agriculture.

Table 3: Summary of erosion by land use for river basins containing intensive agriculture.

Landuse	Area (km2)	Total Erosion (t/y)	Average erosion rate (t/ha/y)	Rate of acceleration
Closed Forest	22,000	2,552,000	1	1.1
Open Forest	228,000	6,900,000	<1	1
Woodland (unmanaged lands)	220,000	103,400,000	5	3
Commercial native forest production	153,000	5,800,000	<1	1.1
National Parks	86,000	76,200,000	9	1.2
Cereals excluding rice	180,000	38,933,000	2	10
Legumes	22,000	740,000	0	3.2
Oilseeds	6,000	2,382,000	4	9.6
Rice	1,500	115,000	1	5.9
Cotton	4,000	2,784,000	7	11
Sugar Cane	5,000	18,623,000	40	57
Other agricultural landuse	2,000	2,329,000	54	34
Improved Pastures	190,000	41,429,000	2	5.3
Residual/Native Pastures	1,673,500	957,939,000	6	3.2
Total Assessment Area	2,793,000	1,260,126,000	5	

Grazing Lands

Grazing is the most significant land use in terms of its contribution to total soil erosion throughout river basins containing intensive agriculture, simply because of the vast area of land use involved and its areal dominance in northern Australia where soil erosion potential is most significant. Grazed land comprises 75% of the assessment area and is composed of woodlands that are the basis of the beef industry in northern Australia as well as pastures. Crop lands comprise only 8% of the assessment area. On average we predict that erosion under pasture lands has increased two fold from natural conditions, with a five fold increase for improved pastures. Soil erosion under woodlands and native pastures contributes 86% to the assessment area total and is much harder to manage than in the crop lands because of the greater areal extent, the lower levels of inputs, and the smaller marginal returns on investment. Structural works and other soil conservation practises are impractical. The greatest scope for improved sustainability is through improved pasture and stock management aimed at maintaining adequate ground cover to protect from erosion at all times. This includes practices such as drought planning, off-stream watering, cell grazing and management of pasture species. These issues of greatest importance in the northern grazing lands where river suspended sediment loads are most increased and where sediment delivery to the coast is most effective (see river sediment delivery below).

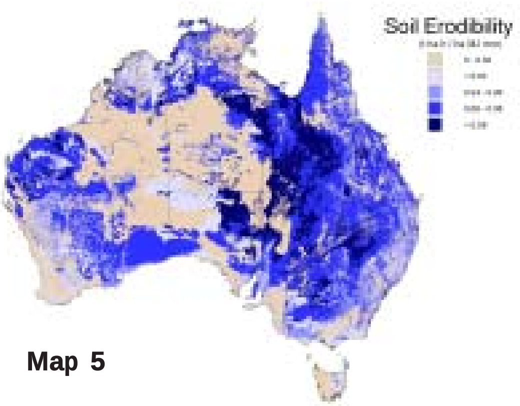
In summary, much has been done to reduce significantly accelerated soil erosion under crop lands. There are still risks of infrequent accelerated soil erosion even using soil conservation practises. The off site impacts of this soil erosion can be minimised by increased attention to riparian management. Of greater significance to the total amount of soil erosion in Australia are the vast areas of extensive grazing lands, particularly those in northern Australia where soil erosion and sediment yields are of greatest concern. To reduce soil erosion in these areas requires improved pasture and stock management techniques.

Factors Contributing to Sheetwash and Rill Erosion

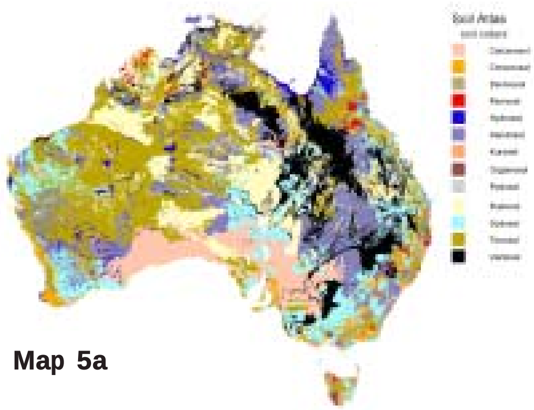
To interpret the predicted patterns of sheetwash and rill erosion across the assessment area it helps to consider the contribution from each of the five factors to the overall picture. The factors are: soil erodibility, rainfall erosivity, cover, slope length and slope gradient.

Soil erodibility picture

Soil erodibility is a measure of the susceptibility of the soil itself to erosion. It is a function of its structural stability and its capacity to absorb rainfall and minimise runoff. Structural stability itself is a function of a soil's particle size distribution, mineralogy and organic matter content. ☞



Map 5



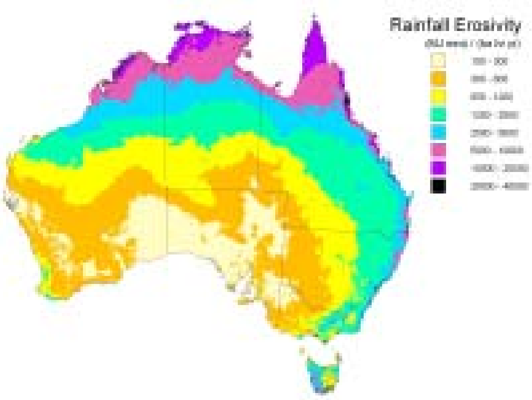
Map 5a

Determining erosion predictions therefore requires knowledge about soil erodibility. For satisfactory direct measurement of soil erodibility, erosion from field plots needs to be studied for periods generally well in excess of 5 years (Loch *et al.*, 1998). This is costly and time-consuming, and data from field studies is scarce. Instead, soil erodibilility can be predicted from surrogate soil property mapping of particle size distribution, organic matter content and soil density.

Comparing the soil erodibility factor with the soils map of Australia (Map 5a) shows that heavy clay soils (Vertosols) and structurally unstable, chemically dispersible sodic soils (Sodosols) are highly erodible. Kandosols and Calcarosols with sandy topsoil are slightly less erodible. Rocky soils (Rudosols) and weakly developed soils (Tenosols) are least erodible. Soils with high organic matter content are less erodible than those with low organic matter content. Much of southwest Western Australia, coastal southeast Australia and Tasmania have low soil erodibility. The map shows an obvious state boundary between South Australia and Victoria which is partly due to land management differences and to original map sources of soil data.

Continental rainfall erosivity picture

Rainfall erosivity refers to the erosive energy of rain, a function of the total amount of rainfall and its intensity in a typical storm.



Map 6:

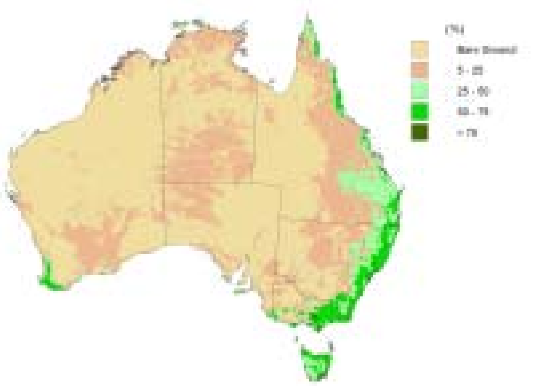
The map shows the predicted spatial pattern of rainfall erosivity and the monthly distributions for selected locations across the continent.

For the northern part of the continent, the monthly distributions generally show peaks in summer, especially between December to February. Approximately 80% of the annual rainfall erosivity occurs during December to March, and a negligible fraction occurs in the months from April to October. For the south-eastern part of the continent, predicted monthly rainfall erosivity distributions change gradually from summer dominance to uniform from north to south. Winter dominant monthly rainfall erosivity distributions are obtained for the coast area of south-western Western Australia. Moving inland this pattern changes to a summer dominance. These predicted patterns are comparable to other observed measures of erosivity.

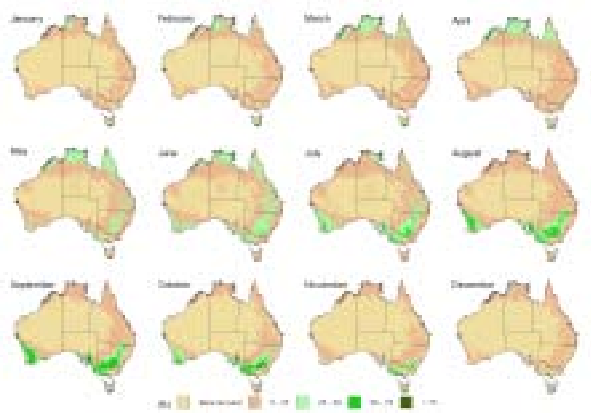
Continental perennial and woody cover and monthly ground vegetation cover

The perennial and woody cover and monthly ground vegetation cover are important for the prediction of large scale erosion. Erosion occurs when the rainfall intensity is high and where the vegetation cover is relatively low and not sufficient to protect the soil.

