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Identifying Priorities for Riparian Restoration Aimed at Sediment Control

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SUMMARY: Riparian vegetation can prevent stream bank erosion and it can trap sediments and nutrients derived from hillslopes, but these two functions are quite independent. Consequently, riparian restoration aimed at preventing bank erosion should have a fundamentally different design to that aimed at buffering streams from hillslopes. There is a need to understand where each process is significant in terms of easily identifiable features of catchments. This study summarises the results of sediment budgets from three diverse Australian environments. Hillslope erosion dominates sediment yield in far north Queensland, while gully erosion dominates in the Southern Tablelands of NSW. From these and other results, guidelines are suggested for defining where each process is a significant sediment source.

THE MAIN POINTS OF THIS PAPER

- Identifying whether sediment comes from channel or hillslope sources is important, for it leads to quite different catchment management.
- Factors that lead to significant hazard of hillslope sediment delivery are: intensive land use, high rainfall intensity, steep slopes, and poorly structured and erodible soils.
- Factors that lead to significant hazard of channel and gully erosion are: recent expansion of channel networks, dense networks of incised channels, bare channel banks, and erodible bank materials.

1. INTRODUCTION

Many landholders, community groups and government agencies are actively involved in improving riparian management, because they recognise the environmental benefits that can be achieved. Riparian management can serve several functions, as listed in Table 1. Restored or remnant riparian vegetation can trap sediment, nutrients and other contaminants running off farmland before they reach the stream. It can also reduce rates of bank erosion. The loss of riparian vegetation has been implicated as at least partly responsible for massive historical channel expansion (Brooks and Brierley, 1997) and declining water quality in historical times. Both channel erosion and accelerated hillslope erosion increase the supply of sediments to rivers.

An over-supply of muds or sand can smother the stream bed and fill deep pools, making streams uninhabitable for many native fish and invertebrates. An increase in the supply of silt and clay 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 which can be released into the water, fuelling nuisance and toxic levels of algae and other primary production. In their natural state, Australian coastal and highland streams had low amounts of primary production and low dependence of ecosystems on primary production. Consequently there is well-founded interest in the potential of riparian management to reduce the amount of sediment and nutrient being transported in our rivers, as well as concerns to achieve other riparian functions listed in Table 1.

Table 1. Potential Functions of Riparian Land

- Trap sediment, nutrients and other contaminants
- Reduce rates of bank erosion
- Reduce downstream flooding
- Provide shade to streams to reduce temperatures and primary productivity
- Provide a source of food and diverse habitat for stream animals
- Provide a location for conservation and movement of wildlife
- Provide recreation, and deliver an aesthetically pleasing landscape

Sediment and attached nutrient that is transported in streams can be derived from two types of processes. Surface wash processes on hillslopes and erosion of the stream channels themselves, including recently formed stream channels such as gullies. Distinction between hillslope and channel erosion is important for three reasons outlined below.

1. Sediment eroded from stream banks is delivered immediately to the stream and consequently impacts on in-stream ecosystems. In contrast, much sediment generated from hillslope erosion is deposited on footslopes, alluvial fans and terraces before reaching the stream.

2. Hillslope and channel erosion entail quite different management approaches. Stream bank and gully

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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. Hillslope erosion is best targeted by promoting consistent groundcover, maintaining soil structure, promoting nutrient uptake and using riparian buffer strips. In terms of riparian management, bank erosion is treated by focussing vegetation on the banks themselves, often using trees whereas buffer strips focus on the use of dense ground cover in the flatter streamside land before runoff reaches the banks.

3. Hillslope erosion can respond to short-term changes in land management, and trends are often reversible, whereas channel erosion reacts over longer time scales, and is mostly in response to the major clearing of vegetation upon introduction of modern land use. Channel erosion tends to go through a trend of rapid initial change and then gradual adjustment to a new equilibrium condition.

In many catchments one process dominates in terms of delivering sediments and nutrients to streams. Given the differences outlined above, it is important to identify the most significant process so that land management is targeted effectively. Two case studies that reveal extremes in process dominance are presented in this paper. A set of controlling factors on sediment sources is then proposed by combining the case studies with our knowledge of erosion processes.

