CHAPTER 6

The influence of riparian management on stream erosion

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Summary

Many of the conclusions in this chapter can be summarised in an acronym that can be remembered by the phrase "Please Think" — PLS–T.

1. **P**ROCESS — Managers will be most effective in targeting riparian revegetation if they first understand the erosion mechanisms (the processes) that are acting in a particular stream or river reach.
2. **L**EVERAGE — Once we understand the erosion mechanism, then we can understand the influence (the leverage) that specific revegetation or other riparian management will have on that mechanism.
3. **S**CALE — Size is everything! Where you are in a catchment and the size (scale) of the channel influences both the erosion processes that operate, and the leverage that riparian vegetation and management have over those mechanisms.
4. **T**IME — the interaction between the vegetation and the erosion mechanisms will change with time as the vegetation grows, and as the vegetation alters other aspects of the system.

Introduction

This chapter discusses how riparian management influences the different types and processes of stream erosion. Maintaining or replanting native riparian vegetation is a core part of most stream restoration projects, so much of the discussion focuses on the influence of that vegetation on erosion. This includes vegetation growing on the bank face, along its top, and in the channel. We consider the likely effects of past vegetation clearance, and of revegetation either by natural regeneration or deliberate replanting. This chapter includes data and results from a review of the relevant literature, and also reports many of our own research results as there have been few other detailed studies of this topic in Australia.

All streams erode. Stream erosion is a natural and essential process of rivers that has been accelerated by human impacts, often to unacceptable levels. Streambank erosion is a dominant source of sediment in many river systems (e.g. 37% in the River Ouse, UK (Walling et al. 1999); 50% in the Midwestern streams, USA (Wilkin & Hebel 1982); 78% in the Gowrie Creek, Murray Darling Basin, Australia (Howard et al. 1998), 80% in the loess area of Midwest United States (Simon et al. 1996); and up to 92 % (including channel scour) in Gelbaek stream, Denmark (Kronvang et al. 1997)). Sediment loads in Australian streams have generally increased by 10 to

The tree roots show how much soil has been lost by erosion.
Photo John Dowe.

15 times in comparison with pre-European loads in intensively used river basins (National Land and Water Resources Audit 2002). Riparian and in-channel vegetation can reduce rates of stream erosion, but it is unrealistic to expect revegetation to eliminate all erosion.

Riparian revegetation is the most common stream management action in Australia. One of the major reasons why managers revegetate streams is to reduce stream erosion rates, and so reduce sediment (and nutrient) loads in streams. It is true that planting trees and shrubs along streams will probably reduce erosion rates, but it is no longer good enough to do this in an untargeted way and hope for the best. Australian stream managers are now embarking on multi-million dollar programs to revegetate riparian zones across whole catchments. Further, riparian revegetation is now being targeted at specific management goals such as catchment scale targets for turbidity and nutrients. For both reasons, it is now essential to be able to predict what effects riparian vegetation and revegetation have on stream erosion in particular situations. The key message from a decade of research into riparian vegetation and erosion (in fact, from all riparian research), is that all riparian vegetation is not equal in its effects. The main aim of this chapter is to summarise the relative effects of riparian vegetation on erosion mechanisms so that managers can:

1. plant vegetation where it will have the most effect on a specific process or catchment target,
2. plant the right sort of vegetation in the right amounts (e.g. densities) to have an effect at catchment scale.

The other aim is to alert managers to what to expect when they do revegetate riparian zones, including the potential for unintended consequences.

We summarise the state of knowledge by considering the following questions:

Question 1. What are the types and magnitudes of erosion in meandering streams?

Question 2. What is the effect of riparian vegetation on specific erosion mechanisms:
- a. mass failure,
- b. fluvial scour of cohesive sediments,
- c. fluvial scour of grassed surfaces?

Question 3. Given all of these processes, what is the gross effect of vegetation on stream morphology?

Question 4. What erosion response, over time, can managers expect when they do revegetate the riparian zone of small streams?

Question 5. At the scale of whole catchments, where should managers concentrate their riparian revegetation to have the most effect on end-of-valley sediment and nutrient targets?

In-channel wood can provide valuable protection to an eroding bank toe and provide an opportunity for natural or planted revegetation. Photo Gary Caitcheon.

Channel type 1. A typical small upland stream. Photo Roger Charlton.

Channel type 2. A small but active gully. Photo Roger Charlton.
Channel type 3, below: Typical of many incised streams in rural landscapes. Photo Biz and Lindsay Nicolson.

Question 1: What are the types and magnitudes of erosion in meandering streams?

Stream types

This review is not designed to provide a classification of stream types in Australia. However, there is little point in considering the effect of riparian revegetation unless a manager appreciates the type of stream that they are managing. Here are six basic types of rural streams that will probably be the target for riparian revegetation. This classification is, of course, a continuum. Small upland tributaries are often gullied, and incised streams grade into larger meandering reaches.

1. Small upland tributaries (1st to 3rd order streams)

These are the small (mainly 1st and 2nd order), cleared, rural streams that dominate the Australian rural landscape. These are the type of streams that will be most affected by riparian revegetation, and by removing grazing.

2. Gullies

Gullies are strictly a product of stream network extension. They may be small enough to be heavily influenced by riparian vegetation, particularly in stabilising the channel floor.

3. Incised streams

Unlike gullies, these "valley-floor incised streams", developed by the incision of existing stream channels. They are typically tens of metres wide, and several metres deep. These streams pass through predictable stages of evolution, as they incise, then stabilise over decades. The main influence of vegetation on these streams is to stabilise the channel floor in later stages of their evolution.

4. Larger, gravel bed, meandering streams

Occupying the larger valleys, these streams have often experienced bank erosion and widening. The streams may be too big for bank vegetation to have much influence on erosion rates.

5. Larger, meandering lowland, silt-clay streams with anabranches

Moving downstream, meandering gravel streams give way to these larger, sinuous channels, that are dominated by silt-clay banks. Bed material tends to be fine gravel or sand. Vegetation will interact in a completely different way with the resistant, cohesive bed and banks that are very different to the gravel bed of the upvalley streams.

6. Small lowland tributaries

Many people mistakenly believe that small streams must be upland streams. In fact, many small streams are found either: as anabranches on lowland floodplains, or in the headwaters of lowland tributaries. Unlike the stereotypical low-order, upland stream, small-lowland streams tend to have cohesive bed and banks, and a sandy bedload.

Stream lengths

Although we cannot estimate the length of each of these types of streams, it is useful to appreciate the length of streams that managers are dealing with. In Victoria, for example, there are over 300,000 kilometres of streams defined on the 1:25,000 map-sheets. This number does not include the massive length of anabranching streams on lowland floodplains. Of this 300,000 kilometres of streams, only 41,000 kilometres (or under 14%) have catchment areas over 110 km^2.

Erosion mechanisms

In order to understand the role of vegetation in bank erosion we must understand the erosion processes themselves. Streambank erosion is a complex phenomenon in which many factors (notably flow, sediment transport, and bank properties) play a role. Bank properties include:

- bank material (its weight, texture and strength),
- bank geometry (height and angle),
- bank hydrology (ground water level and bank permeability),
- stratigraphy (pattern of layers of sand, gravel, clay) of the bank materials, and
- type of vegetation.

Interactions between the bank and the flow can be grouped into the following three broad categories of bank erosion processes:

1. subaerial erosion of bank material,
2. direct scour of bank sediment, and
3. mass failure mechanisms.

All of these erosion processes tend to act in concert along the entire length of rivers, but their relative importance at any one point down the catchment varies. The key to managing erosion with vegetation is to recognise the erosion processes and treat them with the correct suite of tools, of which vegetation is often the most important.

Channel type 4. Photo Andrew Brooks.

Channel type 5. above. Photo Guy Roth.
Channel type 6, below: An example of a small lowland stream. Photo Ian Rutherfurd.

1. Subaerial erosion

Streambanks that are exposed to air are subject to erosion from a variety of processes which are largely external to river flow. Such processes are collectively termed subaerial erosion (summarised in Table 6.1). Some of these processes directly cause erosion, while others render bank material more susceptible to later erosion by wind or by water scour.

Subaerial processes are active on exposed banks in all parts of the catchment but they are usually much less important than the processes of scour and mass failure described below. Usually, they are only apparent when these other erosion processes are limited, or where the climate is extremely cold or wet. Thus, subaerial processes tend to be most important in small upper catchments, and in the dispersive soils of gullies. Also, subaerial processes can *prepare* the banks of streams for erosion by scour. This is particularly true of desiccation. One way to see if subaerial processes are important in your stream is to look at erosion processes on banks that are isolated from the main flow, such as cutoff meander bends or old channels.

2. Scour

Scour occurs when the force applied to a bank by flowing water exceeds the resistance of the bank surface to withstand those forces. The potential for scour is traditionally described by boundary shear stress, which is a measure of the drag exerted on a unit area of the channel perimeter, which is a function of flow depth and slope. Scour is most pronounced at the outside of meander bends.

Vegetation profoundly influences scour rates because it affects both force and resistance. It affects force by creating backwaters that slow flow against the bank face and weaken secondary circulation in bends (Thorne & Furbish 1995). Since boundary shear stress is proportional to the square of near-bank velocity (Ikeda 1981), a reduction in flow velocity produces a much greater reduction in erosion. For example, recent measurements in the Thurra River in East Gippsland suggest that flow velocities against a vegetated bank were half those on a bare bank at bankfull flow (Andrew Brookes pers. comm.). This difference produces a four times decrease in shear-stress.

Table 6.1. Summary of subaerial preparation processes. Photo: Subaerial erosion by desiccation and rilling along a tropical stream.

Process	Mechanism	Effects of vegetation
Windthrow	Shallow-rooted, stream-side trees are blown over, delivering bank sediment into the channel	More common in large overstorey trees, and in brittle trees like willows
Frost heave	In cold climates, bank moisture temperatures fluctuate around freezing, promoting the growth of ice crystals which expand and dislodge bank material	Vegetation insulates bank material, reducing ice formation
Rilling	Overbank runoff erodes bank sediments	Vegetation limits overbank runoff by promoting infiltration and slowing velocity
Rainsplash	Rainsplash dislodges sediment and directs it down the bank into the flow	Vegetation intercepts raindrops
Desiccation	Drying promotes cracking and ped dislocation	Vegetation reduces fluctuations in bank moisture
Slaking	Soil aggregates disintegrate when air trapped in them escapes when banks are rapidly submerged	Vegetation maintains a more porous bank material structure, and bonds aggregates together
Trampling	Unrestricted stock access loosens bank soil and transfers sediment into the flow	Vegetation cannot resist stock trampling

Photo Ian Dixon.

The rigidity of vegetation also influences scour. At low discharges, the high flow resistance associated with grasses and smaller shrubs standing rigid and unsubmerged often reduces the velocity below that required for bank material entrainment. At higher discharges, submerged grasses and shrubs often bend downstream, forming a flattened layer which, although having low flow resistance, protects the bank from scour by reducing physical contact (see Kouwen 1988 for further details).

Trees are not as effective as grasses and shrubs at retarding near-bank velocities when the flow is slow; as velocity increases, the much stiffer trunks of trees continue to retard the flow close to the bank. However, the local acceleration of flow around the trees may itself generate scour. This scour can often be seen around large river red gums on floodplains. The density of the tree stand is important. To be effective in reducing flow attack on the bank, trees must be close enough together to ensure that the wake zone of one tree extends downstream to the next tree. This prevents re-attachment of the flow boundary to the bank in between trees (Thorne 1990). Similarly, isolated clumps of trees on banks can act as hardpoints that could be outflanked by the flow.

Another form of bank scour is that due to wave action. Reed-beds are particularly useful where wave action from boat traffic is responsible for bank attack because they act as a buffer in absorbing wave energy. A reed-bank 2 metres wide can absorb about two thirds of the wave energy generated by wash from pleasure craft (Bonham 1980). Additionally, emergent aquatic macrophytes restrict the near-bank flow velocity and provide some reinforcement to the bank surface through their shallow root mat. Frankenberg et al. (1996) credited reduced erosion rates at some sites on the Murray River, near Albury-Wodonga, to the presence of *Phragmites* spp.

Resistance to scour

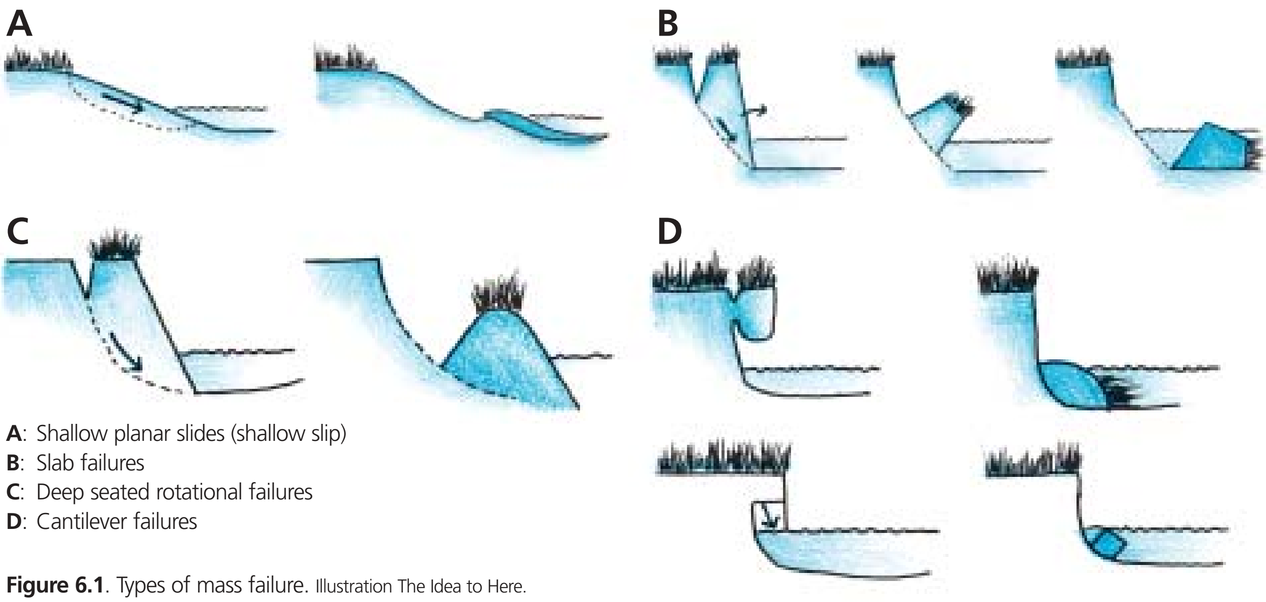
Vegetation on the bank face also reduces the effects of scour by directly strengthening the banks. A dense root mat, such as produced by willows, and several native species (such as river oaks, *Casuarina* and *Melaleuca* spp. and weeping myrtle, *Waterhousia*) directly protects the bank face from scour. Even if the bank is directly exposed to scour, the fine roots, in particular, hold bank material together. It is not uncommon to see eroded banks covered in fine roots where the peds of sediment have had to be dragged off the root networks for erosion to continue.