The maps (Maps 7 and 7a), derived from satellite remote sensing, show the estimated perennial & woody cover and monthly ground vegetation cover in percentage terms. They compare well with the known distribution of vegetation, showing good forest cover on the Eastern seaboard, Tasmania and SW Western Australia. This cover reduces the rate of soil erosion. Monthly ground vegetation cover maps (Map 7a) show strong seasonal variations for the southern Australia crop belt, where the ground cover peaks around September, when the crops are in full growth. Many other features are represented such as the country having better ground cover during the winter compared with summer, the tropical monsoon induced summer peak greenness in the north part of the country, and grass dieing back after lack of rainfall during late winter to early summer.



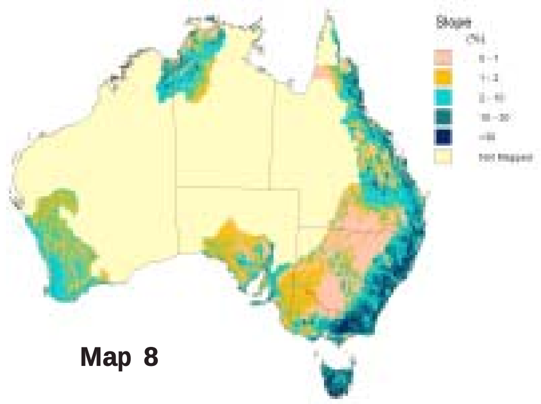
Map 7



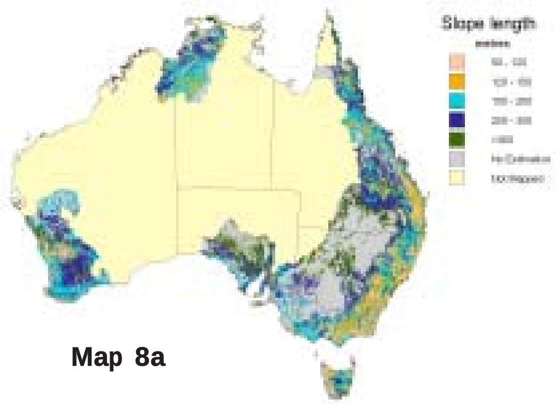
Map 7a

Length and Slope factors

The hillslope length factor is used to represent the increased propensity for rill erosion on longer hillslopes under crop land use. It does not apply to other types of land use. The slope steepness factor is defined as the ratio of soil loss from the field slope gradient to that from a 9% slope. Both maps were derived from relationships between high resolution digital elevation models (DEMs) and the national 9" DEM. The slope gradient factor shows the high gradients of Tasmania, coastal Eastern Australia and the Darling Range in Western Australia. The lowest gradients are the extensive alluvial plains of the MDB (Map 8). The slope length factor shows shorter slope lengths in the more dissected terrain of the wet tropics and longer hillslopes in drier areas (Map 8a).

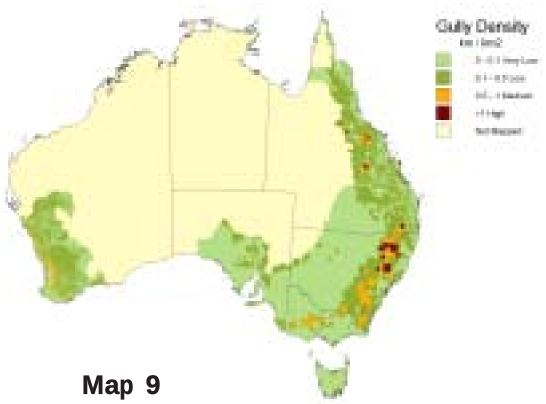


Map 8



Map 8a

3.2 Gully erosion picture



Map 9

The extent of gully erosion throughout the assessment area is expressed in Map 9 as gully density, the total length of any gullies that exist within a one square kilometre 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 their approximate age. The average sized gully is 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 y, the mean annual rate of erosion is 1.5 t/ha/y, as shown on Map 9.

Map 9 shows that some of the highest gully densities occur in the eastern highlands. Much of this area was subject to early European settlement and gullies developed late in the 19^{th} C. These gullies continue to contribute fine sediment and poor quality water, although gully expansion is largely complete. This contrasts with the situation in the north Queensland grazing lands where gullies developed more recently and in places are continuing to expand and therefore are supplying significantly more sediment at present. There is low to moderate gully erosion in SW Western Australia 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.

In Table 4 we have classified the range of gully densities observed into three classes.

Gully Density	(km/km^2)
Low	< 0.1
Medium	0.1 – 1
High	1- 3.5

The highest gully density predicted is 3.0 – 3.5 km/km^2 in the Nogoa R. sub-catchment of the Fitzroy R. basin. Initially, this was an area predicted to be of high gully density but where no sample aerial photographs were analysed. Subsequent checking of photographs has confirmed the model results. Similarly high values of gully density are possible for isolated patches of NSW and Victoria but were not detected because of the averaging over large areas.

Some areas of historical gully erosion which are now forest covered 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.

Figure 4 shows the area covered by moderate and high gully density in each region.

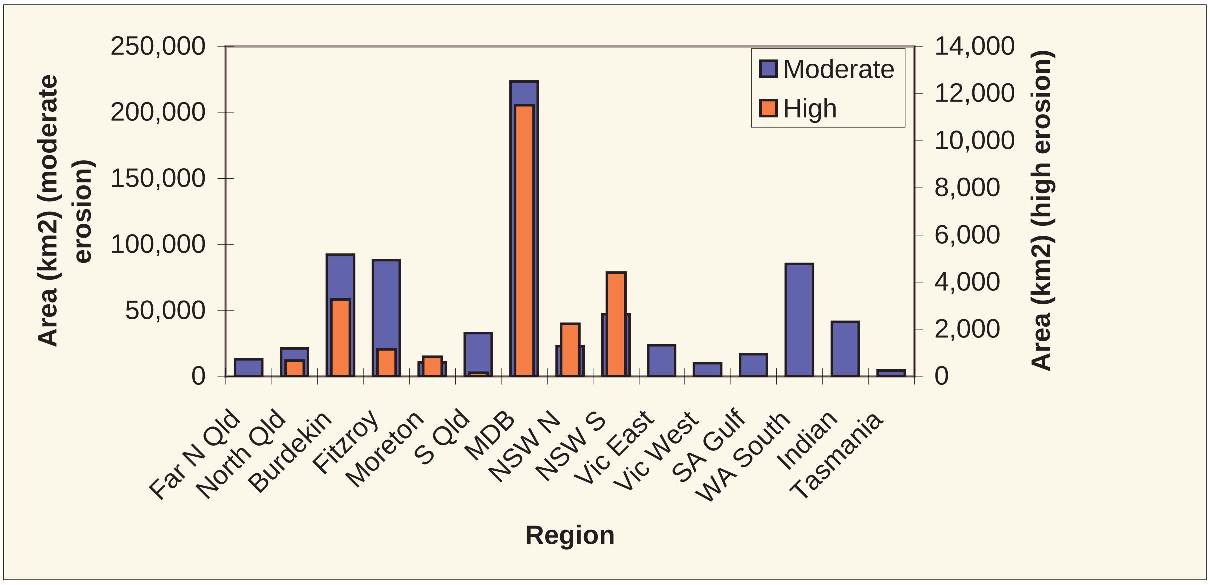


Figure 4

The Murray-Darling Basin (MDB) contains 30% of the moderately eroded land in the assessment ara and 50% of the highly eroded land. This partly reflects that the MDB contains 40% of the land in the assessment area, but all of the erosion is focussed on the southern and eastern rim of the basin where it presents a substantial impact on rivers in an area where sheetwash and rill erosion is at a low rate. 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 containing intensive agriculture is 0.13 km per 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. Thus although the gross volume of sediment generated each year by gully erosion is considerably less than by sheetwash and rill erosion the influence on stream sediment loads is comparable. Sheetwash and rill erosion are more significant for farm productivity as they occur across the landscape whereas gully erosion is limited to intense erosion of valleys. The greatest on site problem of gully erosion is its threat to fences, tracks, roads and buildings.