2. CASE STUDY OF JOHNSTONE RIVER, FAR NORTH QUEENSLAND

The Johnstone River drains from the Atherton Tableland to a coastal lowland dominated by sugar cane and banana cropping. It enters the Great Barrier Reef Lagoon near Innisfail.

An extreme tropical storm in March 1996 enabled me to survey the sources and stores of sediment in detail for a 1 km^2 sub-catchment used as a banana plantation. The results (Figure 1) show that there was substantial loss of soil from slopes, equivalent to 20 t/ha, and a much smaller amount of sediment was derived from channels, mainly from gully erosion on recently formed plantation. Only 1-3 % of the soil that eroded from slopes was trapped in riparian zones and only 10-15 % of sediment was stored in the headwater channels. By far the bulk of sediment was washed downstream into the North Johnstone River.

Several conclusions can be drawn from this survey. First, extreme storms can cause substantial soil loss even on well managed land and with well structured krasnozem soils. This is a result of the extreme rainfall intensities of the tropics. Second, the hillslopes fall straight into streams (without footslopes or alluvial flats) so that riparian zones trap little sediment in their present condition. At present, crops continue close to the stream banks and there is little other vegetation. McKergow and Prosser (this volume) show that even in this extreme environment, managed riparian filter strips can trap significant amounts of sediment and nutrient.

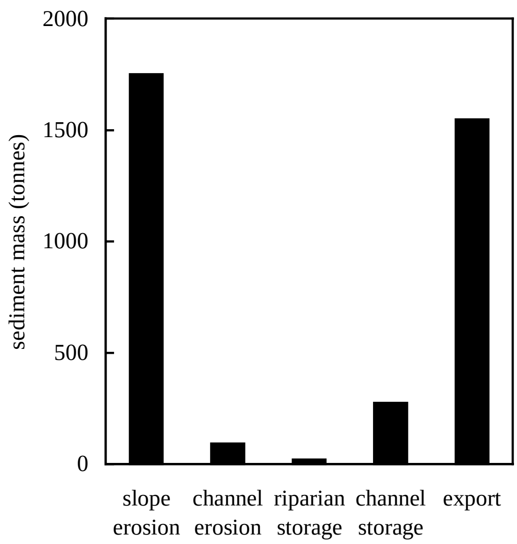

Figure 1 Sediment masses eroded and stored during intense rain of March 1996 in a 1 km^2 sub-catchment of the Johnstone River.

Examining the fate of sediment across the whole catchment, shows that cropland erosion produces far more sediment than erosion of the river banks (Figure 2). In fact, deposition along river banks outweighs bank erosion. The sediment in the banks is clay and silt derived from upstream soil erosion. This deposition resulted in the river narrowing by approximately 10 m between 1942 and 1983.

The long-term sediment budget for the catchment also shows deposition of eroded soil in tributary streams. Silt and clay have accumulated in the flat lower reaches of these creeks, promoting the invasion of weeds such as para grass. This has increased flooding and crop damage, and the fine-grained sediment has created an uninhabitable environment for aquatic organisms. The sediment has drowned what was previously a deep channel flowing on a cobble bed. Sediment is occasionally dug from these creeks but a longer term solution is to use trees to shade-out the para grass (Bunn et al., 1998) and riparian filter strips upstream to cut-off the source and prevent further sediment clogging the channels. Liberation of stored sediment from the tributaries does not pose a problem as it would be a small proportion of the total annual sediment load delivered to the sea.

Figures 1 and 2 show that the majority of sediment eroded from agricultural land is not stored within the catchment but is quickly delivered to the mouth of the river. Thus improved trapping of sediment in riparian buffers provides one of the few opportunities to stop eroded soil from leaving the catchment without clogging streams.

Figure 2 shows that channel erosion (mainly of banks) is small in terms of the amount of sediment it contributes to river loads. There are, nonetheless, isolated sites of serious bank erosion which pose a threat to cropland and roads. The worst effected sites are where the banks on the eroding outside bank are vertical and over 12 m high. Riparian vegetation alone is not a solution to this type of erosion because it is caused by undercutting of a weak layer at the base of the bank and tree roots would not penetrate far enough from the top of the bank to stabilise this layer. Engineering methods, and subsequent riparian revegetation, are more appropriate in such cases.