3. Mass failure

Bank erosion can occur by whole blocks of material sliding or toppling into the water. Mass failure of river banks typically occurs in floodplain reaches, where banks usually consist of cohesive material resistant to scour. Cohesive banks are eroded primarily by mass failure under gravity. The shape and extent of mass failure is a function of the geometry of the bank section, the physical properties of the bank material, and the type and density of vegetation.

A number of factors increase the resistance to sliding including matric suction — negative pore pressures (Fredlund et al. 1978), hydrostatic pressure from stream water acting on the bank face (Simon et al. 1991), riparian vegetative buttresses (Thorne 1990c) and surcharge due to trees on the lower bank face (Coppin & Richards 1990), root-reinforcement (Vidal 1969), and the slope-normal component of bank material weight. Several factors decrease the shear resistance of materials e.g. positive pore-water pressure (Darby et al. 2000, Simon et al. 2000), development of vertical tension cracks (Darby & Thorne 1994, 1997, Thorne et al. 1981), seepage force (Budhu & Gobin 1995), bank hydrology modifying — preferential flow of infiltrated water along the root system (Collison & Anderson 1996, Simon & Collison 2002, Thorne 1990c).

Fluvial scour at the high water toe of a bank. Photo Guy Roth.



A: Shallow planar slides (shallow slip)
B: Slab failures
C: Deep seated rotational failures
D: Cantilever failures

Figure 6.1. Types of mass failure. Illustration The Idea to Here.

Types of mass failure

The way in which bank failure occurs depends on the geometry of the bank. The four broad failure types are (Figure 6.1):

~ shallow planar slides (shallow slip),
~ slab failures,
~ deep-seated rotational failures, and
~ cantilever failures.

Shallow slip. Failure by shallow slip has a less immediate impact on river banks than the other failure types, but the high frequency of shallow slips makes them important. Failure takes place along an almost planar surface parallel to the bank surface. Very often the failure occurs when the bank substrate is saturated following heavy rains or high channel flows. These failures are common when an organic rich layer is draped over a stiffer clay on the bank face. The failure plane is at the contact of the two layers.

Slab failure. Low, steep banks (generally steeper than 60°) are prone to slab failure when a block of soil topples forward into the channel. In many cases the upper half of a potential failure block is separated from the rest of the bank by a near-vertical tension crack — the result of tensile stress in the bank. Sometimes this crack is apparent before the failure, running parallel to the bank face behind the failing mass. More usually, however, the bank fails as soon as the tension crack is opened: there is no outward sign of tension cracking before the failure occurs. Tension cracks are important because they weaken the banks directly; in addition, the passage of water through the cracks leads to softening, leaching and possible piping, all of which act to reduce the effective cohesion at the failure plane.

Rotational slip. High, less steep banks (less than 60°) fail by rotational slip along a curved surface, which usually passes just above the toe of the bank (Thorne 1990). The failure block is back-tilted away from the channel. Rotational slips may be a base, toe or slope failure depending on where the failure arc intersects the bank face. Large bank failures (more than 1 metre or so wide) usually have a curved failure plane (Terzaghi & Peck 1948) and often have tension cracks.

Cantilever failure. Figure 6.1 also shows the principal mechanisms of cantilever failure. These failures occur when undercutting leaves a block of unsupported material on the bank top, which then slides or falls into the stream. (For a more detailed discussion of cantilever failures see Thorne and Tovey (1981).)

Riparian vegetation tends to discourage mass failure processes. For example, Abernethy and Rutherfurd (1998) found that in the lower reach of Latrobe River, Victoria, Australia, riparian trees increased the bank sub-strata strength against mass failure by maintaining higher and steeper bank geometries. The elastic plant roots of very high tensile strength in close growing vegetation reinforce soils; which then behave as a composite block, prevent tension crack in banks, and impart additional bank strength and apparent cohesion (Abernethy & Rutherfurd 1998, 2000b, 2001, Kirkby & Morgan 1980, Thorne 1990c, Waldron & Dakessian 1981) via friction between the root surface and soil particles (Gray & Sotir 1996). In this context, Thorne et al. (1998) describes that roots of riparian vegetation frequently increase significantly the strength of cantilever blocks. Deep-rooted trees buttress the bank materials, and thereby retain soil material above the plant system (Abernethy &

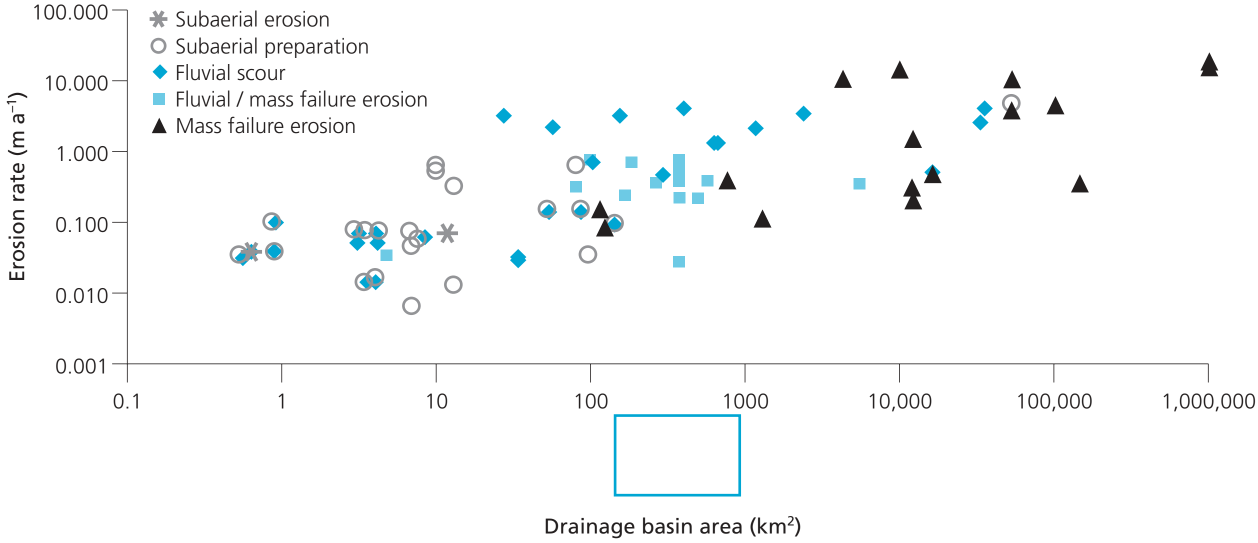


Figure 6.2. Relationship between different erosion processes and catchment area (based on a review of global data by James Grove). The blue rectangle shows the erosion domain for the Kiewa River described below.

Rutherfurd 1998) and reduce mass failure. Soil arching and surcharge (Coppin & Richards 1990, Styczen & Morgan 1995) are some other influences that vegetation exerts that reduce mass failures. Vegetation also contributes to better drainage of banks, lowers the bulk weight of soil mass and increases soil cohesion (Rutherfurd et al. 2002). Anything that dries the bank out will reduce the chances of mass failure.

Distribution of erosion types

So far we have described the effects of riparian vegetation upon erosion processes. However, both the vegetation and the erosion processes vary dramatically from the top of a stream catchment to the bottom, as the channel gets larger and changes form as the flow changes, and as the vegetation communities change. A review of literature indicates that all erosion processes operate in most streams, but there is a definite relationship between the types of erosion and the size of streams (Figure 6.2). Subaerial erosion seems to be more important in streams with catchment areas below 100 km^2. Similarly, fluvial scour dominates in catchments of 10–1000 km^2. Mass failure becomes the dominant process in streams with catchment areas over 1000 km^2.

Rates of erosion

Although we can classify major erosion types, there is scant information about the rates of the different erosion mechanism in Australian streams. As part of Land & Water Australia's Riparian Lands R&D Program, we began the first long-term monitoring program of erosion in an Australian stream. This work was done by Dr James Grove, partially funded by a Fellowship from the United Kingdom Royal Society. James monitored erosion on five outer banks of the Kiewa River, north-east Victoria, from 2002 until 2004. The Kiewa is an upland tributary of the Murray River, and is characteristic of a gravel bed, meandering channel (channel type 4 described earlier) (Figure 6.3, overleaf).

Each of the five sites had about 40 erosion pins (bicycle spokes) inserted into the banks. The length of the pin was measured approximately monthly from May 2002 until December 2004.

Erosion rates on the Kiewa River are about one tenth of the global averages for a stream with its catchment area (Figure 6.2), ranging from 50 to 200 millimetres of bank retreat per year (Figure 6.4, overleaf). There is also a strong positive relationship between the size of the stream and erosion rates (Figure 6.4). Mass failure was the dominant erosion mechanism in the catchment as a whole, accounting for two thirds of all erosion in the period:

~ Mass failure = 63% (*0.051 t/m²/a*)
~ Fluvial entrainment = 27% (*0.022 t/m²/a*)
~ Subaerial erosion = 10% (*0.008 t/m²/a*)

Other findings were:

~ Bank erosion along the Kiewa progresses by small slab failures rather than large rotational failures.
~ Processes occurring between flow events are the major control on bank erosion on low banks (in this case, desiccation of bank soil making it available for later removal when flow increased).
~ Shading by riparian vegetation is probably the major control on desiccation.

One of the most interesting aspects of the Kiewa project was how deceptive a visual assessment of erosion can be. We would visit the Kiewa sites and conclude from visual

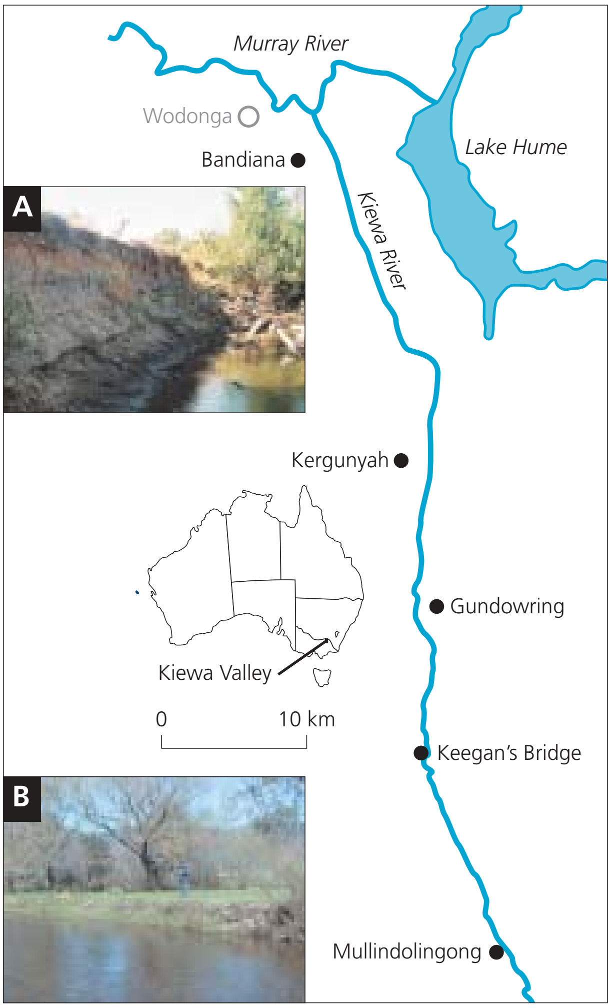


Figure 6.3. Erosion measurement sites on the Kiewa River, Victoria. (A) Bandiana, the most downstream site. Note the increase in bank height downstream. (B) Mulindolingong, the most upstream site.

inspection that nothing had changed, only to find from the measurements that there had been dramatic erosion. Overall, a visual assessment at an erosion site seems to be a poor basis for deciding on the dominant erosion mechanism.

The preliminary results from work on erosion along streams in the tropics (both wet, and wet/dry) suggests that:

~ Bank erosion rates observed on study streams were of similar magnitude to those of equivalent sized streams observed worldwide.
~ Early results are that the proportion of clay in the banks has more of an effect on erosion rates than does root density.
~ Whilst the majority of sites that are eroding quickly lack substantial riparian vegetation, there is no significant difference in erosion between vegetated and un-vegetated sites. It is not yet clear whether this is the case for all three erosion processes (subaerial, fluvial scour, and mass failure), and hence vegetation has little effect overall or whether it can influence certain types of erosion.

Relationship between vegetation, erosion and channel size

It is likely that there is some threshold channel size (and catchment area) above which riparian vegetation is no longer the dominant control on channel morphology. Examples cited in the literature, in which grassed channels are smaller than forested ones, only occur at catchment areas less than tens of square kilometres (Zimmerman, Goodlett et al. 1967, Davies-Colley 1997).