Amelioration of gully erosion can range from fencing out stock to encourage revegetation, through structural works to stabilise the gully head, to filling the gully and constructing erosion control dams and grass waterways. These works can range in cost from around $2,000 to $50,000 per kilometre of gully depending upon the nature of works. To treat all gullies in the assessment area at an average cost of $20,000 per kilometre would total $6.5 billion. Such resources are clearly not available, nor are they needed, for gullies naturally stabilise over time and many no longer pose an erosion problem. Remedial works should thus be focussed on those gullies that continue to erode and threaten structures, or that yield considerable sediment or poor quality water. Local observations of gully movements and water quality can provide the information required to identify problem gullies.

It should be noted that gully erosion, like other forms of erosion is a natural process, but prior to European settlement gullies formed for only a hundred years or so every few thousand years, and only in a few valleys at any time. The extent of erosion along valleys is also considerably longer than occurred naturally. The current extensive and relatively synchronous erosion of many valleys represents the effects of increased runoff and disturbance of valley floors and is unprecedented over at least the last 15,000 y.

3.3 Streambank erosion picture

One of the major drivers of streambank erosion is degradation of the *riparian zone*. The modelling shows that, throughout the river basins containing intensive agriculture, there are some 120,000 kilometres of cleared streams that, at a conservative cost of $10,000/km for fencing and replanting, would require $1.2 billion to restore! There are additional costs for maintenance, gates, weed control, flood gates etc. This is another example of the scale of addressing erosion or other land degradation problems in Australia. Clearly, such investment is not feasible at present and not all areas of cleared riparian lands will be a high priority for restoring degraded streams. Thus effort is needed for strategic targetting of restoration works at a regional, state and national level. The outputs of the NLWRA provide a basis for such an exercise.

A total of 181,500 km of streams were mapped, and on average 65% of this length has cleared riparian vegetation. In addition to increased susceptibility to erosion, riparian clearing presents problems of removal of fish and bird breeding habitats, and loss of food sources and stream shading.

A regional analysis of riparian degradation is shown in Figure 5. ☞

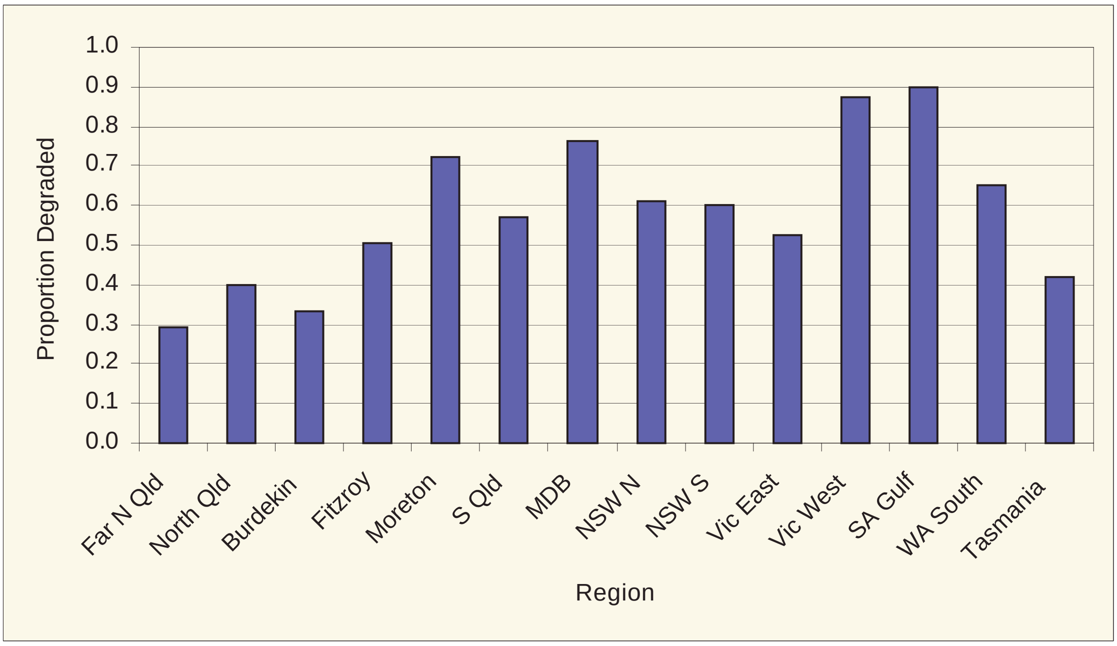


Figure 5

Western Victoria and the South Australia gulf region are predicted to have the highest amount of stream clearing but these are regions with extensive native grasslands rather than riparian forests, so the extent of clearing is probably over estimated. Regions with the greatest proportion of cleared vegetation are not surprisingly found in the more developed parts of Australia. This includes Moreton, MDB, the NSW coast and WA south. The MDB is of particular concern because it represents 40% of the assessment area, while Moreton Bay is an area with a large open estuary where increased supply of sediment from the catchment has been identified as a significant problem (External Link to Estuary Storyboards relevant to Moreton Bay).

Loss of riparian vegetation has at least two effects on bank erosion. First tree roots add substantial strength to streambanks and effectively prevent them from slumping and other forms of bank collapse, even where streams have deepened or are undercut. Second, overhanging and emergent vegetation such as *Phragmites* used to be much more prevalent along our rivers and has the effect of reducing flow velocities and the ability for scour of the bank.

Loss of riparian vegetation reduces the resistance of the banks to erosion but erosion may not occur immediately and its intensity will differ between rivers. In many cases large floods are needed to overcome the strength of banks and cause significant erosion. The Hunter River system, and particularly the tributary of Wollombi Brook, on the NSW Coast is an example. Riparian vegetation was cleared late in the 19th century as was common throughout coastal NSW but major erosion of streambanks did not occur until a sequence of large floods in the 1950s. For example, floods between 1946 and 1955 caused on average 304 m of erosion along an 82 km stretch of the Hunter River (Erskine and Bell, 1982). In higher energy rivers such as the Bega River the cleared banks were capable of being eroded by even relatively small floods and channel widening occurred in the first few decades of clearing. In contrast, rivers such as the Lachlan in central western NSW are of such low energy that there has been relatively little erosion despite extensive clearing.

4 THE SEDIMENT DELIVERY STORY

Soil that is eroded and transported to and reworked through channels causes numerous physical habitat impacts. To limit these impacts, management strategies need to target problem sources in order to be effective and economic. ☞

Determining which rivers and catchments are likely to deliver high loads of sediment involves a thorough understanding of the major processes of hillslope erosion, gully erosion and stream bank erosion. Table 5 shows the main components of the river sediment predictions summed for river basins containing intensive agriculture. The sources of sediment are described further in the soil erosion story of section 3.

Table 5: Components of river sediment budgets across the assessment area.

Gross sheetwash and rill erosion	666 Mt/y
Delivery to stream from sheetwash and rill erosion	50 Mt/y
Gully erosion rate	44 Mt/y
Riverbank erosion rate	33 Mt/y
Total load	**127 Mt/y**
Total suspended sediment stored	66 Mt/y
Total bed sediment stored	36 Mt/y
Sediment delivery from rivers	25 Mt/y
Total stores and losses	**127 Mt/y**

Soil erosion on hillslopes dominates the sediment budget but across the assessment area we predict that only 5% of that soil actually reaches the stream on an annual basis. Much of it is redeposited on hillslopes. This has been shown by the differences between erosion rates measured on small plots to those at the scale of small catchments and whole hillslopes (Edwards, 1993).

The predicted masses of gully erosion and streambank erosion are of comparable magnitude to sediment delivery from sheetwash and rill erosion. The certainty of these predictions reduces from hillslope erosion through gully erosion to bank erosion. They are, however, certain enough to know that each process needs to be considered in regional assessments of sediment loads and impacts otherwise there would be a gross underestimate of sediment supplied to rivers, or false attribution of the source of that sediment.

Importantly, only 20% of the total load supplied to rivers is actually delivered to the coast, with the remainder either staying within the river or being deposited on floodplains. This highlights the importance of assessing river loads for patterns of deposition in order to appropriately target management strategies.