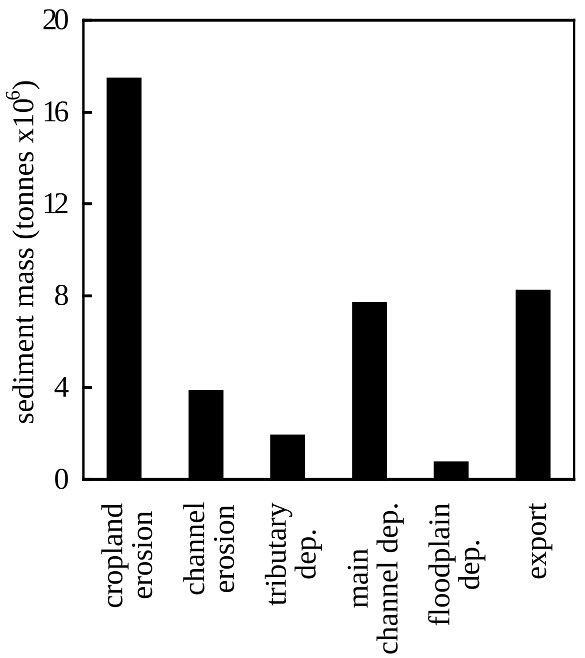

Figure 2 Sediment sources, stores and export for the Johnstone River catchment between 1942 and 1983. The masses come from field surveys of sediment volumes and erosion, aerial photograph interpretation and previous studies.

Most of the lower reaches of the river are denuded of riparian forest but there is dense grass growth and the banks are stable. Riparian restoration is valuable for improving the ecology and aesthetics of these reaches, but it cannot be justified on the grounds of preventing bank erosion.

In summary, sediment loads in the Johnstone River are dominated by sediment derived from erosion of intensive agricultural land. The high rate of sediment supply has drowned aquatic habitat in tributary streams. Bank erosion is outweighed by deposition of sediment along the banks. High rainfall intensity, intensive land use with periodical bare soil, and relatively steep gradients conspire to give high sediment delivery from agricultural hillslopes to streams. The only mitigating factors are good soil structure and recent practices of reduced tillage and retention of cane trash. Stream bank erosion is relatively minor because under a wet tropical climate the channel network was fully developed before clearing with little possibility for subsequent extension. Furthermore, the bank materials are structurally stable and under a wet tropical climate, dense secondary vegetation growth covers disturbed stream banks within a few weeks.

3. CASE STUDY OF THE SOUTHERN TABLELANDS, NSW

The Southern Tablelands of NSW contain the forests and low input grazing lands surrounding Canberra. This is a region that experienced dramatic gully erosion immediately following the introduction of pastoral land use in the 19th Century.

The density of gullies is up to 4.5 km/km^2. Prior to European settlement the major valleys were largely unchannelled, containing swampy meadows that efficiently trapped sediment eroded from hillslopes and narrower upstream valleys. This sediment accumulated as valley fills of 2–8 m depth (Prosser, 1991). Once the valley fills were destabilised, by removing the protective vegetation cover, gullies developed and the stored alluvial sediment was delivered efficiently downstream.

Sediment yields from gullies in tablelands of Eastern Australia are presented in Table 2. Most of the data are derived from the volume of channel excavated, rather than actual measurement of yield. In many cases the precise timing of channel expansion is not known and the period of formation is based on the earliest possible date for initiation and the latest possible date for achievement of the observed volume. Gullies are self-stabilising, reaching a new equilibrium by exponential decay (Graf, 1977). Thus sediment yields in the early stages of erosion are likely to be far greater than values presented in Table 2 for gullies of several decades age. This partly explains why the highest sediment yields are recorded at Bombala, where gully erosion only started in 1988. It is also evidenced by a declining gully erosion rate over time at Gilgandra, where actual rates were measured.