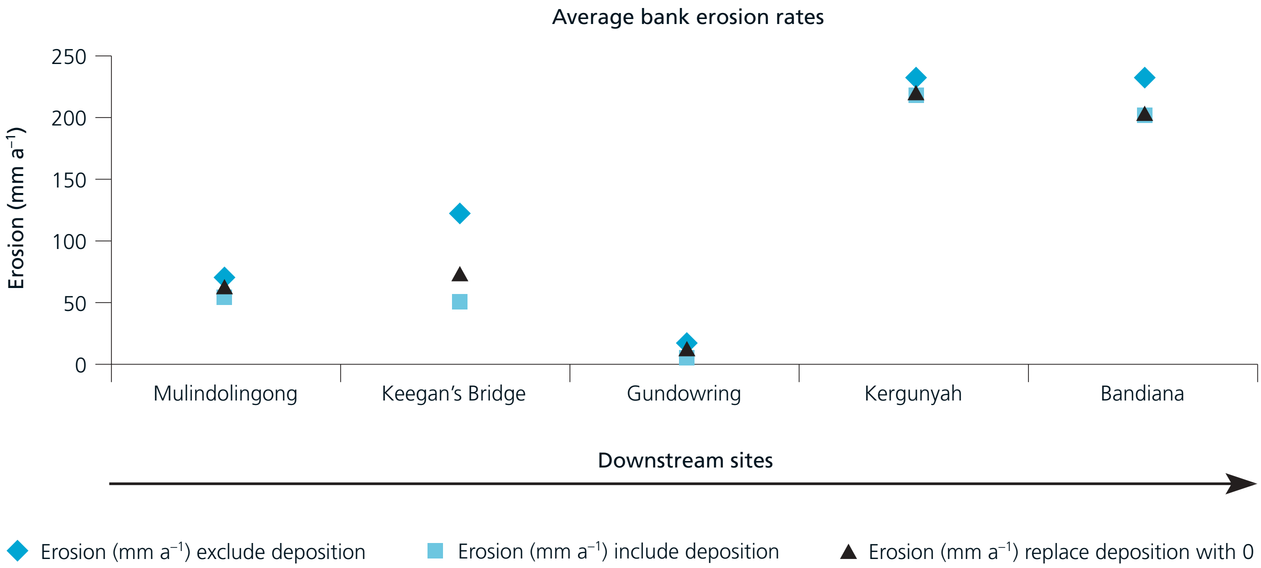


Figure 6.4. Average bank erosion measurements (over the full bank face) at the five sites, over four years of measurement (three sets of erosion measurement are shown, one taking no account of deposition at the site, one subtracting from the measured erosion any deposition, and one using zero for deposition in calculating averages).

The relationships between vegetation and cross-section shape appear to hold even for channels that are up to 50 metres wide, but it is unlikely that the morphology of rivers much larger than this is fundamentally controlled by vegetation. Masterman and Thorne (1992) suggest that at width/depth ratios greater than 30:1, it is unlikely that vegetation will have any influence on channel flow capacity, and very little influence when the ratio exceeds 16:1. Certainly, where the bank height exceeds the rooting depth of vegetation, and where vegetation does not grow on the bank face, trees are unlikely to have much effect on channel geophysical processes. In Australia, the root zone seldom extends below two metres in depth. Although some roots extend deeper than this, they tend to add little extra strength to the banks.

There is some evidence that average erosion rates, as well as maximum erosion rates during floods, are reduced by bank vegetation. Measures of some meandering North American streams suggest that meander bends would, on average, migrate at almost twice the rate through a cleared floodplain than through a forested floodplain (Hickin 1984, Odgaard 1987, Pizzuto & Meckelnburg 1989). Bends of streams in British Columbia (1–2 metres deep, 20–30 metres wide) were found to be five times more likely to have suffered measurable erosion during a flood if they were unvegetated than if they were vegetated (Beeson & Doyle 1996).

Question 2: What is the effect of riparian vegetation on specific erosion mechanisms?

Before we can answer this question, we need to understand the distribution of tree roots in stream banks, as these roots influence the erosion mechanisms.

The distribution and character of roots in stream banks

We cannot predict the effect of roots on bank erosion processes unless we can predict the distribution and character of roots in the riparian zone, particularly on the bank face. For Australian riparian species, there is some data from Bruce Abernethy's work, but we need to (a) extend root strength and distribution data to more species (b) identify the distribution of roots on the bank face (this has not been done before).

Collaboration with Tom Hubble (Sydney University), and his PhD student Ben Docker, has provided root strength and distribution data for four new Australian riparian species (a fifth species, River Oak, is being completed). Ben Pearson is close to completing root work on various tropical species. The aim of this work is to be able to predict the character of the roots based on the character of the above ground parts of tree species. Given tree size and spacing, we will be able to predict the character of the root plate for most riparian settings in eastern Australia. The results are beginning to support the original hypothesis that root strength is sufficiently similar between species that we can now concentrate on root distributions.

A major assumption that has been made in all of the work on roots and bank stability is that the roots on the sloping bank face will be the same as the roots growing on the horizontal floodplain. This is certainly not the case. In her Honours project, Sarah Lewis showed that a) fine river red gum roots grow densely on the bank face, but that the roots extend all the way down to the mean summer water level, b) there are more fine roots in the bank face if the flow is consistent (reliable) (i.e. in irrigation channels, more consistent flow produces denser root mats than in channels with more variable flow). Some of this data is summarised below (Figure 6.5 and Figure 6.6, overleaf).

As part of this research program, Ben Plowman completed a detailed review of the characteristics of riparian roots in order to develop general rules for predicting root characteristics. Scientific papers provide details, but the various controlling factors, and the concept of the 'proto-tree' method, are summarised here.

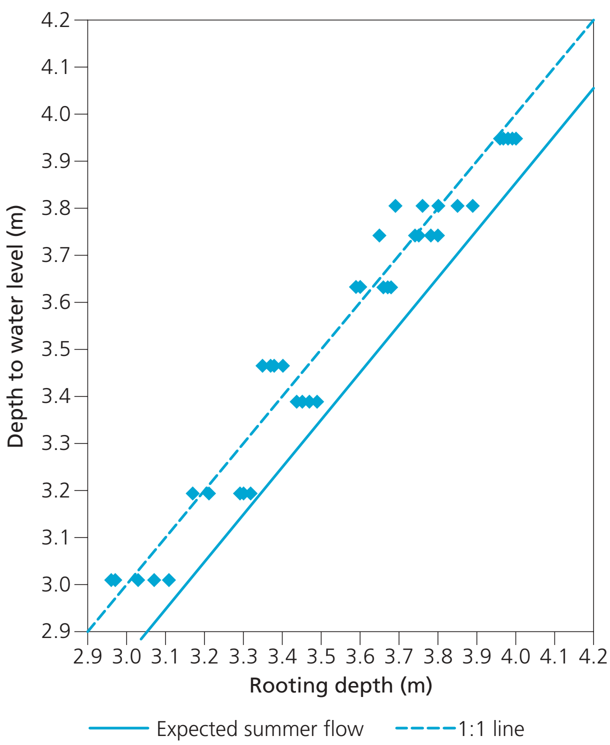


Figure 6.5. Rooting depth versus depth to water level for depths between 300 and 400 centimetres.

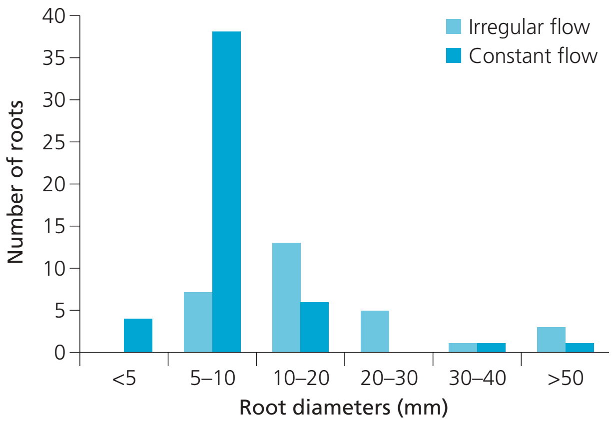


Figure 6.6. Distribution of roots in sites with constant and irregular flow regimes.

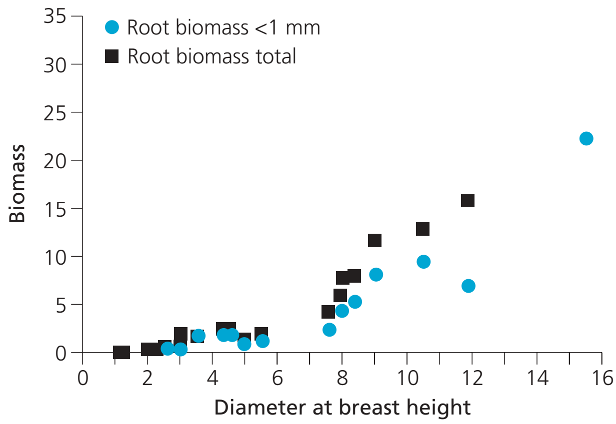


Figure 6.7. Root biomass increases at about the same rate as the size of the tree (diameter breast height).

The following are generalisations that can be made from the literature:

1. **Riparian vegetation and associated roots have a positive effect on stream bank stability with regards to mass failure.** This is through increasing bank cohesion and associated shear strength. While the tensile strength of roots is important, another factor which will also control bank stability is the shear resistance between the roots and the soil, this according to Docker (2003) varies significantly between species. The riparian vegetation due to its size also places a surcharge on the channel bank. However the negative effect of the surcharge is very small when compared to the additional cohesion supplied by the vegetation on the form of roots (tree weight is spread over a large root mat, and is generally much less than the weight of the soil block in which the roots are growing).
2. **The root properties of trees scale with age.** That is, older, larger trees can be considered as simply larger models of younger, smaller trees. There is not some special change that takes place in their root plate, or related root characteristics, as they age (Figure 6.7).
3. **Vegetation and associated roots have different structures and architecture in different climatic zones.** The Australian climatic zones considered in this review, and for which there are some data, are tropical, temperate and arid. The general trend for the architecture of roots is one of increasing root distribution and biomass as percentage of the entire tree with increasing aridity. This will mean that arid species have the greatest positive individual impact on bank stability and tropical species the least. However this may not be true for an entire ecosystem due to overall vegetation density. Another significant point that needs to be considered with tropical vegetation is that the maximum root depth may not be controlled by ground water level (see point 6 for water table controls), the trees may receive all the moisture they need from their surface roots, meaning that deep structural tap roots may not exist. This may mean that tropical vegetation does not have a significant impact on the mass failure of stream banks.
4. **Roots behave differently when in competition with other species.** It is generally accepted that the greater the root density the greater the improvement in stream bank stability. Total root biomass for fine roots is significantly higher when tree species are in competition with each other. This is a strong point in favour of multi-species revegetation rather than mono species revegetation as it will, through competition, more rapidly increase the root density on the stream bank and therefore the stream bank stability (Figure 6.8).
5. **Root density and architecture is influenced by soil properties, although this is particularly true for fine roots**. Root density is also significantly affected by the maturity of the vegetation, with total biomass even after decades of regrowth being only ~50% of that of mature vegetation. There is currently no data to show whether soil strength continues to increase with total root biomass or if it stabilises once the vegetation reaches a certain size and maturity. The data on root density is limited to fine roots and total forest biomass and therefore the magnitude of this influence on mass failure may be quite small. Also the cohesion of the soil which is significantly influenced by moisture is a variable soil property which may have a changing impact on root architecture of the fine roots (<2 millimetres). These impacts have not been quantified.

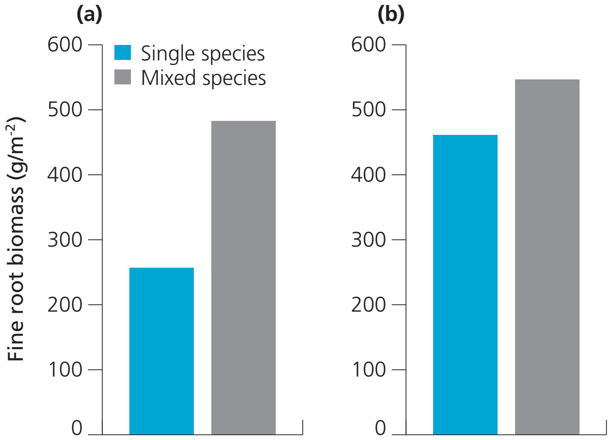


Figure 6.8. Example from North America showing that species in competition have relatively more roots than species that are not in competition. The right hand graph (b) shows a lighter soil than the left hand graph (a), demonstrating the effect of soil clay percentage.

6. **Maximum rooting depth is no deeper than the local groundwater level.** This may cause stability problems for riparian vegetation planted on the banks of streams with artificially high base flows or adjacent to weir pools. These controls will mean that structural roots will extend only to the new water level, and this may cause stability problems if the roots don't develop enough to structurally support the tree above. Therefore, riparian vegetation on natural or unregulated streams is likely to have a greater impact on reducing mass failure than that on regulated systems.
7. **Vegetation and roots adapt to local site conditions such as fire and hydraulic controls on the base flow of streams.** A typical response of trees to sites that get burnt on a frequent basis is to place a greater percentage of their total biomass underground where it is partially protected. These site-specific localised impacts will be difficult if not impossible to quantify, though any increase in belowground biomass as roots will probably also increase the vegetation's positive effect on bank stabilisation.

From these points it is possible to understand the processes and conditions that affect root architecture and its influence on mass failure for a 'proto tree', or typical riparian tree, in a temperate environment. The basic measure of the effect that tree roots have on mass failure is increasing the Apparent Cohesion (C_a). The apparent cohesion will vary with RAR (Root Area Ratio) root density, root length, root volume and biomass of a proto tree if all other bank properties remain the same. The significance of the different site conditions that will influence vegetation and root growth and structure are summarised in Table 6.2. The most important variable

Table 6.2. Shows the significance of site conditions that affect riparian vegetation and its influence on bank stability.

Site condition	Significance
Age of vegetation — time	High
Hydrology — groundwater level — base flow level	↓
Climate	↓
Species mix	↓
Soil properties (generally affects only fine roots)	Low

Two examples of plant roots growing within and on the surface of a streambank. Photos: (above) Andrew Brooks, (below) Ian Rutherfurd.

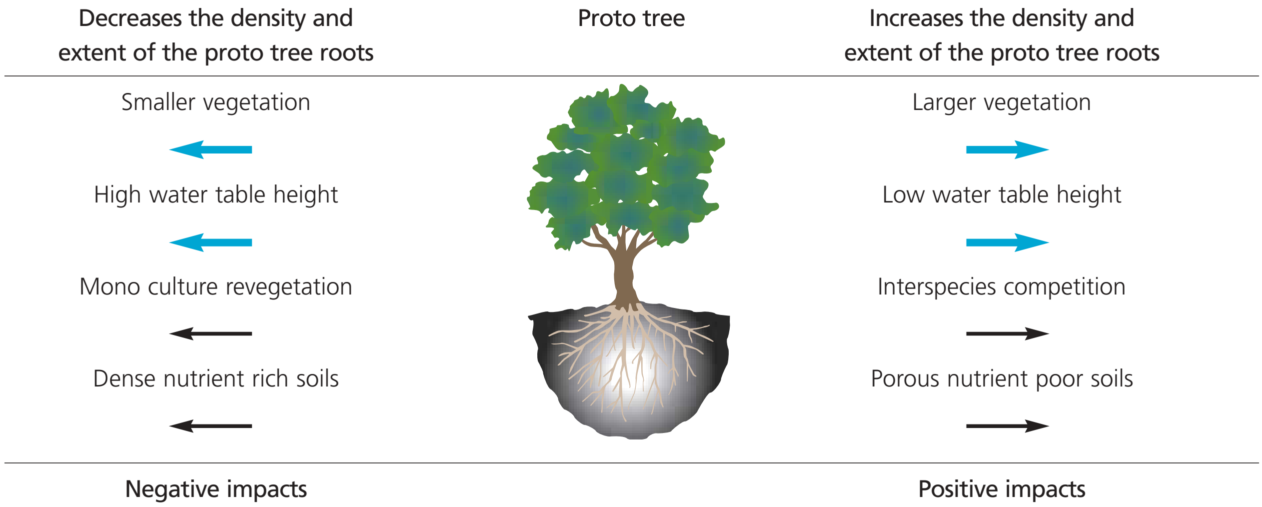


Figure 6.9. The 'proto' tree and the impacts of site conditions that affect root architecture and density are identified with their effects on the root distribution and density of the proto tree.