A regional analysis (Figure 6) shows the amount of sediment supplied to streams from the different sources. ☞

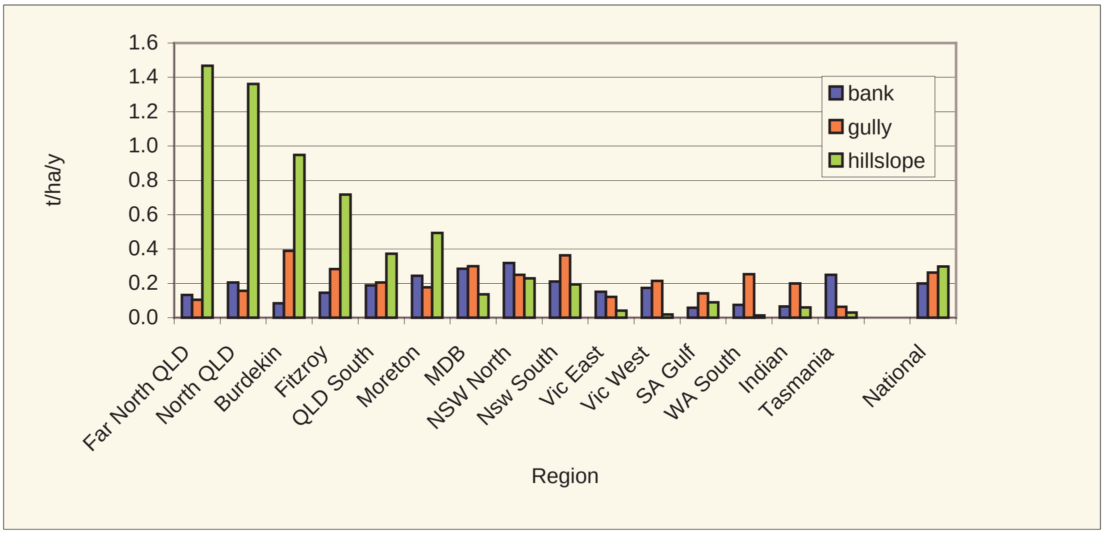


Figure 6

This analysis is based upon the fraction of sheetwash and rill erosion that actually reaches the stream. The predicted dominance of gully and streambank sediment sources over sheetwash and rill erosion in southern Australia is supported by field-based sediment budgets of some catchments and by radionuclide studies which distinguish between surface and sub-surface sources of sediment. For example, sediment transported in the Murrumbidgee R. has a radionuclide signature which suggests that 95% of sediment is derived from sub-surface sources. The most obvious process of erosion of sub-surface materials is gully and stream bank erosion which erode deep into soils, whereas sheetwash erosion is restricted to the very surficial layer of soil.

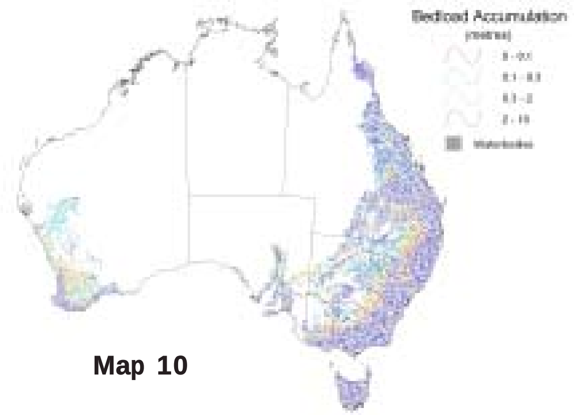
In contrast, northern Australia, particularly Far North Queensland are predicted to be dominated by sheetwash and rill erosion processes. Two factors contribute to this. Gully erosion is less extensive in these areas because soils tend not to accumulate in valleys and hollows because of intensive runoff under tropical storms or because the high runoff results in streams which continue close to the divide. This provides little opportunity for gully erosion following clearing. Secondly, rates of hillslope erosion are much higher in northern Australia because of the much higher rainfall intensities and low ground cover at the break of season.

Based on measured values and modelled predictions of these processes the likely patterns of sediment movement and distribution at the continental scale can be determined.

Some of these include:

- sediment accumulation
- Suspended sediment yield
- Mean sediment concentration
- Ratio of current to natural yield
- Contribution of sediment to the coast

Bedload accumulation



Map 10

A major issue concerning stream quality is the deposition of bedload accumulation - sands and fine gravels - which have increased in supply as a result of increased gully and streambank erosion since European settlement. Streams only have a certain capacity to transport coarse sediment. When the capacity is exceeded, from an increase in erosion for example, streams accumulate the excess load as shown in the map which provides a picture of local instream impacts.

Naturally, many coastal streams of Australia have beds of cobbles, boulders and rock outcrop. These surfaces are ideal habitat for benthic algae, macroinvertebrates and some fish species. In addition there are areas of scour pools and undercut banks, or pools surrounding fallen debris. These are all important refugia and breeding areas for fish and other organisms. During low flows suspended sediment and nutrients accumulate between the rocks or in the deep pools but they are flushed out periodically during large flows, cleaning out accumulated debris and reinitiating surfaces for fresh colonisation of algae.

If supply of sands and gravels from upstream exceeds the ability to flush this material through the reach it starts to accumulate and cover the rocky surfaces and fill the deep pools. The sand and gravel are too unstable for growth of benthic algae and the filling of pools removes refugia and breeding grounds. In the most extreme example of deposition, the bed of the river becomes an inhospitable flat sheet of dry sand during low flow. This deposition, known as "sand slugs", are one of the most severe impacts on aquatic organisms in our rivers. The slugs migrate slowly through the river systems over many decades, inundating new reaches downstream and liberating upstream reaches, but sometimes with consequences of renewed erosion.

Our predictions of bedload accumulation compare mean annual sediment loading with transport capacity. Accelerated deposition of sand is possible in all reaches where sediment supply is increased. The most susceptible river reaches to accelerated sand deposition are either where sand supply has increased the most or where river gradients and discharges are low. High energy rivers are capable of accommodating large increases in the supply of sand and gravel. Bedload accumulation is expressed in terms of the average depth of sediment accumulation over the entire stream link during historical times. Any deposition above natural rates will have negative impacts and the higher the rate of deposition the greater the likely impact. Actual sediment accumulation in the rivers will be patchy with some areas accumulating more than others. Thus reaches with less than 1 m accumulation may have areas of preserved habitat whereas, those areas with greater than 1 m accumulation on average are likely to be fully impacted and contain uniform sheets of sand.

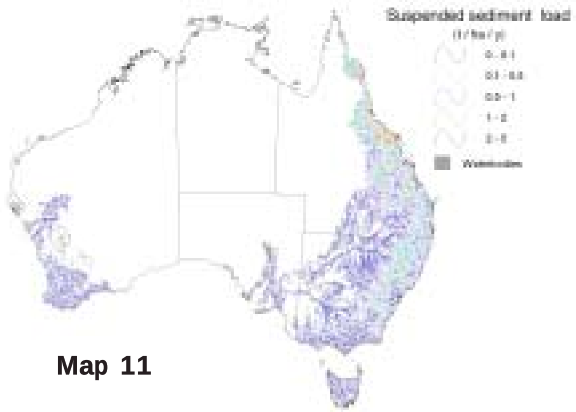
The patterns show extensive sand deposition in reaches immediately downstream from areas of high gully and streambank erosion. This includes the arc of the eastern boundary of the Murray-Darling Basin. Coastal streams to the east of the MDB are less impacted because of their higher gradients and discharges. However, where there are high energy streams, such as are found in much of coastal north Queensland, and Tasmania there is relatively little historical accumulation of sand while the reverse is shown in much of WA where the rivers have low gradients and insufficient energy to carry the increased loads, even though rates of sediment supply are not high on an absolute scale.

Overall there are 30,000 km of stream in the assessment area predicted to be impacted by sediment accumulation of greater than 0.3 m since European settlement. Proportionally the worst effected areas are WA South and the MDB where 30% and 21% of streams are impacted by in stream accumulation respectively. Our assessment is limited to streams affected by supply of sand from gully and streambank erosion. Another significant source of debris is from alluvial mining for gold or tin, or from the supply of mine tailings to rivers. Rivers effected include the Ringarooma, George, King, Queen and South Esk rivers in Tasmania; the Tambo River, Ovens River, Yackandandah Creek and Bendigo area in Victoria; the Rocky and Molongolo rivers in NSW; and Magela Creek in the Northern Territory.

The semi-arid areas of northern Australia and the western MDB have naturally sandy river beds as a result of the climate, natural erosion processes and low slopes which result in sand supply exceeding capacity. It should not be assumed that these are impacted streams and our predictions suggest that there has been little net accumulation of sand in these areas.

This picture presents a snapshot of the current situation. The accumulation is really a pulse of material which will gradually move through the system over time driven by slow movement of sand during flood events. The implication of this is that even if source erosion was stopped today there are large areas of sand deposition which will continue to progress through river systems. In fact much of the sediment deposited in the upper tributaries of the MDB was delivered to streams by erosion in the late 19th C and early 20th C. The sediment will continue to have impacts unless stabilised, extracted or flushed. These are all possible management actions depending upon circumstances.