Table 3 lists rates of hillslope erosion over SE Australia, showing an overlapping range with sediment yields from gullies, but in general rates are one to two orders of magnitude below those for gully erosion. Low intensity grazing is the dominant land use of the Southern Tablelands, for which sediment yields are similar to native forests and considerably lower than for active gully erosion. Much of the data in Table 3 are from erosion plots which record local sediment movement. They provide a maximum estimate of sediment delivery to streams because much sediment that is transported locally on a hillslope is redeposited before reaching the stream. For example, plot studies in the Johnstone R. catchment (Prove et al., 1995) record plot yields four times higher than the average hillslope loss recorded by each of ^{137}Cs, riparian plots, and estimates in the sediment budget of Figure 2.

Table 2. Sediment yields from gullies in Australia; abbreviated from Prosser and Winchester (1996).

Location	Period	Sediment yield (t/km^2/y)
Bombala	1988-1993	2900
Bathurst	1983-1986	705
Wellington	1982-1984	221
Canberra	1966-1987	11-555
Jerrabomberra Ck.	1960-1987	118
Fernances Ck.	1867-1983	116
Bango Ck. Yass	1915-1961	90
Wangrah Ck	1842-1944	72
Gilgandra	1949-1961	47
Gilgandra	1972-1984	19
Gilgandra	1978-1983	9.4

Wasson et al. (1998) constructed a sediment budget for Jerrabomberra Ck, on the Southern Tablelands, quantifying the relative contributions of channel versus hillslope erosion. They concluded that hillslope erosion contributed only 10% of sediment supplied to streams. Similarly, Olley et al. (1993) used radionuclide tracing techniques to conclude that 90 % of sediment yielded from a 5 km^2 catchment near Goulburn was derived from gully erosion.

Gully erosion reworks, in a few decades, much of the sediment that has accumulated from up to several thousand years of hillslope erosion. Hence, it is not surprising that gullies and incised streams can dominate sediment yields. The Southern Tablelands deliver little sediment from hillslopes because of relatively good cover afforded by permanent pasture, relatively low rainfall intensities and well developed colluvial footslopes, alluvial fans and valleys flats that trap sediment before it reaches the stream. However, the massive volumes of sand and finer sediment delivered to rivers from gullies and incised streams have produced profound changes to channel morphology and habitat (Erskine, 1994; Brierley and Fryirs, 1998).

4. CASE STUDY OF KALGAN RIVER, WA

Most landscapes probably fall somewhere between the two extremes of the case studies presented above. In the cereal cropping belt there is intensive hillslope land use, but with lower rainfall intensities than the wet tropics. There is also significant gully erosion but the gullies are smaller and less extensive than in the Southern Tablelands of NSW.

Table 3. Hillslope sediment yields in SE Australia; abbreviated from Prosser and Winchester (1996).

Vegetation cover	Sediment yield (t/km^2/y)
Open forest	0.4 - 130
Forest	0.8 - 154
Woodland	1.5
Undisturbed pasture	3 ± 5
Native pasture	9.8
Grazed pasture	16 ± 23
Cultivated pasture	25 ± 34
Improved pasture	34
Over-grazed pasture	75.7
Crops	57.9

The Kalgan River catchment, near Albany SW Western Australia, is an example of a catchment where both hillslope and channel processes are significant. The catchment is in an ancient landscape of low relief and sandy soils where natural rates of sediment yield are expected to be very low. Land use is a mixture of cereal cropping and sheep and cattle grazing. A survey of farm dam sediment storage recorded hillslope soil losses of 0.2-3 t/ha/y (Throne, 1997). While these rates are very low they are probably considerably higher than natural rates. Gullies have dissected swampy valleys in the area, but in contrast to Eastern Australia the depth of valley fill is less than 2 m and the low relief has meant that the density of gullies is <1 km/km^2. Sedimentation in a farm dam at the downstream end of one of the gullies suggests that sediment yield from gullies is of the order of 2-3 t/ha/y, a figure consistent with the estimated age and volume of the gully.

These preliminary data show that both hillslope and channel erosion sources are significant in the Kalgan River. The results also highlight that sediment yields should be put in the context of natural yields. The yields for the Kalgan River are very low compared with other parts of Australia but there is evidence that accelerated delivery of sand through the river network has drowned freshwater and estuarine habitats.