: High level of confidence in process. : Low level of confidence in process.

with regards to increasing the factor of safety on the stream bank is the size/age of the vegetation for any given cohesive stream bank in a temperate zone. The confidence levels for site impacts having an impact on root distribution and density are shown in Figure 6.9.

In order to make geomechanical estimates of the effect of vegetation on erosion mechanisms, we need to estimate root characteristics. Geomechanical models are crude, so there is no use pretending that we can have precise numerical estimates of root characteristics for the models. Instead we argue that engineers take an 'average' impact from the best measured trees (i.e. trees measured by Abernethy, Hubble and Docker) and then alter the values depending on the characteristics shown in Figure 6.9. Thus, a young tree, in a site with heavy clay, and high water table; can be expected to have less dense roots than a large (old) tree in sandy sediment, with a low water table.

Another way of using this information would be to assist people to predict the effect of trees on the geomechanics of bank failure. This can be done using a specific suite of models, so the most efficient way to have this work adopted is to provide parameters that river engineers or others can readily apply in the models. This would allow managers to answer the questions: how much do (or could) trees stabilise this stream bank? This will be achieved by providing a 'nomogram' that will allow prediction of a factor of safety (or better a probability of failure in any one year) given the following variables:

1. bank height and bank materials,
2. type of tree to be planted,
3. position and spacing of planted trees.

An example of the type of data that would enable these calculations is shown below (Figure 6.10).

Alternatively, the method could be used to tell river managers how they would need to plant their trees in order to achieve an acceptable probability of the bank or section being stable. Variables here would be tree spacing, size/age, and tree position (e.g. on bank face or bank top).

We now turn to research that identifies the influence of vegetation on specific erosion mechanisms under the conditions found commonly along Australian streams. The four main topics are undercutting, mass failure, scour of cohesive sediment, and scour of sediment covered by grass.

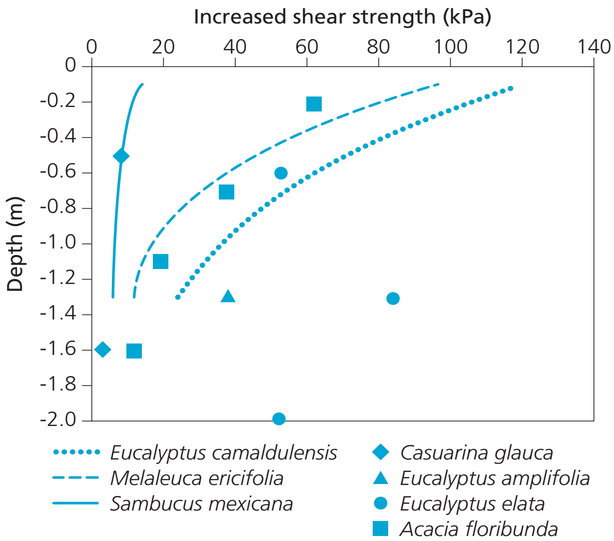


Figure 6.10. Data comparing increased shear strength from various riparian tree species.

A typical abutment, but lone trees are eventually outflanked by erosion. Photo Ian Rutherfurd.

Effects of vegetation on undercutting

Stream bank erosion often isolates the root-plate of a riparian tree on a pedestal of sediment jutting out from the stream bank. Such root-plate abutments are a transitory landform produced as a result of greater erosion resistance provided by trees. The morphology of abutments integrates the many effects of isolated trees on erosion rates. From measuring seven abutments formed along the Acheron River, in southeastern Australia, we conclude the following (Rutherfurd & Grove 2004):

1. That roots from a single tree increase the resistance of impinging banks in a semi-circle centred on the trunk. The abutment has a radius that is always smaller than, (usually less than half) the canopy radius (Figure 6.11). This relationship holds for four dominant riparian tree species along the Acheron River, situated on gravel and sandy-loam banks that are from 1 to 4 metres high.
2. All abutments are deeply undercut, with most of the abutment formed of a 0.5 to 1 metre thick overhanging plate of finer sediments reinforced by roots. However, the deviation of the bank curve at the toe of the bank below trees, indicates that they also provide some strengthening of the bank at the toe, even when the bank is nearly 4 metres high. This strengthening is not enough to materially alter the migration rate of a meander bend. Abutments fail by toppling.
3. The bed is deepened at the tip of the abutment, by up to a third of the bank height in these cases. Thus the abutments themselves have a secondary effect on channel morphology.

The implications of the abutment work are:

~ Single trees will not alter the long term erosion rates of stream banks.
~ Tree roots increase the resistance of gravels to erosion as well as clays.
~ Trees begin to alter erosion rates when the stream bank cuts to within half of the canopy radius, or about 4–5 times the trunk diameter at breast height.
~ Trees need to be planted close enough together to ensure that they cannot be isolated by erosion (that is, their root plates overlap). *This is a critical guide for riparian replanting.*
~ Reinforcing stream banks with trees will probably lead to an increase in stream depth at the bank face.
~ Erosion resistance provided by tree roots decreases rapidly with depth, leading to undercutting when bank height is equal to or more than tree rooting depth.

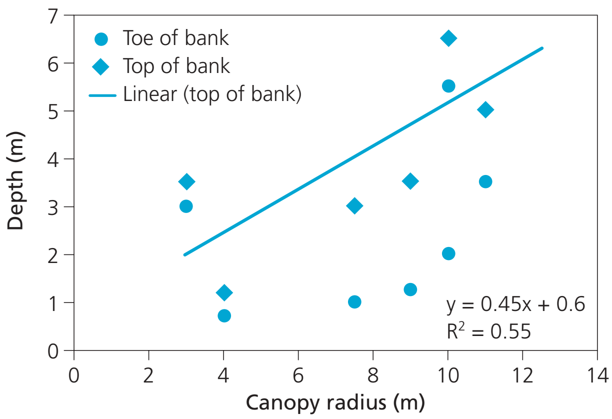


Figure 6.11. Relationship between the radius of the tree canopy (the drip line) and the radius of the abutment along the Acheron River.

Mass failure

Vegetation can influence mass failure through:

~ buttressing and soil arching,
~ transpiration and improved bank drainage,
~ root reinforcement,
~ surcharge.

Some, all or none of these influences might be apparent at any one site and their magnitude depends on local conditions.

Buttressing and soil arching. Buttressing by trees directly supports the upslope bank material and, as noted, may protect the toe against shear failure (Thorne 1990). Well-rooted and closely spaced trees that are growing low down on the face of a river bank can provide an effective buttressing effect. Soil arches may also form in the ground upslope of the trees when the soil is prevented from moving through or around the trees. Slope buttressing effectively increases bank stability against shallow and deep-seated slips.

Transpiration and improved bank drainage. Drier banks are more stable than wet ones because the weight of the soil mass is lower and the soil's cohesion is higher. Vegetation keeps banks drier by intercepting precipitation, by using water that does reach the ground, and by increasing drainage through the soil. Annual evaporation from *Eucalyptus* plantations can be up to seven times that from surrounding grazed pastures when there is a good water supply present in or near the root zone (Greenwood et al. 1985). Furthermore, well-vegetated banks are likely to be better drained than their cleared counterparts. Due to an increased incidence of organic matter and a higher level of biological activity, well-vegetated sites typically have a more diverse pore-size distribution, tending towards larger pores. Macropores (greater than 0.05 millimetres in diameter) contribute to drainage under saturated conditions, while smaller pores are important for water storage (Craze & Hamilton 1991). However, it is unclear whether the effects of transpiration by, or improved bank drainage resulting from, trees are sufficient to affect bank stability during and immediately after a flood wave, when the bank material is saturated and ripe for failure.

Root reinforcement. Probably the most obvious and important way that trees affect bank stability is by increasing the strength of bank material with their roots. Plant roots tend to bind banks together, acting in much the same way as steel reinforcement in concrete. Ground cover species do not generally contribute to mass stability of banks because of their limited root depth. For mass failure of treed banks to occur, the roots that cross the failure plane must either pull out of the soil or break under tension.

The extent to which vegetation acts as reinforcement depends on a number of root properties. The most important two properties are: the geometry of the tree root system (how far it extends for various species); and the root tensile strength that contributes to the cohesion of the banks.

The most difficult aspect of modelling vegetative reinforcement of a soil slope is establishing the geometry of the tree root system (Docker & Hubble 2001b, Abernethy & Rutherfurd 2001). The choice of appropriate values for the additional cohesion provided by roots is less problematic, but again only a few studies provide data for Australian species (i.e. Abernethy & Rutherfurd 2000a, 2000b and Docker & Hubble 2001a). Field examination of the roots of trees exposed in the slump scars, and the published studies of *Eucalyptus*, *Casuarina* and *Melaleuca* (Florence 1996, Docker & Hubble, 2001b), indicates a conservative, estimate of the reinforced zone as being 4 metres divided into a 2.5 metre thick upper zone containing abundantly distributed roots and a 1.5 metre thick lower zone of sparsely distributed roots.

Mass failure following undercutting at an outer meander bend. Photo Gary Caitcheon.

Probably the most important factors are the root tensile strength, the roots' frictional resistance to movement within the soil, and root density. Generally, smaller roots are the main contributors to additional soil strength. Roots over about 20 millimetres in diameter are usually treated as individual anchors. Root strength depends on the species, size, age and condition of the root.

Bank material strength is a function of its internal angle of friction and cohesion. The effect of small roots is to increase the 'effective' cohesion of the sediment. Cohesion is a complex variable, depending on moisture content and the character of the material (that is, low for sands and high for clays). Small roots of northern hemisphere species can increase cohesion by an average of 20%, although this can be up to 50% (Coppin & Richards 1990, Greenway 1987). Our own work suggests that the effect of tree roots may be even greater than this, with perhaps up to a 200% increase in cohesion close to the trunks of riparian trees. Recent studies of the contribution of roots to cohesion have been completed in 'temperate', lowland streams by Abernethy (1999) and Docker (2003). Docker (2003) examined four tree species on the Nepean River, *Casuarina glauca*, *Eucalyptus amplifolia*, *Eucalyptus elata* and *Acacia floribund*, and Abernethy (1999) examined the *Eucalyptus camaldulensis* (River Red Gum) and *Melaleuca ericifolia* (Swamp Paperbark). A summary of this data was provided earlier in Figure 6.10.

Cohesion can range from zero in clean sand, to 30 kPa in clays. Trees can increase this cohesion from 1 kPa to about 17.5 kPa, with an average of about 6 kPa (Wu et al. 1979, Waldron & Dakessian 1981, Hemphill & Bramley 1989, Docker & Hubble 2001a). Overall, thus the small roots can increase cohesion, and resistance to bank failure, by an average of 20%, although this can be up to 50%.

To put an increase in cohesion from roots into a practical context, additional cohesion may be thought of as increasing stable bank height — that is, bank failure may occur on a bank of a given height that is devoid of vegetation, whereas the same bank reinforced with roots will not fail. Experiments on the Latrobe River in Victoria suggest that a 10 kPa increase in apparent bank cohesion from tree roots, applied throughout the profile, extends the stable height of a 90° bank by some 2 metres (Abernethy & Rutherfurd 1998). For banks that are less steep, the improved stability due to roots yields greater increases in stable height. The stable height of a 45° root-reinforced bank is 4 metres higher than for its bare counterpart.

An important physical principle to understand, is that the effect of vegetation roots is usually greatest close to the soil surface. Here the root density is generally highest and the soil is otherwise weakest. Strength is imparted to the soil by cohesion between particles and by the frictional resistance of particles that are forced to slide over one another to move out of interlocked positions. As depth increases, the overburden increasingly applies a confining stress on the soil particles. This increases the force that is required to move particles out of their resting position. The increasing confining stress also applies to roots: a root of given length and diameter is more firmly bound by the soil at depth than at the surface.

Although root densities are highest close to the soil surface, the full reinforcement potential of the roots may not be realised unless they penetrate to depth. However, roots may pull out of the soil before their peak strength is reached. Longer and more firmly implanted roots provide greater reinforcement than do their shorter and loosely anchored, but equally strong, counterparts. Hence, trees provide more reinforcement to the general stability of a river bank than do shallow-rooted grasses.

The root masses of *Melaleuca fluviatilis* protect and reinforce this streambank. Photo John Dowe.

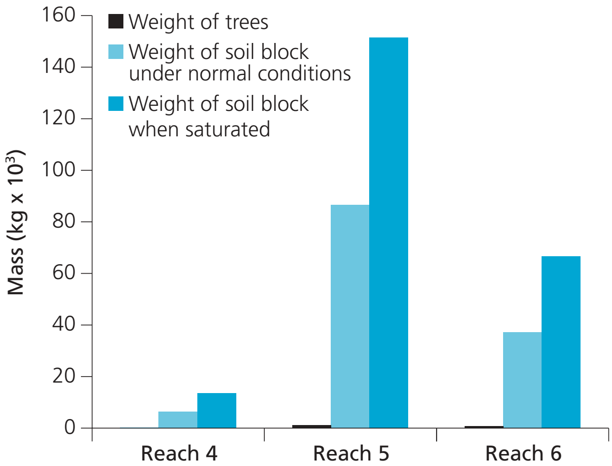


Figure 6.12. Surcharge from wattle trees along three reaches of the Latrobe River (from Abernethy & Rutherfurd, 2000a).