Suspended sediment

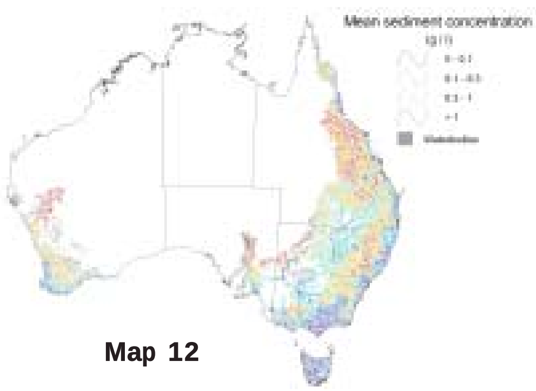


Map 11

Suspended sediments - mainly suspended clay and silt particles - impact streams by covering surfaces, decreasing light availability, carrying increased loads of nitrogen and phosphorus and clogging of gills. Increased delivery of suspended sediment from rivers can cause deposition in estuaries and inshore marine environments. This can smother important habitats such as sea grass beds which support estuarine ecosystems. (External link to estuary storyboards).

There is no comprehensive single indicator of suspended sediment. The mean annual loads of rivers, their yield per unit area, the mean concentration of sediment and the increase in yield in historical times all contribute to the story.

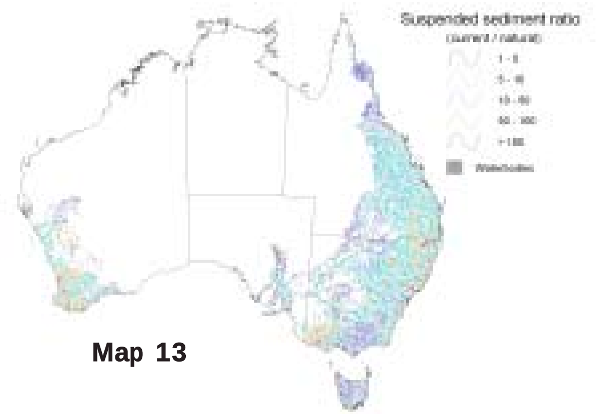
The mean annual yield of suspended sediment is lower in southern Australia, where erosion rates are lower, and where there are few large high energy rivers. The highest absolute loads in the river basins containing intensive agriculture are from the large Queensland catchments of the Fitzroy and Burdekin rivers which each deliver over 2.5 Mt/y to the coast. These are large catchments with significant erosion, both natural and accelerated and where floodplain deposition is limited. Other catchments which deliver over 1 Mt/y are the Murray-Darling Basin, and the Normanby. The Murray-Darling Basin has an area nearly five times larger than the Fitzroy basin but a lower sediment yield because the high erosion areas are in the headwaters of the catchment, on average the erosion rate is lower, and there are substantial lowland floodplains, and many reservoirs which prevent most of the sediment from reaching the coast. It should be noted that river discharge is not used directly as a means of predicting sediment loads, so there is no enforced reason why rivers with high discharges have high sediment load. For example, the Murray River has a similar mean annual flow to the Burdekin River yet the Burdekin River yields three times more sediment than the Murray River. Regions of low erosion rate, such as south west WA have low sediment yields from rivers regardless of deposition potential.



Map 12

The absolute sediment loads of rivers are strongly influenced by the catchment area, as described above. A better view of the intensity of river sediment transport is seen by dividing the suspended sediment loads by the upstream catchment area to produce loads per unit area (the specific sediment yield). This shows that specific sediment yields are high on the central and north Queensland coast where hillslope erosion rates are high. There are also moderate to high specific yields on the eastern part of the MDB and in the Hunter region of NSW where gully and streambank erosion processes are significant. These yields decrease markedly downstream in the MDB as a result of deposition and lower erosion rates in the western parts of the basin. Specific sediment yields are low in parts of the assessment area - coastal Victoria, Tasmania, WA, and SA - because of the low erosion rates in those areas. The suspended sediment yields can also be divided by the mean annual flow to show mean sediment concentration, which reveals similar patterns.

Changes since European settlement

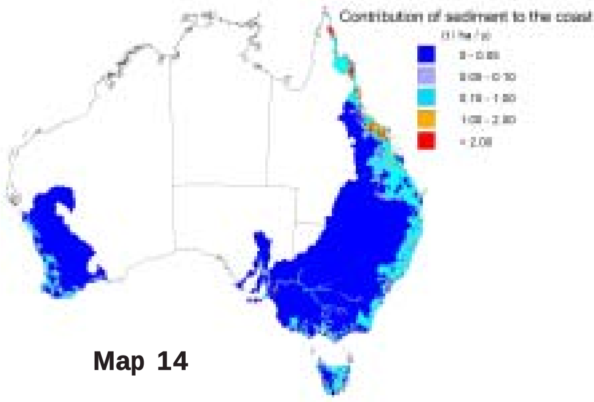


Map 13

An assessment of river sediment impacts in terms of the loads is inadequate as there are naturally strong differences across Australia in river loads and it is reasonable to expect that local ecosystems are in some way adjusted to those loads. Southwest WA for example has naturally low loads, and those of today are low by comparison to the rest of the continent but river sediment impacts on coastal ecosystems have been recorded (Kalnejais and Robb, 1999; McComb and Davis, 1993). It is useful then to examine the ratio of current mean annual suspended load to the predicted natural mean annual suspended sediment load. The natural suspended load has been estimated in an indicative way by using the pre-European sheetwash and rill erosion prediction (Internal Link) and assuming negligible bank and gully erosion under natural conditions. ☞

The ratio of current to natural suspended sediment yield predicts that 12% of the assessment area has loads greater than 50 times the natural sediment yield. Such inflated rates are supported by measurements of sediment loads in the Southern Uplands of Australia, where it was found that sediments loads increased by 4 – 400 times after European settlement (Wasson *et al.*, 1996). The map predicts that the current suspended sediment yields in southwest WA are commonly 50 – 100 times greater than the natural rate. This is a result of the very low natural erosion rate so that even low magnitudes of streambank and gully erosion significantly inflate sediment yields. Other areas of large increases in load are the Dundas Tableland the eastern part of the MDB and coastal NSW and Qld as far north as the Herbert River. Areas of low impact include much of Tasmania, NE Victoria and far north Queensland. All of the areas of inflated sediment loads are ones of potential concern over ecological impacts on rivers, floodplains and estuaries.

Contributions to the coast



Map 14

Estuaries are of particular concern for suspended sediment impacts as they are areas of suspended sediment deposition. Increased rates of deposition can smother significant estuarine habitats such as sea grass beds. The sediment can also be a supply of nutrient, and change the food web structure of the estuary. Given that only 20% of sediment delivered to streams within the assessment area actually reaches estuaries in any year, it cannot be concluded that increased erosion upstream in a catchment results in a significant increase of sediment supply to an estuary or the coast. For erosion upstream to link to an estuary there must be efficient delivery of the sediment through the river network. In many of the bigger catchments there are source areas of sediment hundreds of kilometres from the coast and many opportunities for the sediment to be deposited in floodplains as it travels through the network.

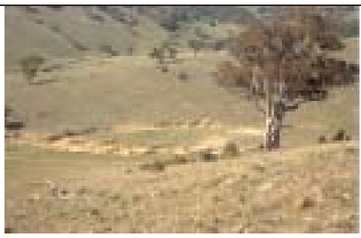
We have taken the sediment load of each river reaching the coast in the assessment area and traced upstream to find where that sediment is contributed from. This is expressed in terms of sediment loss in t/ha/y from each subcatchment that reaches the coast. Mathematically, the sediment delivery to the coast from each sub-catchment is the sediment delivery to streams in the sub- catchment multiplied by the probability of that sediment passing each river link on its way to the coast. The probability of sediment passing through an individual river link is merely the ratio of the sediment yield of the link over the load supplied to the link. Subcatchments which make a substantial contribution to the coast are those with high erosion and limited floodplain extent between the source and sea. Thus subcatchments close to the coast are more likely to contribute to the coastal yield. This is the overall pattern shown by the results (Map 14). Sediment is derived from inland areas in catchments such as the Fitzroy where there are significant sources inland and where the rivers are relatively high energy and confined, thus having more efficient delivery to the coast. In these catchments there is a very strong relationship between actions undertaken on the ground at farm scale having direct impacts on coastal systems. By contrast, subcatchments of the MDB deliver very little to the coast because the areas of high erosion are in the headwaters over a thousand kilometres from the mouth with extensive lowland floodplains and large reservoirs along the route. The issue in the MDB is internal redistribution of sediment and potential impacts on the lowland rivers.

A result of the sediment delivery process is that 90% of sediment delivered to the coast comes from only 20% of the assessment area. This means that while soil erosion is a widespread issue across the assessment area targetted management can be used to address specific problems. If the goal is to reduce sediment loads to the coast then remedial works can be focussed on particular sediment sources and the land uses and erosion processes found there. Relatively little attention is needed for the rest of the catchment. Sediment delivery to the coast is not the only concern and the same principles can be applied if the target is to reduce sediment delivery to particular reservoirs, lakes or individual river reaches of high value.