5. GUIDELINES FOR IDENTIFYING SEDIMENT SOURCES

To research sediment sources for every catchment where sediment supply is of concern is an enormous and unnecessary task. Fortunately, with knowledge of the erosion processes, we can propose a framework to guide the identification of sediment sources across a diverse range of environments.

The controls on hillslope erosion are well understood from decades of soil erosion research. These controls are perhaps best encapsulated in the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The most significant factors are surface cover and land use practise. Significant surface wash 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 slope erosion are illustrated by the data in Table 3.

Hillslope erosion is accentuated by high rainfall intensity (measured over 30 min. duration), particularly if it occurs when the soil is bare. Thus there is a tendency in Australia for hillslope erosion to increase as one moves north, where rainfall intensities are higher. 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.

In terms of sediment delivery potential to streams, we also need to consider the potential for the eroded sediment to actually reach the stream. 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. Table 4 summarises the factors that lead to significant hazard for surface wash erosion.

Quite different considerations need to be made for gully and channel erosion because of the tendency of erosion to heal over time. Gully and channel erosion are likely to be significant wherever channels have expanded in historical times. The greater the density and size of expanding unstable channel, the greater the hazard of sediment delivery. Areas of highest hazard are where channels are only just starting to expand now, which applies to areas of recent land use intensification. For areas cleared in the 19th Century, the bulk of the sediment is already working its way through the river and is no longer being generated from the source. 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. Thus sub-surface soil erodibility and current vegetation cover are good indicators of channel erosion hazard. The form of gullies and incised streams is a poor indicator of erosion hazard as many gullies with vertical walls and deep headcuts have eroded little over the last 40 y as the toes of the bank are stable and the banks have high tensile strength. Factors contributing to significant gully erosion are summarised in Table 5.

6. CONCLUSIONS

It is unlikely that riparian rehabilitation needs to address all functions listed in Table 1 in each catchment. Because of the different designs needed to achieve each function it is necessary to identify the most significant functions as part of the planning process. In terms of sediment sources the significant functions are buffering against hillslope sediment delivery and preventing channel erosion.

The factors in Table 4 suggest the focus of riparian buffer strips should be on the cropping belt, and northern semi-arid rangelands. They suggest that southern Australian pasture and forested areas are at relatively low risk of hillslope erosion. Attention should also be given to source streams before major river channels

In terms of ameliorating channel and gully erosion, Table 5 suggests priorities in upland grazing areas, coastal streams of SE Australia and areas or current agricultural expansion.

7. ACKNOLWEDGEMENTS

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Table 4. Guidelines for identifying significant hillslope sediment delivery. A high hazard in two or more factors is likely to lead to a significant sediment source (modified from LWRRDC in press).

Factor	Examples of Hazard		
	Low	Medium	High
Amount of bare soil	Complete year around ground cover	Degraded pasture or minimum tillage	Annual traditional tillage
Rainfall erosivity	Mediterranean climate of southern Australia	Sub-tropical or semi-arid	Wet and wet-dry tropics
Hillslope morphology	Slopes <5% over all near stream areas	<10% gradient hillslopes with no alluvial flats	>10% gradient hillslopes with no alluvial flat
Erodibility of soils used for crops	Large water stable aggregates	Sandy or weakly aggregated soils	Dispersive, slaking or silty soils

Table 5. Guidelines for identifying channel and gully erosion hazard. A high hazard in two or more factors is likely to lead to a significant sediment source (modified from LWRRDC, in press).

Factor	Examples of Hazard		
	Low	Medium	High
Extent of historical channel incision	No response of channels in historical times	Frequent small changes to channel dimensions	Massive channel enlargement and gully erosion
When did channel erosion first commence?	19^{th} C	Last 20-50 y	Within last 20 y
Vegetation cover on channel and gully banks	Complete cover	Patchy cover	Bare, degraded banks
Sub-soil erodibility	Well aggregated and well-drained soils	Poorly structured or sandy soils	Dispersive sub-soils