Surcharge. Trees are often considered to add an extra weight to a stream bank (called 'surcharge' in engineering) that will encourage the banks to collapse. This seems reasonable when a large eucalypt (such as a river red gum) might weigh 10 tonnes and a clump of wattles could weigh a few hundred kilograms. This weight will be increased by the extra forces generated by wind loadings on the canopy. That is, a wind blowing toward the stream bank will produce a 'turning moment' in the tree canopy that will tend to push a block of soil with the potential to fail (a 'failure block') away from the bank.

In reality, however, the weight of trees can seldom be used as an argument for not planting them. Imagine a rotational slump failure. The effect of surcharge depends upon whether the weight of the tree is directed onto the portion of the failure that is more or less than 45°. If it is less than 45°, then the surcharge from the tree actually strengthens the bank against failure (Styczen & Morgan 1995). For this reason, the lower down the bank slope you plant the trees, the better for the prevention of mass failure (so long as you have rotational failures).

Modelling experiments have shown that, even in places where the typical failure plane is greater than 45°, planting trees can be beneficial. This is because, in those cases where the roots of the tree cross the failure plane, the extra strength provided by the roots far outweighs any surcharge effects of the trees.

Where the root ball of a tree is entirely within the potential failure block, the tree is likely to be so small relative to the size of the block that surcharge will not be important (Figure 6.12).

The only situation where surcharge could be a problem is in shallow slide-type failures, where one layer of sediment slides over another one. If all of the roots are enclosed in the top and the slide is over 45°, tree surcharge could accelerate the failure.

Fluvial scour of cohesive sediments

Many researchers conclude that vegetation, through a living root network, has the potential to increase bank stability by decreasing the erosion rate on banks exposed to fluvial forces by retarding the flow (i.e. increasing roughness) and increasing sediment shear strength through binding and buttressing of the tree roots (Frankenberg et al. 1996, Hickin 1984, Huang & Nanson 1997b, Micheli & Kirchner 2002, Millar 2000, Smith 1976, Wilson et al. 1995). Unfortunately, the influence of fine roots (diameter <5 millimetres) on the process of fluvial entrainment has had little scientific investigation. It is believed that the apparent cohesion caused by the root reinforcement and imbrication of particles leads to an increase in the critical shear strength necessary for fluvial entrainment of the bank particles by corrasion (Abernethy & Rutherfurd 1996, Thorne & Osman 1988). Not only can the tree roots directly bind the sediment particles together, but the over-story of the vegetation may be able to decrease the subaerial processes by shading, and so protect the bank face from temperature fluxes and direct impact from precipitation. On the other hand, tree canopies may shade out or suppress understorey vegetation such as shrubs and grasses which could be more of a factor in binding bank materials and resisting fluvial entrainment (Lawler et al. 1997).

As cohesive soil dries, volumetric shrinkage occurs that forms a 'ped' fabric of soil blocks separated by desiccation cracks (Couper & Maddock 2001). Desiccation cracks, or micro fissures, then form planes of weakness due to the contrast of higher cohesion with the soil peds (Thorne 1990a). In some instances, desiccation processes may prepare the bank surface, increasing fluvial scour (Couper 2003). The degree to which subaerial 'preparation', specifically desiccation, enhances fluvial erosion is highly dependent on the temporal spacing of the events, where the influence might be more pronounced if a high flow event immediately follows a period of substantial subaerial activity (Couper & Maddock 2001). One particular theory suggests that, initially, the presence of roots induces more planes of weakness as cracks in the clay, but once the individual peds become isolated the erosion is reduced (Gaskin et al. 2003, Glinski & Lipiec 1990). This reduction may have been due to roots anchoring the peds or inducing greater roughness to the flow once the roots began to be exposed. Clearly, a complicated relationship exists between various sediment and biological root properties. To summarise, fine roots affect erosion of cohesive banks by drying out the bank face. Erosion of the cohesive toe of stream banks is the most

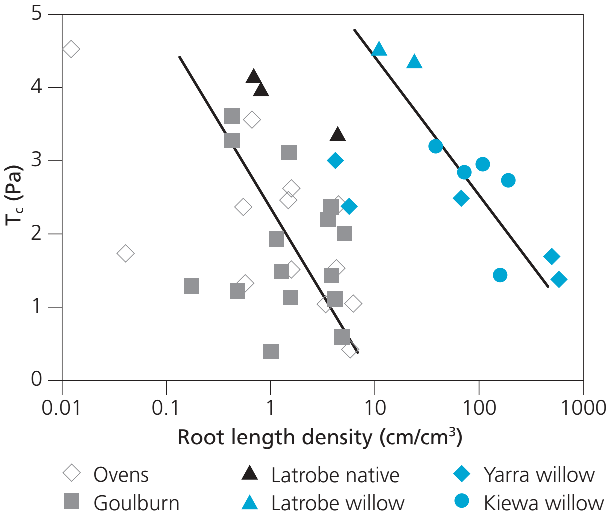


Figure 6.13. Critical shear stress (measured by the hydraulic jet device) required to erode sediment with different root length densities (measured by the root scanner device).

Fluvial scour underneath a willow root mat. Photo Lizzie Pope.

poorly understood aspect of stream bank erosion processes. The role of roots in such processes is even less understood. The resistance of cohesive sediments to erosion is poorly predicted by simple measures of sediments, such as plasticity or median particle size. As a result we have turned to a new method to measure resistance of cohesive sediments, the hydraulic jet apparatus. This allows us to identify the role of tree roots in stabilising cohesive sediments.

After overcoming numerous tough technical problems we were able to apply the jet to natural cohesive stream banks containing various types of roots, including red gum, wattle and willows. The results we got were surprising. Our hypothesis was that more roots would mean more resistance to erosion (i.e. greater critical shear required to erode). Our results showed the opposite: the more roots, the lower the critical shear required to erode the sediment. The explanation for this result is that the sediment controls the erosion rate, but it also controls the volume of roots. In the past researchers have always treated the roots as being independent of the sediment type. However, trees need more roots in well drained sandy soils (which hold little moisture), and less roots in heavy clays (which do hold moisture).

Thus we conclude that the character of the clay controls the erosion rate, and also controls the root content of the bank. The effect of the roots is a second order influence on bank erosion rates.

The result for willow roots is also interesting. We found that willow roots do not have a particularly higher critical shear stress than do the roots of native trees. This is surprising as willow roots are very dense, and in experiments have always been found to be resistant to erosion. The reason that we appear to find modest erosion resistance is that willow roots trap sand, and build out into the channel. The sand is less resistant to erosion. Thus, the willow roots act as 'pseudo clay' to bring the sandy banks back up to the same erosion resistance as 'normal' cohesive' banks.

The implication of this work is that vegetation roots appear to have a much greater role in stabilising clay banks against mass-failure than against fluvial scour.

Fluvial scour of grassed surfaces

Most of the discussion so far in this document, and in most riparian research, deals with woody vegetation. This ignores the fact that the most common vegetation type in streams is almost certainly grass. This point is demonstrated by analysis of over 6000 photographs of Victorian rivers taken for the Index of Stream Condition assessments by the Department of Sustainability and Environment. Dom Blackham analysed these photographs and concluded that 20% of streams have horizontal surfaces of some type in the bed of the channel, and of those surfaces, three-quarters were covered with pasture grass (Figure 6.14). Dom then explored whether these grass surfaces would survive the shear stresses experienced when the stream was in flood. This is an important question for gully management, for example. If grass can be established in the bed of a gully, will it stabilise the stream? How will grazing alter the resistance of grass in streams?

Whether grass is eroded depends on the shear stress applied to the surface (this is a function of the depth of the flow, and the slope of the water surface), and to the length of time that that shear stress is applied (duration). There has been considerable agricultural research into the scour resistance of grasses. This is mostly related to

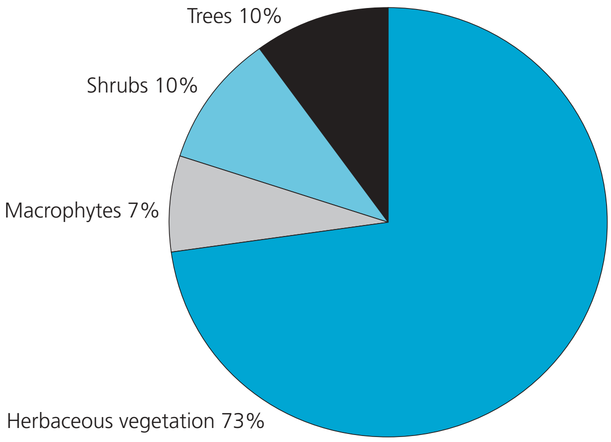


Figure 16.14. Occurrence frequency of vegetation types on vegetated horizontal surfaces in Victorian streams (percentage of vegetated horizontal surfaces with each type of vegetation).

erosion of paddocks and crops. None of this research covers the shear stresses and durations experienced in natural streams; neither does it consider the range of substrates found in streams. To do this, Dom collected swards of a pasture grass (*Paspalum*) from streams, and placed them into a large flume. The shear stress and duration required to erode the grass could then be compared with the shear stress and duration of flows in natural streams.

The results were very clear: mature grass growing in the bed of a Victorian stream is able to easily resist the shear stress exerted by the great majority of Victorian streams (Figure 6.15). For example, Creightons Creek experiences a maximum 60 N/m^2 for a duration of 80 hours, whereas mature grass requires a shear stress of 250 N/m^2 for nearly 100 hours before it will erode. Although grass grown in sandy and gravel is less resistant than grass grown in silt/clay, neither will erode in Victorian streams. The reason that the grass is so resistant to shear, is that it lies down and physically protects the surface.

Young (sub-mature) grass is much less robust than mature grass. It will erode in the larger, longer flows experienced in Victorian streams, particularly if the grass is growing in sand or gravel. However, Dom's experiments also clearly show that grazing of grass makes it very susceptible to erosion at natural shear stresses and durations. Grazed grass is more easily eroded than young grass, because grazing removes the long, flat blade. It is this blade that protects the surface when it lies down. Juvenile grass just has a shorter blade.

The implications of this research are that grass is tremendously effective at stabilising stream beds if it is able to grow to maturity, and particularly if it is not grazed.

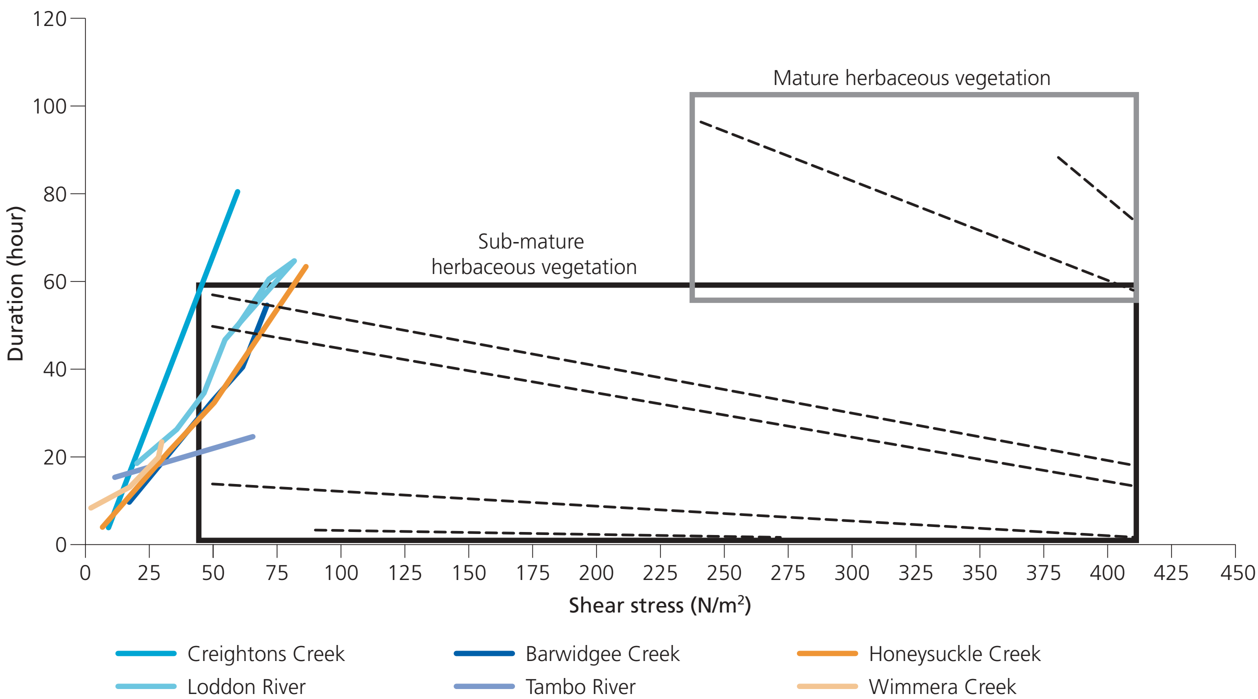


Figure 6.15. Summary graph showing erosion prediction analyses for all combinations of tested herbaceous vegetation and substrate at each study site (the coloured lines show the shear stress and duration of flows experienced in the streams listed, the black dashed lines show the duration and resistance curves from the flume data). The black framed box shows that erosion resistance curves for mature herbaceous vegetation on silt/clay and sandy gravel substrates generally exceed stream conditions and are resistant to erosion. The grey framed box shows erosion resistance curves for medium and short herbaceous vegetation on silt/clay and sandy gravel substrates are generally less than conditions experienced in streams, so this vegetation is likely to erode under the more extreme conditions.

Grassed bars in an incised stream. Such grassed bars and benches are common in rural lands. Photo Ian Rutherfurd.

In summary:

- Grassed benches, bars and banks are a dominant feature of many streams in Victoria and, from observation, elsewhere.
- The flume study shows that erosion of grassed surfaces within a channel is a product of the duration of flow as well as the peak shear stress.
- If typical grasses growing in Victorian streams are able to grow to a dense sward on benches and bars, then the grass will not be scoured by the shear force and duration encountered in those streams. This means that grass that establishes in a stream will continue to stabilise the bed unless it dies for some reason, or is grazed, or rolled-up by erosion that gets underneath the sward.
- Grazing reduces the resistance of grass to the point where it can be eroded by the forces and durations experienced in Victorian streams. The size of the substrate is also an influence on this threshold.
- The probability of erosion of horizontal surfaces with herbaceous vegetation varies with stem length — the probability of erosion at a site will decrease as herbaceous vegetation grows towards maturity.
- Erosion resistance of herbaceous vegetation is inversely correlated with substrate particle size — the probability of erosion of horizontal surfaces at two comparable sites will vary depending on the substrate size on horizontal surfaces.
- Channel incision caused by fluvial scour of horizontal surfaces will be arrested by a mature community of herbaceous vegetation.
- The effectiveness of herbaceous vegetation in controlling horizontal surface erosion peaks in the upper section of a catchment, reflecting variation of shear stress exerted on horizontal surfaces through the catchment.