5 PICTURE THUMBNAILS

SoilPic1: Gully Detail (AS)

SoilPic2: Sheet Erosion (PH)



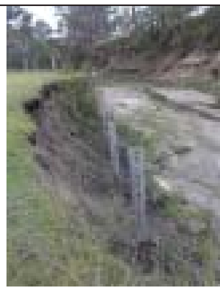
SoilPic3: Gully Landscape (IP)

SoilPic4: Alluvial Fans and Terrace (FM)

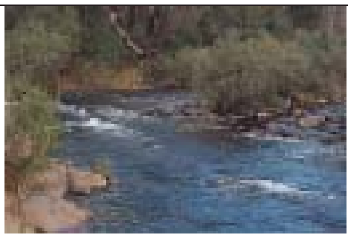
SoilPic5: Rill Erosion (BA)

SoilPic6: Sheetwash (IP)

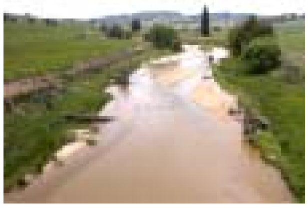
SoilPic7: Buffering (IP)



SoilPic8: Streambank Erosion (GC)



SoilPic9: Stream with no Deposition (FM)



SoilPic10: Deposition (IP)

Credits indicated in brackets as follows:
Willem van Aken (WA), Gary Caitcheon (GC), Peter Hairsine (PH), Frances Marston (FM), Ian Prosser (IP), Anthony Scott (AS).

6 REFERENCES

Abernethy, B. and Rutherfurd, I.D. (2000). The effect of riparian tree roots on riverbank stability. *Earth Surface Processes and Landforms* 25:921-37.

Brooks, A. (1999). Lessons for river managers from the fluvial tardis. In *Second Australian Stream Management Conference: The Challenge of Rehabilitating Australia's Streams*, Rutherfurd, I.D. and R. Bartley (Eds.), pp. 121-8. Cooperative Research Centre for Catchment Hydrology: Melbourne.

Brune, G.M. (1953). Trap efficiency of reservoirs. *Transactions, American Geophysical Union,* 34(3): 407-418.

Edwards, K. (1993). Soil erosion and conservation in Australia. In *World Soil Erosion and Conservation*. Pimental, D. (Ed.) pp 147-69. (Cambridge University Press: Cambridge.)

Erskine, W and Bell, F.C. (1982). Rainfall, floods and river channel changes in the upper Hunter. *Australin Geographical Studies* 20:183-195

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

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

Kalnejais, L. and Robb, M. (1999). Water quality in Wilson Inlet 1995-1997: a resport on the monitoring data collected between 1995 and 1997. *Report (Western Australia, Water and Rivers Commission)*, no. WRT14, 61p.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L., and Leslie, J.K. (1992). Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. *Australian Journal of Soil Research*, 30(5):757-774.

Loch, R. J., B. K. Slater, B. K. and Devoil, C. (1998). Soil erodibility (Km) values for some Australian soils. *Aust. J. Soil Res.*, 36, 1045-55.

McComb,A.J. and Davis, J.A. (1993). Eutrophic waters of southwestern Australia. *Fertilizer Research*, 36(2):105-114.

McCool, D.K., Foster, G.R., Mutchler, C.K., and Meyer, L.D. (1989). Revised slope length factor in the Universal Soil Loss Equation. *Transactions of the American Society of Agricultural Engineers*, 32(5):1571-1576.

Moore, I.D. and Burch, G.J. (1986). Physical basis for the length-slope factor in the universal soil loss equation. *Soil Science Society of America Journal* 50:1294-1298.

Prosser, I. P. and Winchester, S.J. (1996). History and processes of gully initiation and development in Australia. *Zeitschrift Fur Geomorphologie Suppl.-Bd* 105:91-109.

Prosser, I., Rutherfurd, I.D., Olley, J.M., Young, W.J., Wallbrink, P.J. and Moran, C.J. (2001). Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research* 52:81-99.

Renard, K.G., Foster, G.A., Weesies, D.K., McCool, D.K., and Yoder, D.C. (1997). Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation. Agriculture Handbook 703, United States Department of Agriculture, Washington DC.

Rosewell, C.J. (1993). SOILOSS - A program to assist in the selection of management practices to reduce erosion. Technical Handbook No. 11 (2nd edition), Soil Conservation Service of NSW, Sydney.

Rutherford, I. (2000). Some human impacts on Australian stream channel morphology. In *River Management: The Australasian Experience*, Brizga, S. and Finlayson, B. (Eds), John Wiley and Sons Ltd.

Sharman, P.E.V. and Murphy, B.W. (1991). Soils their properties and management: a soil conservation handbook for New South Wales. Sydney University Press in association with Oxford University Press, Australia and Soil Conservation Service of New South Wales.

Wasson, R.J., Mazari, R.K., Starr, B. and 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.

Wasson, R.J., Olive, L. J., and Rosewell, C. J. (1996). Rates of erosion and sediment transport in Australia. *Erosion and Sediment Yield: Global and Regional Perspectives*. IAHS Publ. No. 236: 139-148.

Whittow, J. (1986). Dictionary of physical geography. Penguin Books, Middlesex, England.

Wischmeier, W. H. and Smith, D. D. (1978). Predicting rainfall erosion losses: A guide to conservation planning. US Department of Agriculture. Agriculture Handbook No. 537. (US Government Printing Office: Washington, DC).

7 APPENDIX: RIVER BASIN ANALYSIS

This section presents summary statistics in the context of the AWRC basin definitions, ie with reference to standard basin names and numbers.

EACH TABLE ITEM (COLUMN) IS DESCRIBED AS FOLLOWS:

Basin Name: as defined by the AWRC.

Basin No.: as defined by the AWRC.

Area (km^2): the area in km^2 of each basin as derived from the DEM.

Sediment supply (t/ha/y) : This is the total sediment supplied to streams on an annual basis from the following sediment sources; hillslope erosion, bank erosion and gully erosion. The contribution from each source is summed in tonnes per year for each basin and then divided by the total area in hectares of each basin to give sediment supply in t/ha/y.

Proportion from hillslopes and bank erosion and percentage from gullies: This is calculated for each basin by dividing the sum of each component (t/y) by the total sediment supply value for each basin (t/y).

Proportion of length with bed deposition greater than 0.30 m. This is calculated by summing the stream length in each basin with deposition greater than 0.30 m then dividing by the total stream length in each basin.

Sediment Ratio (Euro/Pre-European). This is the average ratio of item 2 under *present land use conditions* to that of item 2 under *natural conditions* for each river basin.

Sediment export to the coast (t/y). This is the mean annual amount of sediment delivered by each basin to the coast in tonnes per year. It is has been summed for each basin.

Specific sediment export to the coast (t/ha/y). This is the above item divided by the area in hectares for each basin.

River sediment delivery ratio (export/supply to streams). This is item 6 for each basin divided by item 2 in t/y.

POINTS TO NOTE ABOUT THE ACCURACY OF THE MODEL OUTPUTS.

1. All but one of the MDB catchments do not export directly to the coast. The figures for individual MDB basins (no's 401 – 425) in items 6 , 7 and 8 are therefore the contribution of each basin to the MDB total export to the coast, which is made by basin number 426.
2. The model ouputs for the lowland MDB catchments have been derived from low quality data, which primarily results from the physical properties of the rivers and the somewhat arbitrary AWRC basin boundaries.