Question 3: Given all of these processes, what is the gross effect of vegetation on stream morphology?

We have discussed the effects of riparian vegetation on a range of erosion processes under different stream conditions. Now we turn to the question: how will stream channel morphology change if we remove, or replant, vegetation in and along streams? In this discussion we will not consider the effects of changing catchment vegetation on hydrology.

Effects of riparian vegetation on channel width

The following work on channel width is a summary of an Honours thesis by Lizzie Pope (Pope 2005).

A review of all previous studies which have looked at the effect of riparian vegetation on bankfull channel width found that results have been conflicting. Six studies have reported that reaches with woody vegetation have narrower channels compared to those without, five have observed the reverse and one study found no difference between the two (Table 6.3, overleaf). Only one study by (Trimble 1997, 2004) has investigated the effect of vegetation on base width. It found that channels with trees were significantly wider at base flow than those without.

These studies have looked at the effect of 'with trees' compared to 'no trees'. A few studies have gone slightly further by considering more than one level of tree density, however, what is almost entirely absent from the literature, is investigations into the effect of different vegetation species or communities on channel width. This is despite several reviews demanding that vegetation type be considered (Hickin 1984) (Thorne 1990b) and the one previous study indicating that the effect is substantial (Huang & Nanson 1997b).

As we emphasised earlier in this chapter, any effects of riparian vegetation on river processes, are mediated through channel size. Much of the variation in the literature in Table 6.3 is the result of stream size. A recent review suggests that for streams with small catchments, forested streams are wider than un-forested streams with the same catchment area, or bankfull discharge. The explanation usually given for this 'switch' is that grass does not grow in the shade of the forest, so in small streams without trees the grass does grow, it does protect the banks of the small stream more strongly, and the channel is narrower. Planting forest that then shades out the grass will lead to widening as the grass dies back (as we will see overleaf, this is exactly what happened in an experiment at Echidna Creek

Table 6.3. Summary of the results from studies that have compared the bankfull width of channels lined with trees to those without.

Author	Bankfull width of channels with trees compared to grass
(Zimmerman et al. 1967)	Wider
(Murgatroyd & Ternan 1983)	Wider
(Sweeney 1992)	35–250% wider
(Davies-Colley 1997)	Up to 100% wider
(Allmendinger et al. 2005, Hession 2001, Hession et al. 2003)	Wider
(Charlton et al. 1978, as cited in Murgatroyd & Ternan 1983)	30% narrower
(Andrews 1984)	26% narrower
(Hey & Thorne 1986)	Up to 55% narrower
(Huang & Nanson 1997b)	Narrower
(Rowntree & Dollar 1999)	Narrower
(Wasson & Wasson, 2000a)	Narrower
(Trimble 1997, 2004)	No significant difference

in south-east Queensland). However, as the stream channel gets wider and deeper downstream, grass has less influence on stream processes (because the toe of the bank is below the root zone of the grass), so shading out grass with forest will not lead to widening by bank erosion. In general, the literature suggests that this effect of grass does not operate when the catchment area is larger than about 20 km^2 (Figure 6.16). Above this size, streams with treed riparian zones are almost always *narrower* than streams with cleared banks. Do Australian streams have the same neat relationship between channel size and vegetation?

Only two studies examined the effect of Australian native riparian trees on stream width. The study by Huang and Nanson (1997c) on four small streams in New South Wales found that streams lined with few or no trees were wider than those with native trees at similar discharges (Figure 6.17). Wasson and Wasson (2000b) also observed this trend in their study on the Upper Naas River near Canberra.

Many streams in south-west Australia have been invaded by introduced willow species (*Salix* spp.) (Figure 6.18). What is the effect of willows on stream morphology?

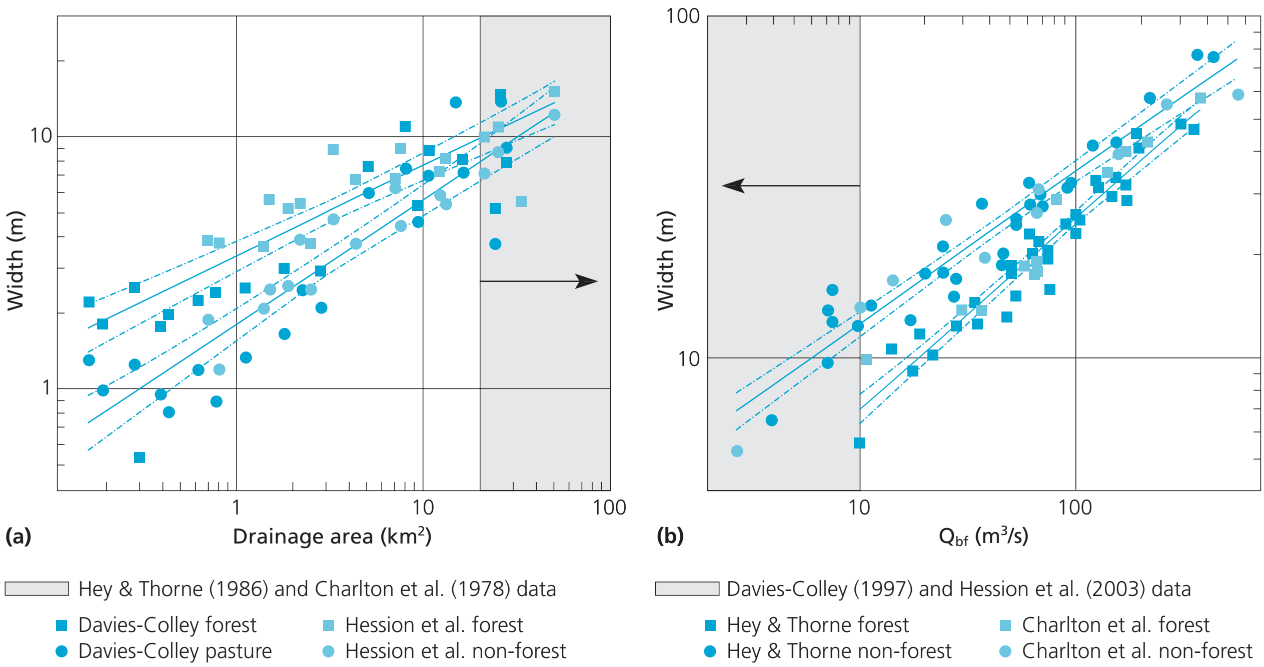


Figure 6.16. Graphs of data from four studies on the effect of vegetation on channel width. Graph (a) shows forested streams with small drainage areas are wider than un-forested streams of the same size. Graph (b) shows that larger forested streams are narrower than un-forested streams with the same discharge (Anderson et al. 2004, p. 1163).

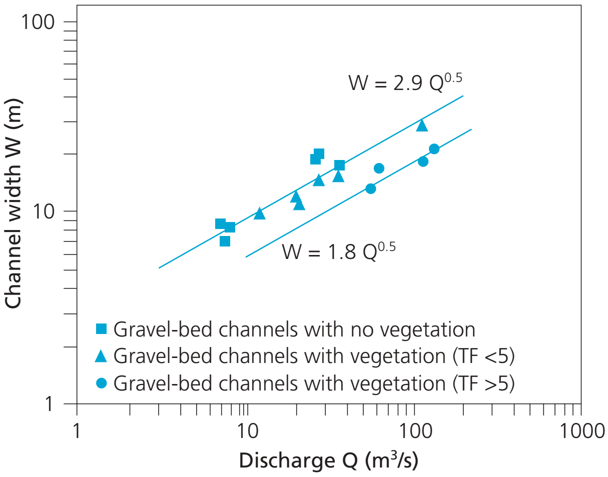


Figure 6.17. At a given discharge, channels lined with Australian Native vegetation were found to be narrower than those with few or no trees (Huang & Nanson 1997b, p. 243).

Figure 6.18. A willow (*Salix* species) trapping sandy sediment and growing out into the stream. Photo Lizzie Pope.

Three studies have been conducted on the morphology of streams lined with willows compared to grass in their native countries (Sweeney 1992, Trimble 1997, Zimmerman et al. 1967). The studies by (Zimmerman et al. 1967) and (Sweeney 1992) found that sites with willows were wider at bankfull than comparable sites with grass. Trimble (1997) found that there was no significant difference in the bankfull width of sites, but that sites with willows had greater base widths. A study on the impact of introduced willows in South Africa by Rowntree and Dollar (1999) found that sites with willows were narrower than those with grass.

Only one study has previously been carried out on the effect of willows on channel width in Australia (Huang & Nanson 1997b). They found that sites with willows on the bed, and natives on the banks, (vegetation type C) were consistently wider than sites with only native trees on the bank (vegetation type B) (Figure 6.19).

In her study, Lizzie Pope (2005) investigated whether streams lined with native vegetation (trees and understorey), willows, or grass, had different widths (Figure 6.20).

Sites with willows were significantly wider than those with native trees or grass at small catchment areas, but that difference became insignificant at catchment areas above approximately 90 km². The data collected from Victorian streams suggests the following conclusions.

1. The greater width of grassed streams compared with treed streams, that has been reported for northern hemisphere and New Zealand, does not seem to apply to Victorian streams. This may be because treed Australian streams do not have the same limit to grass growth because the canopy of the native riparian vegetation is relatively open.

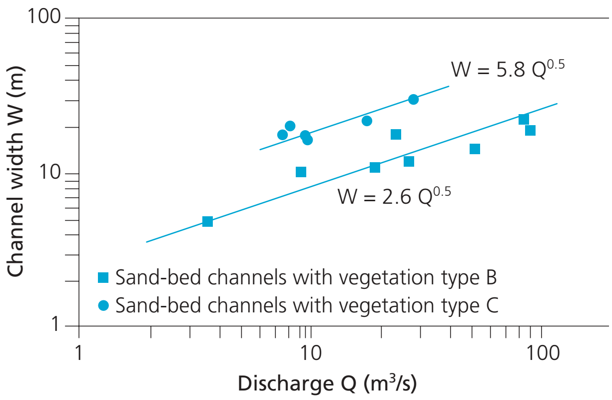
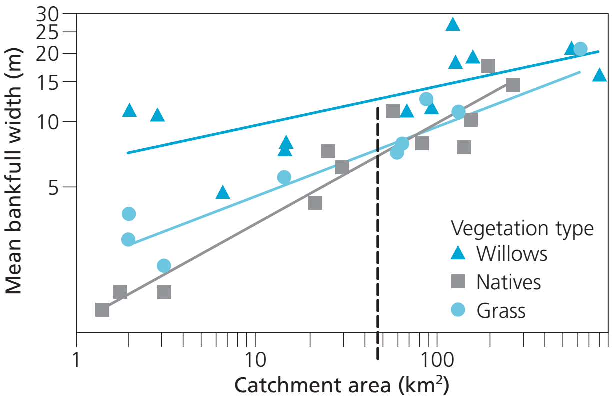


Figure 6.19. Graph showing the results from a study on the width of streams with native Australian trees on the bank (Type B), compared to the width of streams with willows on the bed as well as natives on the bank (Type C) (Huang & Nanson 1997b, p. 245).



Regression equations				
	Willows	$y = 6.31x^{0.18}$	$R^2 = 0.48$	(0.4)
	Natives	$y = 1.24x^{0.45}$	$R^2 = 0.93$	(3.5)
	Grass	$y = 2.22x^{0.31}$	$R^2 = 0.86$	(3.6)

Figure 6.20. Scatter plot on log-log scale showing data points and regression lines comparing the mean bankfull width of streams related to catchment area and vegetation type (grass, natives and willows). The dashed line indicates the approximate point at which sites with native vegetation become narrower than those with grass (~60 km²).


Photos illustrating (left) the dense undergrowth and grass cover found at some field sites with a cover of native riparian trees and (right) the cover of grass present at sites with willows. Photos Ian Rutherfurd.

2. At sites with native vegetation, the majority of trees were located on the upper bank or on the floodplain. In contrast, at sites with willows almost all trees were located within the channel, either on the lower bank or in the channel bed.
3. In small streams, the flow is shallow enough that willows can invade the stream bed. When they invade the bed they encourage erosion around their trunks, causing erosion and widening of the channel (see photos above).
4. Above a catchment area of 80–100 km^2, the type of riparian vegetation appears to have little impact on channel width.
5. At catchment areas above 80–100 km^2, the streams are too deep for willows to colonise the stream bed. Instead they colonise the banks, where they encourage deposition. Thus, willows tend to widen small streams, and narrow larger streams, depending on whether the trees can colonise the floor of the channel.

Effect of clearing on catastrophic channel change

Many streams in south-east Australia dramatically widened following European settlement (Rutherfurd 2001). The best known examples of such widening occurred on the lowland tracts of large coastal streams of NSW. There has been considerable debate about whether this erosion was triggered by natural cycles of flood and drought, or by the clearing of riparian vegetation from the stream banks (e.g. Erskine & Warner 1988, Brooks & Brierley 1997).

Research by Tom Hubble demonstrates that, on the lower reaches of the Nepean River, bank failure and widening of the channel required both changes to deepen the channel: clearing of the banks, and a series of floods. This is the first study to quantitatively link riparian vegetation with major channel changes in large Australian rivers. Following are some details of that research.

Hubble inspected five sets of aerial photographs (1947, 1956, 1961, 1965 and 1970) of a 34 kilometre section of the Nepean River between Theresa Park and Menagle Weir. A flood-dominated regime (FDR) began in 1950, and extended up to 1991. Hubble recorded bank slumps, vegetation density, and channel curvature. The results (Figure 6.21) indicate that a) neither cleared or vegetated banks failed before 1950, b) after 1949, the onset of the FDR led to numerous bank failures (most on inside banks), but only in the sections of bank that were cleared of riparian vegetation. This led us to hypothesise that dramatic erosion and widening of the river required both clearing of vegetation to weaken the banks, and regular flooding both to deepen and widen the bank toe, and to remove failed bank material that could protect the bank toe. However, this coincidence of failure and clearing needed to be mechanically tested to see if the relationship was real. Hence, Tom Hubble completed a geo-mechanical analysis of bank failure in this section of the Nepean River.

The geomechanical stability of eight bank sections on the Nepean River was analysed. Geomechanical models for vegetated and devegetated banks in fully saturated

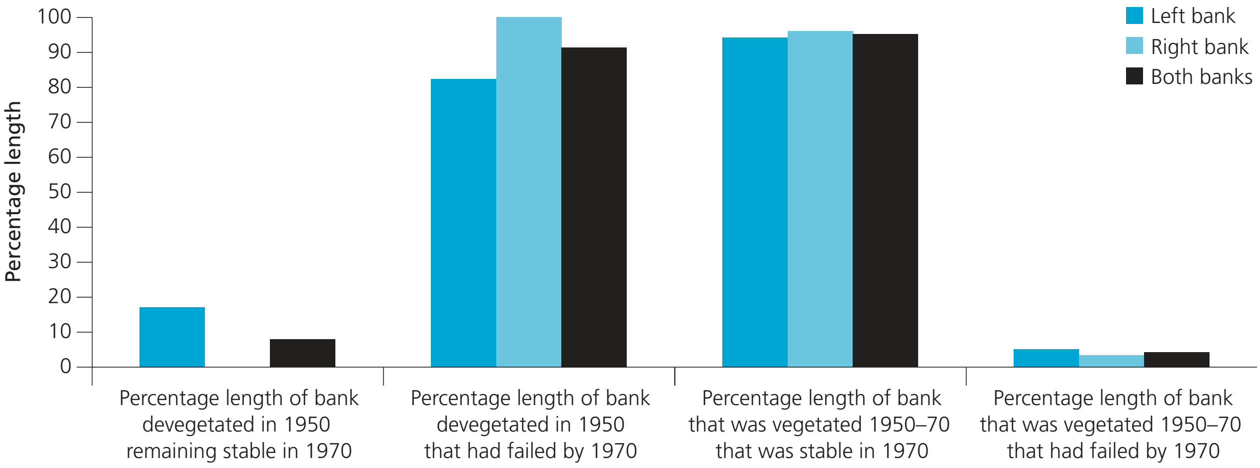


Figure 6.21. Bank failure in vegetated and cleared sections of bank in the Nepean River.

conditions were calculated by XSLOPE (Balaam 1994) according to Bishop's Slip Circle method (Bishop 1955). The analysis (Figure 6.22) indicates that vegetated banks had a factor of safety above one (i.e. they were unlikely to fail). Removing the bank toe (as happens in an FDR) always reduced the factor of safety to below one in cleared banks, and to close to one in vegetated banks. These geo-mechanical results support the hypothesis that both clearing and floods were required to trigger major widening of banks in the Nepean River. This result does not say that the same is true for all rivers that suffered major widening over the last 150 years, but it does suggest that clearing of riparian vegetation is almost certainly a factor in much of this widening.

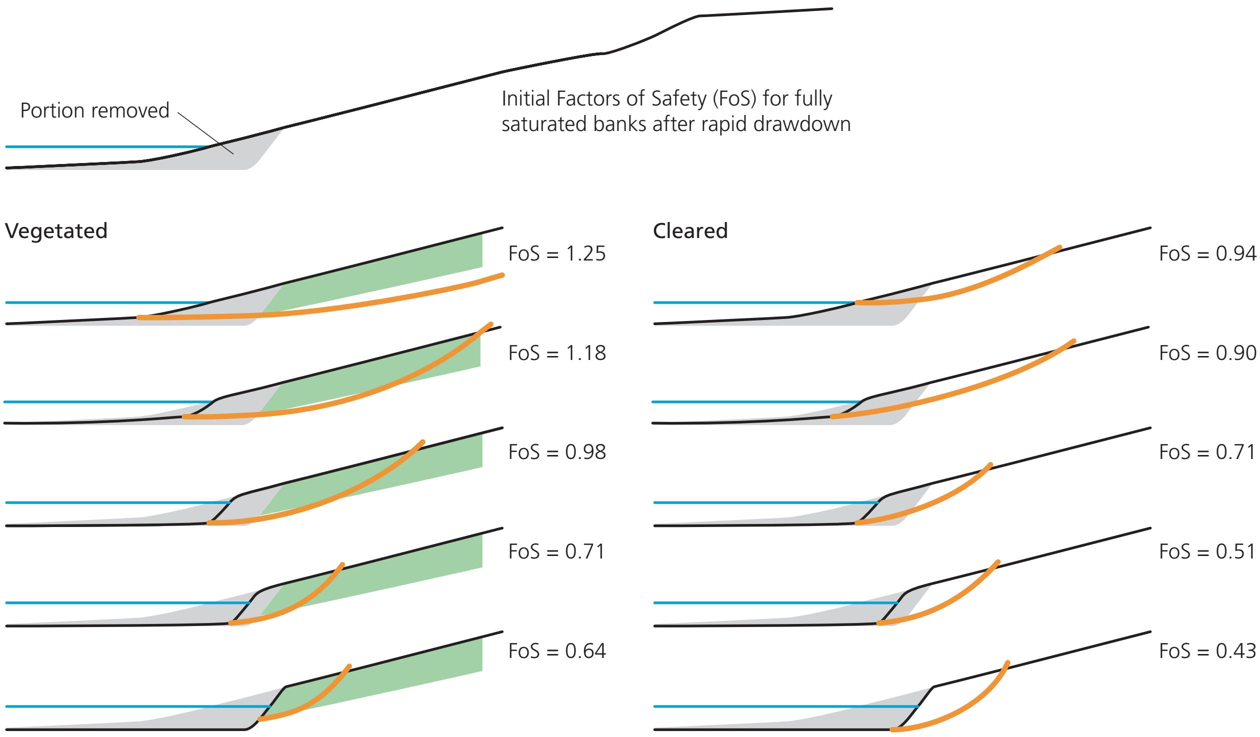


Figure 6.22. Simulation of the effects of channel widening after the onset of an FDR on bank stability for vegetated and cleared banks. Channel widening is assumed to occur due to toe erosion. The bank profile used in the Xslope modelling is shown at the top of the diagram. The consequences of progressive erosion of the bank toe are depicted in the detailed views of the bank toes. The grey shaded area indicates the extent of the bank toe removed. Model parameters used in the modelling: fully saturated conditions; a friction angle of 41.1°, soil weight of 18.5 KPa; tree surcharge weight of 2.5KPa; soil cohesion of 0.5 KPa; tree root cohesion comprised a upper near surface zone 2.5 metres thick at 5 KPa and a lower zone 1.5 metres thick at 2.5 KPa. Note that in the case modelled an initially stable vegetated bank with a FoS of 1.25 becomes critically stable after about 3 metres of the original bank toe is removed. In contrast the devegetated bank is initially unstable (0.94) and its stability reduces such that it is virtually certain to fail (FoS 0.7) after 3 metres of toe removal.

Question 4: What erosion response, over time, can managers expect when they do revegetate the riparian zone of small streams?

Managers often assume that revegetating a riparian zone will simply return the functions that were lost when the stream was cleared. This will seldom be the case. First, the stream has changed its form and function over the years, and so the vegetation is interacting with a new channel. Second, riparian vegetation is seldom the only thing that has changed in a catchment. There is grazing, changed landuse, and so on. Although we have a good idea of the effects of removing vegetation from streams, we have a much less clear idea of what happens when we return riparian vegetation to degraded systems. In part, this is because riparian vegetation takes many years to grow in southern Australia, and few research projects can wait that long for results. Second, it is difficult to isolate the effects of the growing vegetation from the many other changes that are always taking place in catchments.

We attempted to examine the effects of riparian revegetation by re-surveying sites that had been treated in the past. For example, there have been at least 66 projects in north-east Victoria over the last two decades that have involved riparian revegetation in some form. Our hypothesis was that, out of these sites, we could find a set that were sufficiently similar, that we could isolate the effect of 'time since revegetation' as a variable. This approach is called a 'space-for-time substitution (SFTS) approach'. In order for the method to work, the sites have to be similar in all regards except for time. Also, time is assumed to be a surrogate for the effect of growing vegetation (i.e. older vegetation has more influence than younger vegetation.

When the sites were revisited, it was concluded that a SFTS approach was not valid because:

1. the sites were physically very different from each other, which would confound the method,
2. the type of riparian vegetation planted over time had changed, so this was another variable in addition to time (vegetation maturity),
3. riparian revegetation was seldom the only thing done at each site. Only in the last 5 years has riparian revegetation been done on its own along streams in this region.

In short, apart from general observations about processes, we could learn little from the many riparian revegetation projects that had already taken place in this region. This is likely to be the case for many areas outside north-east Victoria as well. This led us to conclude that we needed to begin direct monitoring of processes in streams in order to isolate the effects of riparian vegetation on geomorphic processes.

Fortunately, there are now some large scale riparian revegetation experiments being monitored. Here we report on one undertaken by Dr Nick Marsh, that isolated physical changes associated with other variables within the wider catchment. Nick Marsh (Griffith University) and colleagues revegetated the riparian zone of a small catchment in south-east Queensland (Echidna Creek), and began monitoring temperature, erosion and sediment yield relative to a reference and a control site. To gauge the impact of stream revegetation on suspended sediment (SS) yield we installed turbidity loggers at three similar sized (1.5 km^2) tributaries of the South Maroochy River in south-east Queensland from December 2000 until March 2004. The treatment stream (Echidna Creek) was revegetated in February to April 2001 by clearing scrubby weeds and planting tube-stock of endemic species at 2 metre centres. The second stream was a nearby control stream (Dulong Creek) where the riparian zone is vegetated with pasture grass (mostly Kikuyu). The third stream was a reference stream (Piccabeen Creek) with a fully forested catchment located in nearby Mapleton State Forest. All streams had similar elevation, topography and geology. Note that this is the first riparian revegetation project in Australia to have both control and reference sites for comparison to help isolate treatment effects.

For each stream we used automatic turbidity loggers to record the turbidity at 15 minute intervals. The turbidity record was converted to a SS record via a rating curve of turbidity against suspended sediment concentration.

The results of the four years of monitoring at Echidna Creek show that the unforested stream (pasture and grazed) yielded 14.5–87.8 $t/km^2/a$ compared to the forested stream yielding 3–78 $t/km^2/a$. Thus SS yield from a forested subtropical stream is around 30% less than from an adjacent fully cleared (but grassed) catchment. The treatment stream initially had a similar suspended sediment yield to the control stream. The revegetation activities in the treatment stream resulted in an initial increase in suspended sediment yield (to approximately double that of the control stream; 12.3–212.2 $t/km^2/a$). Data showing SS yields in kg/ha are shown in Figures 6.23 and 6.24.

Why did revegetation lead to this initial dramatic increase in sediment yield? The revegetation process required the removal of existing invasive pasture grass, ground cover and woody weeds. This ground cover was killed by herbicide before the new vegetation was

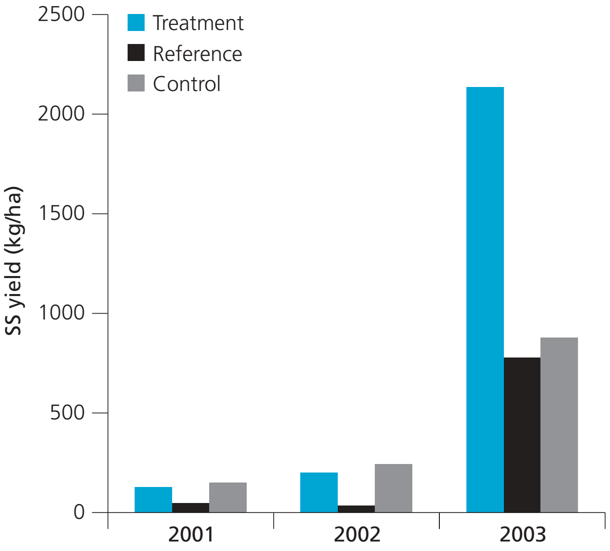


Figure 6.23. Total suspended sediment yield for Echidna Creek, showing that the increase in yield from the treatment stream relative to the control and reference sites.

established. We suspect that this disturbance of the riparian zone, and the period taken for the planted trees to become established, has caused the increase in suspended sediment yield from the treatment stream. Recall the wider channels found in forested streams in studies from the northern hemisphere and New Zealand (Table 6.3). This effect was due to shading out of the grass under the trees — a very similar effect to the results at Echidna Creek.

We expect the suspended sediment yield in the treatment stream to reduce to below the control stream once the riparian vegetation is fully established and any resulting channel change is complete; recent data suggests that this is indeed happening This process should take about seven to eight years from the start of the project. Note too that the rehabilitation work monitored in this study was mostly out of channel and required no heavy machinery in and around the channel. If soft restoration activities such as presented here can double the suspended sediment yield, then one would expect a much greater effect from more invasive stream rehabilitation work such as willow removal or in-stream habitat creation. The primary conclusion to be drawn from this study is that stream rehabilitation work is likely to at least temporarily cause an increase in suspended sediment yield, although ultimately we would expect a lower suspended sediment yield than pre-rehabilitation. Rehabilitation plans should take into account the temporary increase in suspended sediment yield and any effect that this may have on in-stream biota. Where stream ecosystems are already under stress due to a highly degraded waterway, managers must consider the likely impact of dramatic but short lived increases in suspended sediment yield from large scale works compared to lower magnitude but longer duration of impacts from staged local rehabilitation work.