Summary statistics for river basin analyses

Basin Name	Basin No.	Area (km2)	Sediment supply (t/ha/y)	Proportion from hillslopes (%)	Proportion from bank erosion (%)	% from gullies	Prop. of length with bed deposn. > 0.30m	Sed Ratio (Euro/ pre-Euro)	Sediment export to the coast (t/y)	Specific sediment export to the coast (t/ha/y)	River sed. delivery ratio (export/supply to streams)
Jacky Jacky Creek	101	1,731	2.5	85	11	4	0.00	52	329,832	1.9	0.77
Olive / Pascoe Rivers	102	3,849	2.6	79	18	3	0.00	46	712,764	1.9	0.71
Lockhart River	103	2,008	0.4	22	77	0	0.00	23	37,137	0.2	0.49
Stewart River	104	2,346	1.4	70	24	7	0.05	10	160,798	0.7	0.51
Normanby River	105	24,440	1.6	88	3	9	0.02	3	1,620,279	0.7	0.42
Jeannie River	106	2,589	1.9	94	4	2	0.00	3	355,885	1.4	0.71
Endeavour River	107	1,951	3.1	97	2	1	0.00	5	486,871	2.5	0.80
Daintree River	108	1,548	0.7	82	17	1	0.00	4	94,132	0.6	0.84
Mossman River	109	318	0.6	78	21	2	0.00	5	15,131	0.5	0.80
Barron River	110	2,151	1.2	79	10	10	0.00	8	145,877	0.7	0.57
Mulgrave-Russell River	111	1,664	1.7	70	28	2	0.04	6	222,425	1.3	0.78
Johnstone River	112	2,240	1.7	65	29	6	0.00	29	305,142	1.4	0.78
Tully River	113	1,743	0.9	33	63	5	0.00	6	88,084	0.5	0.59
Murray River	114	716	0.5	27	65	8	0.00	6	17,098	0.2	0.53
Herbert River	116	9,605	1.4	75	12	14	0.08	8	664,787	0.7	0.51
Black River	117	705	1.7	92	4	4	0.01	3	82,887	1.2	0.69
Ross River	118	1,143	1.8	88	4	8	0.00	2	58,383	0.5	0.28
Haughton River	119	3,763	1.9	81	5	13	0.13	10	172,454	0.5	0.25
Burdekin River	120	129,454	1.4	67	6	27	0.11	15	2,443,232	0.2	0.13
Don River	121	3,018	3.1	86	3	11	0.04	11	509,528	1.7	0.55
Proserpine River	122	1,847	2.0	88	7	5	0.07	31	227,314	1.2	0.63
O'Connell River	124	1,980	2.4	89	8	4	0.06	45	366,309	1.9	0.77
Pioneer River	125	1,689	2.3	86	10	4	0.00	28	288,343	1.7	0.73
Plane Creek	126	1,534	1.1	78	13	9	0.00	46	114,860	0.7	0.67
Styx River	127	2,510	1.2	78	8	14	0.09	31	136,011	0.5	0.44
Shoalwater Creek	128	2,664	0.5	57	18	25	0.19	12	45,166	0.2	0.37
Water Park Creek	129	562	0.2	65	14	21	0.00	27	7,940	0.1	0.67
Fitzroy River	130	142,831	1.1	63	13	25	0.19	21	2,635,482	0.2	0.16
Calliope River	132	1,947	0.8	50	16	34	0.15	35	60,772	0.3	0.37
Boyne River	133	2,488	0.4	31	37	33	0.00	8	16,974	0.1	0.16
Baffle Creek	134	3,390	0.6	64	15	21	0.04	29	103,376	0.3	0.50
Kolan River	135	2,796	0.7	55	19	26	0.11	36	61,589	0.2	0.30
Burnett River	136	33,741	0.9	44	24	32	0.15	96	728,607	0.2	0.25

Summary statistics for river basin analyses

Basin Name	Basin No.	Area (km2)	Sediment supply (t/ha/y)	Proportion from hillslopes (%)	Proportion from bank erosion (%)	% from gullies	Prop. of length with bed deposn. > 0.30m	Sed Ratio (Euro/ pre-Euro)	Sediment export to the coast (t/y)	Specific sediment export to the coast (t/ha/y)	River sed. delivery ratio (export/supply to streams)
Burrum River	137	2,931	0.3	53	27	20	0.00	36	33,624	0.1	0.40
Mary River	138	9,398	0.7	39	44	17	0.11	18	266,713	0.3	0.40
Noosa River	140	1,227	0.2	10	52	38	0.04	15	7,288	0.1	0.39
Maroochy River	141	1,077	0.7	52	29	19	0.00	28	45,525	0.4	0.57
Pine River	142	1,258	0.5	45	34	21	0.00	40	20,687	0.2	0.35
Brisbane River	143	13,602	0.9	54	26	20	0.07	37	247,194	0.2	0.19
Logan-Albert River	145	4,045	1.2	58	25	18	0.19	35	189,138	0.5	0.40
South Coast	146	1,104	0.4	21	54	25	0.00	10	20,641	0.2	0.44
Tweed River	201	1,055	0.9	53	41	6	0.25	16	58,498	0.6	0.64
Brunswick River	202	133	0.2	49	35	16	0.00	5	2,158	0.2	0.68
Richmond River	203	6,760	0.8	42	41	17	0.13	32	240,825	0.4	0.43
Clarence River	204	22,084	0.8	25	44	32	0.07	198	683,379	0.3	0.40
Bellinger River	205	3,082	0.5	7	65	28	0.08	101	61,591	0.2	0.43
Macleay River	206	11,395	0.9	30	29	41	0.13	65	345,455	0.3	0.34
Hastings River	207	4,209	0.5	7	70	24	0.09	332	83,255	0.2	0.44
Manning River	208	7,939	0.7	15	47	39	0.03	56	224,159	0.3	0.42
Karuah River	209	3,665	0.5	16	40	44	0.15	161	72,363	0.2	0.41
Hunter River	210	21,138	1.4	33	20	46	0.33	630	743,606	0.4	0.25
Macquarie - Tuggerah Lakes	211	1,384	0.3	11	30	59	0.32	111	13,915	0.1	0.37
Hawkesbury River	212	21,636	0.5	21	28	50	0.08	211	233,011	0.1	0.21
Sydney Coast - Georges R.	213	1,511	0.2	7	53	40	0.09	323	11,226	0.1	0.30
Wollongong Coast	214	490	0.4	12	21	67	0.00	3	8,904	0.2	0.42
Shoalhaven River	215	7,172	0.6	14	26	60	0.10	27	135,530	0.2	0.33
Clyde River - Jervis Bay	216	2,666	0.3	5	28	68	0.18	20	34,173	0.1	0.39
Moruya River	217	1,505	0.4	14	19	66	0.10	44	24,362	0.2	0.40
Tuross River	218	1,902	0.4	7	22	72	0.13	41	23,959	0.1	0.34
Bega River	219	2,507	0.5	9	31	61	0.12	191	40,908	0.2	0.33
Towamba River	220	1,708	0.4	4	29	66	0.04	48	26,302	0.2	0.39
East Gippsland	221	5,103	0.1	6	47	47	0.01	36	25,818	0.1	0.40
Snowy River	222	15,360	0.5	21	26	53	0.04	16	303,309	0.2	0.37
Tambo River	223	4,249	0.1	9	59	32	0.02	19	18,114	0.0	0.30
Mitchell River	224	4,749	0.1	11	85	3	0.02	3	25,330	0.1	0.36
Thomson River	225	6,443	0.2	6	81	13	0.01	108	23,583	0.0	0.21

Summary statistics for river basin analyses

Basin Name	Basin No.	Area (km2)	Sediment supply (t/ha/y)	Proportion from hillslopes (%)	Proportion from bank erosion (%)	% from gullies	Prop. of length with bed deposn. > 0.30m	Sed Ratio (Euro/ pre-Euro)	Sediment export to the coast (t/y)	Specific sediment export to the coast (t/ha/y)	River sed. delivery ratio (export/supply to streams)
Latrobe River	226	5,102	0.2	6	92	2	0.08	5	31,953	0.1	0.26
South Gippsland	227	4,680	0.2	15	85	0	0.01	15	41,644	0.1	0.40
Bunyip River	228	2,714	0.2	6	83	11	0.00	>1,000	21,882	0.1	0.34
Yarra River	229	4,092	0.3	3	78	19	0.00	7	37,091	0.1	0.28
Maribyrnong River	230	1,432	0.5	8	57	35	0.00	10	26,644	0.2	0.36
Werribee River	231	1,847	0.3	23	46	31	0.01	9	8,885	0.0	0.17
Moorabool River	232	1,964	0.4	12	39	48	0.04	70	16,766	0.1	0.23
Barwon River	233	3,276	0.3	7	59	33	0.13	35	23,601	0.1	0.21
Lake Corangamite	234	2,038	0.3	8	40	52	0.12	53	0	0.0	0.00
Otway Coast	235	3,024	0.2	11	82	6	0.09	16	22,950	0.1	0.42
Hopkins River	236	8,902	0.5	3	44	53	0.22	198	64,382	0.1	0.14
Portland Coast	237	3,532	0.2	4	79	17	0.04	>1,000	19,143	0.1	0.30
Glenelg River	238	11,622	0.6	2	30	68	0.38	309	147,721	0.1	0.21
Millicent Coast	239	3,583	0.2	4	82	15	0.06	77	0	0.0	0.00
East Coast	302	4,351	0.2	24	35	40	0.01	5	44,400	0.1	0.51
Coal River	303	580	0.6	34	23	43	0.09	11	15,544	0.3	0.48
Derwent River	304	9,556	0.4	13	65	22	0.03	47	149,437	0.2	0.43
Kingston Coast	305	117	0.1	32	36	32	0.00	3	727	0.1	0.66
Huon River	306	2,964	0.4	7	82	11	0.00	16	57,413	0.2	0.51
South-West Coast	307	3,531	0.5	5	95	0	0.03	9	99,086	0.3	0.51
Gordon River	308	5,311	0.5	2	95	3	0.00	186	127,593	0.2	0.46
King-Henty Rivers	309	1,620	0.1	24	76	0	0.00	96	4,903	0.0	0.59
Pieman River	310	3,899	0.1	12	86	2	0.00	138	16,698	0.0	0.45
Sandy Cape Coast	311	180	0.3	1	99	0	0.00	102	2,712	0.2	0.49
Arthur River	312	2,475	0.2	4	94	2	0.00	36	19,726	0.1	0.51
Smithton-Burnie Coast	314	3,362	0.2	6	86	8	0.00	27	34,941	0.1	0.49
Forth River	315	1,110	0.2	12	49	38	0.00	1	6,339	0.1	0.37
Mersey River	316	1,898	0.6	6	56	38	0.00	6	51,007	0.3	0.48
Rubicon River	317	443	0.3	3	37	61	0.00	12	7,020	0.2	0.47
Tamar River	318	11,068	0.4	9	70	21	0.07	6	195,373	0.2	0.42
Piper-Ringarooma Rivers	319	3,029	0.3	5	49	47	0.00	7	39,746	0.1	0.46
Upper Murray River	401	16,177	0.4	23	45	32	0.03	8	2,783	0.0	0.00
Kiewa River	402	1,924	0.6	13	62	25	0.00	3	4,582	0.0	0.04