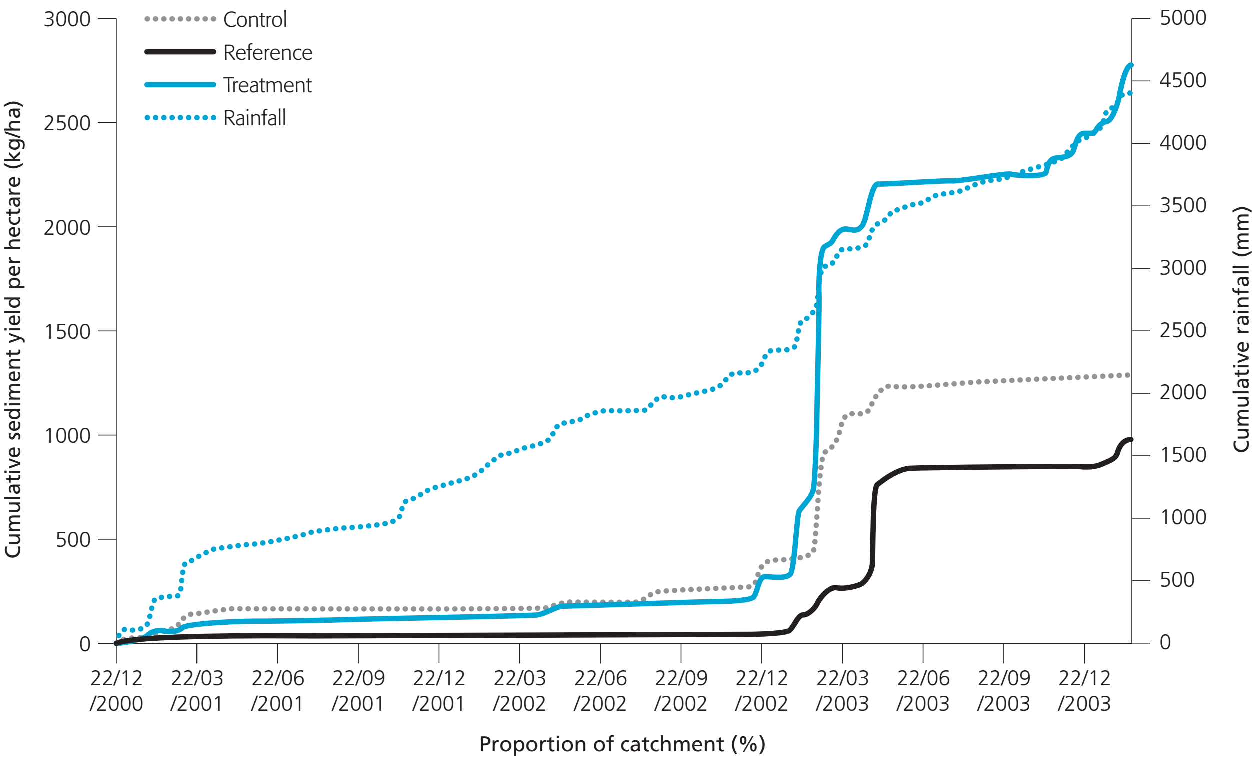


Figure 6.24. Cumulative suspended sediment yield per effective catchment area for the control, reference and treatment catchments.

Question 5: At the scale of whole catchments, where should managers concentrate their riparian revegetation to have the most effect on end-of-valley sediment and nutrient targets?

We have discussed the erosion and sedimentation processes affected by vegetation. Readers would now be aware of the processes that vegetation affects, the leverage that vegetation has over those processes, and the influence of scale (or position in the catchment), on that leverage. However, where does a catchment or stream manager go from here? Fortunately, there is a new generation of catchment scale process models that can assist managers to target their actions. In short, these allow managers to match actions (levers) with targets. Here we want to consider one example of these models: the Sednet model that allows managers to assess the effectiveness of riparian revegetation in different parts of a catchment, on end-of-valley suspended sediment and nutrient targets (Lu et al. 2004). The messages from this work are a) that a huge amount of money and effort can be wasted if revegetation is not done in the right part of a catchment, b) the amount of revegetation work that we are presently doing in Australia is of the scale that can achieve end-of-valley targets.

Lu et al. (2004) examined the effect of various management actions on sediment yields across catchments of the Murray–Darling Basin, using the Sednet model. This model estimates the amount of sediment from catchment, gully and in-stream erosion, that is produced, delivered, or stored in large catchments over decades. A consistent conclusion of the research is that about 80% of the sediment in a catchment in the Basin is generated from just 20% of the area of that catchment, be it from gullies, stream banks or steep lands (Figure 6.25). These sediment sources are called 'hotspots' of sediment production.

Whilst it would seem logical to concentrate management effort at these hotspots, this is not always the case. Lu et al. (2004) modelled the effect of four scenarios (Figure 6.26) within four Basin catchments:

1. random distribution of sediment control works around the catchment — these works included riparian revegetation, gully stabilisation, and managing hillslope erosion (scenario A),
2. targeting the works at hotspots (scenario B),
3. targeting the works at sites that are well connected to the stream network, but that may not be hotspots (scenario C), and

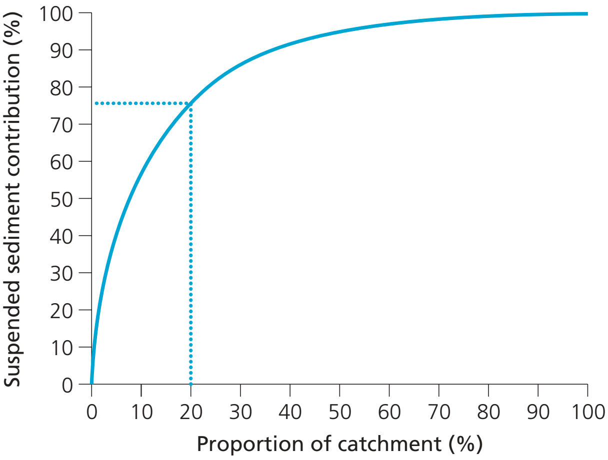


Figure 6.25. Cumulative sediment yield plotted against proportion of total area for catchments of the Murray Darling Basin (data from Sednet modelling). Note that nearly 80% of the sediment comes from only 20% of the catchment area.

4. targeting works at hotspots that are also closely connected to the stream network — i.e. sites where the eroded sediment actually gets to the stream system, and then passes through it to the catchment outlet (scenario D).

The results in Figure 6.26 are startling. Targeting hotspots that are also well connected to the stream network dramatically reduces the cost of achieving catchment sediment yield targets. Taking the Goulburn River catchment as an example, with random works in the catchment (which is the type of model that is probably practiced now) it will cost over $150 million to reduce sediment yield to half. By targeting well-connected hotspots, this can be achieved for under $20 million dollars. In the Namoi Catchment, just targeting hotspots is actually less successful than a random distribution. The reason is that the random approach more often treats well-connected sites than does treating the hotspots alone. Treating the hotspots of sediment generation that are also well-connected to the stream network is again the most cost-effective strategy.

A sand-slugged river. Photo Louise Gallagher.

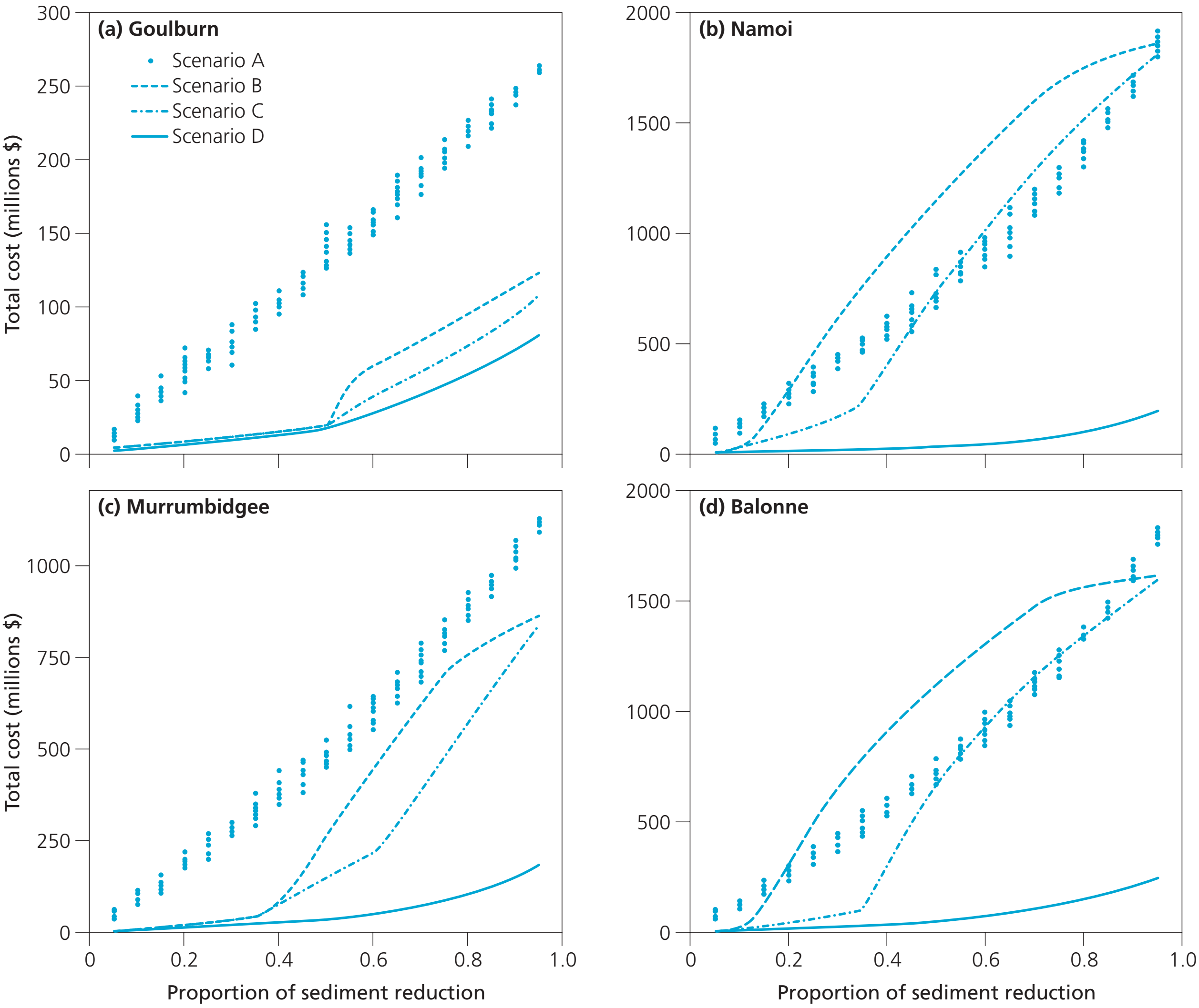


Figure 6.26. Cost versus sediment reduction curves for the four scenarios described above. Scenario A is random distribution of works, scenario B is treating hotspots, scenario C is treating well-connected sites, and scenario D is treating well connected hotspots.

The implication of this work is that well targeted management actions, at the scale that we are presently contemplating, can achieve our catchment goals. We are already spending (or plan to spend) in several catchments the sort of money that should be able to halve end-of-valley sediment yield — and this will also have an impact on achieving nutrient targets.

Conclusions

Riparian management, particularly in the form of the very popular riparian revegetation, can influence and control stream bed and bank erosion. But the effectiveness of vegetation varies greatly depending upon the particular processes driving erosion, the position within the catchment, the type and location of the vegetation, and the scale of both the erosion and the revegetation. Time is the other important variable to consider.

There is little point attempting to understand the role of vegetation in bank erosion mechanisms if we do not understand bank erosion **processes** and rates, so this should be the first step taken by river managers. Once the processes and rates at a site or within a reach or catchment have been identified, then the most effective management options can be determined.

Field monitoring has confirmed that riparian vegetation generally has a second order impact on bank erosion processes, but this **leverage** can still be important in slowing erosion to an acceptable rate. The ways in which vegetation can influence subaerial loosening, fluvial scour and mass failure, the three key erosion processes, are now better understood.

Scale should be considered next, in terms of catchment position, channel and bank size, and hence the scale of vegetation required to have the desired effect. The location of revegetation, both within the catchment to maximise cost-effectiveness, and at the specific reach or site (top and/or toe of bank, planting width and spacing), should be considered now.

Past changes within the catchment and reach are part of the **time** considerations — are there responses to past change still working through the stream network? Time for replanted or regenerating vegetation to grow and exert its maximum leverage on erosion is also important. Field data shows that the initial response to riparian revegetation can be the opposite of what was expected, for example an initial increase in sediment yield, and this needs to be planned for and explained. Some specific issues to keep in mind are:

~ Riparian vegetation is very effective at preventing or reducing the subaerial processes that loosen bank soil and make it available for removal by fluvial scour — unmanaged grazing by domestic, native or feral animals will reduce this effectiveness.
~ Effects on erosion by mass failure remain the most important influence of tree roots on the stability of cohesive stream banks.
~ Isolated trees along a bank are doomed to fail, but trees at a spacing of about half their mature canopy radius (so that their root plates overlap) protect each other.
~ Plant roots do not particularly alter the inherent erosion resistance of cohesive stream banks to fluvial scour.
~ But trees will begin to affect rates of fluvial scour when the stream bank is within half a canopy width of the tree (which is usually 5–6 times the tree trunk diameter) due to physical protection by roots.
~ If grass establishes itself in the bed or lower bank of a stream, it will resist almost any shear stress that is likely on Victorian (and many other) streams.
~ Grazing significantly reduces the resistance of grass along stream beds and banks to shear stress and erosion.

Many of the conclusions in this chapter can be summarised in an acronym that can be remembered by the phrase "Please Think" — Process, Leverage, Scale–Time.

This table shows the names and activities of people who have contributed to this chapter or the projects that underpin it.

Name	Affiliation	Contribution
Prof. Ian Rutherfurd	University of Melbourne (UoM)	Project management
Prof. Ian Prosser	CSIRO, Land and Water	Project advisor
Dom Blackham	PhD student (UoM)	Erosion resistance of grasses
Subhadra Jha	PhD student (UoM)	Incorporating vegetation effects into models of bank erosion
Dr James Grove	Royal Society Research Fellow (UoM)	Measuring bank erosion rates on the Kiewa River
Dr Tom Hubble	University of Sydney	Geomechanical modelling of the effect of roots on rotational failures
Assoc. Prof. Rob Millar	University of British Columbia	Incorporating the results of the research into catchment scale geomorphic models
Dr Nick Marsh	Griffith University	Erosion rates and processes following riparian revegetation
Chad Bailey	Research assistant (UoM)	Using a hydraulic jet device to measure the effect of plant roots on bank erosion
Ben Pearson	PhD student, James Cook University	Identifying the role of vegetation in the stability of stream banks in tropical streams
Sarah Lewis	Honours student (UoM)	Measuring the distribution of roots in the face of stream banks
Sam Marwood	Honours student (UoM)	Measuring subaerial erosion of stream banks
Lizzie Pope	Honours student (UoM)	Measuring the effect of native vegetation and willows on stream width
Various	3rd year summer students from the University of Melbourne	Surveying the characteristics of Victorian streams as a basis for extrapolating results

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