Summary statistics for river basin analyses

Basin Name	Basin No.	Area (km2)	Sediment supply (t/ha/y)	Proportion from hillslopes (%)	Proportion from bank erosion (%)	% from gullies	Prop. of length with bed deposn. > 0.30m	Sed Ratio (Euro/ pre-Euro)	Sediment export to the coast (t/y)	Specific sediment export to the coast (t/ha/y)	River sed. delivery ratio (export/supply to streams)
Ovens River	403	8,083	0.5	10	50	40	0.09	24	15,788	0.0	0.04
Broken River	404	4,795	0.5	6	45	49	0.22	17	6,635	0.0	0.03
Goulburn River	405	16,133	0.6	8	45	47	0.19	11	46,712	0.0	0.05
Campaspe River	406	3,980	1.1	3	18	80	0.52	23	10,690	0.0	0.02
Loddon River	407	11,937	0.7	3	25	72	0.47	44	4,459	0.0	0.01
Avoca River	408	5,956	0.8	4	16	80	0.55	40	0	0.0	0.00
Murray-Riverina	409	10,552	1.0	1	88	10	0.25	103	101,001	0.1	0.09
Murrumbidgee River	410	63,011	0.7	12	36	51	0.34	434	109,163	0.0	0.02
Lake George	411	275	0.9	27	7	66	0.94	29	0	0.0	0.00
Lachlan River	412	63,497	0.7	14	30	56	0.30	22	21,627	0.0	0.00
Benanee	413	3,146	1.4	1	99	0	0.27	9	95,127	0.3	0.21
Wimmera - Avon Rivers	415	9,839	0.7	4	24	72	0.47	63	0	0.0	0.00
Border Rivers	416	43,133	1.1	19	23	59	0.47	268	1,548	0.0	0.00
Moonie River	417	9,685	0.3	25	48	28	0.22	22	1	0.0	0.00
Gwydir River	418	21,812	1.4	21	24	55	0.34	45	1,415	0.0	0.00
Namoi River	419	38,373	1.3	28	25	47	0.32	74	1,671	0.0	0.00
Castlereagh River	420	14,430	0.7	17	43	40	0.33	220	178	0.0	0.00
Macquarie-Bogan Rivers	421	67,927	0.8	21	43	36	0.25	107	1,109	0.0	0.00
Condamine-Culgoa Rivers	422	102,723	0.5	28	34	38	0.28	34	231	0.0	0.00
Warrego River	423	44,649	0.4	43	37	20	0.17	16	91	0.0	0.00
Paroo River	424	39,906	0.3	47	40	13	0.09	13	0	0.0	0.00
Darling River	425	50,853	0.7	9	81	10	0.25	24	169,797	0.0	0.05
Lower Murray River	426	24,229	0.8	13	75	12	0.41	14	564,300	0.2	0.27
Fleurieu Peninsula	501	409	0.9	3	8	90	0.00	12	13,310	0.3	0.38
Myponga River	502	132	0.1	45	31	24	0.00	1	641	0.0	0.43
Onkaparinga River	503	679	0.2	16	50	35	0.00	4	3,820	0.1	0.31
Torrens River	504	890	0.2	15	68	18	0.00	2	3,223	0.0	0.24
Gawler River	505	4,300	0.3	12	43	45	0.18	11	25,422	0.1	0.22
Wakefield River	506	1,397	0.3	13	30	57	0.15	10	5,466	0.0	0.12
Broughton River	507	11,931	0.3	16	29	55	0.11	9	56,140	0.0	0.16
Mambray Coast	508	4,485	0.2	49	9	42	0.07	29	29,033	0.1	0.26
Willochra Creek	509	6,001	0.4	20	18	63	0.48	13	0	0.0	0.00
Lake Torrens	510	14,113	0.4	48	8	44	0.32	13	1,434	0.0	0.00

Summary statistics for river basin analyses

Basin Name	Basin No.	Area (km2)	Sediment supply (t/ha/y)	Proportion from hillslopes (%)	Proportion from bank erosion (%)	% from gullies	Prop. of length with bed deposn. > 0.30m	Sed Ratio (Euro/ pre-Euro)	Sediment export to the coast (t/y)	Specific sediment export to the coast (t/ha/y)	River sed. delivery ratio (export/supply to streams)
Spencer Gulf	511	8,069	0.1	47	27	26	0.01	37	21,507	0.0	0.20
Eyre Peninsula	512	1,720	0.1	12	70	18	0.03	3	3,373	0.0	0.30
Kangaroo Island	513	3,039	0.2	3	27	70	0.01	63	17,111	0.1	0.34
Esperance Coast	601	14,683	0.2	7	19	75	0.07	259	40,274	0.0	0.15
Albany Coast	602	16,765	0.3	6	20	75	0.22	76	80,131	0.0	0.19
Denmark River	603	2,582	0.4	1	17	82	0.09	36	31,091	0.1	0.32
Kent River	604	2,376	0.2	1	18	81	0.11	426	14,816	0.1	0.27
Frankland River	605	4,686	0.4	1	16	83	0.57	92	26,392	0.1	0.14
Shannon River	606	2,450	0.1	1	39	61	0.00	170	5,264	0.0	0.41
Warren River	607	4,404	0.2	1	32	67	0.08	80	27,922	0.1	0.25
Donnelly River	608	1,714	0.1	1	30	69	0.01	57	5,886	0.0	0.37
Blackwood River	609	22,970	0.3	3	27	70	0.37	247	97,576	0.0	0.12
Busselton Coast	610	2,315	0.3	3	35	62	0.05	817	24,238	0.1	0.34
Preston River	611	1,168	0.6	2	33	65	0.00	29	24,565	0.2	0.34
Collie River	612	3,698	0.3	3	39	58	0.11	>1,000	21,630	0.1	0.21
Harvey River	613	1,460	0.4	3	45	52	0.11	106	17,138	0.1	0.31
Murray River (WA)	614	9,583	0.5	2	23	75	0.55	598	84,754	0.1	0.18
Avon River	615	42,881	0.4	4	20	76	0.60	470	75,636	0.0	0.05
Swan Coast	616	7,239	0.5	2	24	74	0.32	418	89,746	0.1	0.24
Moore-Hill Rivers	617	11,535	0.5	3	16	82	0.54	32	50,819	0.0	0.10
Yarra Yarra Lakes	618	6,125	0.2	17	14	69	0.10	229	0	0.0	0.00
Ninghan	619	976	0.2	22	21	58	0.00	415	0	0.0	0.00
Greenough River	701	18,076	0.4	6	18	76	0.45	91	116,012	0.1	0.16
Murchison River	702	50,658	0.3	25	21	54	0.14	9	21,096	0.0	0.01
Minimum		**117**	**0.1**	**1**	**2**	**0**	**0.00**	**1**	**0**	**0.0**	**0.0**
Median		**3,531**	**0.5**	**14**	**30**	**32**	**0.07**	**29**	**30,062**	**0.1**	**0.3**
Maximum		**142,831**	**3.1**	**97**	**99**	**90**	**0.94**	**817**	**2,635,482**	**2.5**	**0.8**
Total		**1,667,300**							**21,139,700**		