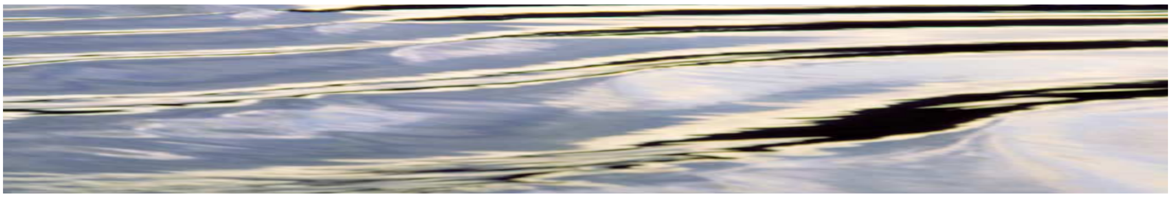
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

GUIDELINES FOR STABILISING STREAMBANKS WITH RIPARIAN VEGETATION

TECHNICAL REPORT 99/10

September 1999

Bruce Abernethy / Ian D. Rutherfurd



COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

NATURAL RESOURCES
Queensland

Land & Water Resources
Research & Development Corporation

Guidelines for stabilising streambanks with riparian vegetation

Bruce Abernethy and Ian D. Rutherfurd

Cooperative Research Centre for Catchment Hydrology
Department of Geography and Environmental Studies
University of Melbourne, Parkville, Victoria, 3163

September, 1999

Preface

In Australia, poor management practices have fostered the substantial and ongoing degradation of riparian lands. Removal, fragmentation and alternation of vegetation cover, combined with changed flow regimes, has increased the incidence of riverbank erosion. Decreased riverbank stability results in accelerated changes in channel morphology, lost agricultural production and reduced water quality. Poorly managed riparian zones have also led to increased movement of sediments, nutrients and other contaminants from surrounding lands into river systems.

Over the past six years, the Land and Water Resources Research and Development Corporation has run a national program of research aimed at improving the management of riparian lands throughout Australia. Within this framework, the Cooperative Research Centre for Catchment Hydrology has conducted a range of scientific investigations to quantify the physical influence of riparian vegetation over river processes, including bank erosion and nutrient and sediment movement through buffers.

Good progress has been made in this research and we are now in a position to communicate some of the results to landholders and stream managers. One issue that is of particular interest to stream managers is how wide vegetated riparian strips need to be along streams to perform various functions. In this regard, the Queensland Department of Natural Resources contracted the Cooperative Research Centre for Catchment Hydrology to write technical guidelines, now produced in this report. The guidelines provide techniques to help specify the width and composition of vegetated riparian zones, for bank erosion control. A companion report to this one, published by CSIRO Land and Water (Karssies & Prosser, 1999), provides detail on the design of riparian zones to filter sediment and nutrients from overland flow entering streams.

Abstract

This report provides guidelines for establishing riparian plantations that will stabilise riverbanks, within acceptable limits. Riparian vegetation interacts with a range of geomorphological, geotechnical, hydrological and hydraulic factors to affect the type and extent of riverbank erosion. The enhanced lateral channel stability offered by well-vegetated riparian zones can also reduce the need for engineered stabilisation and heavy maintenance.

The density and type of riparian vegetation cover strongly influence all aspects of riverbank erosion. Riparian forests are typically composed of overstorey, understorey, groundcover and macrophyte species. Vegetation condition is assessed in terms of the Raine and Gardiner (1995) 'traffic light' classification: green, yellow red for riparian vegetation in good, intermediate and poor condition. The main consideration when designing riparian revegetation works for bank stability is continuity of cover.

Different types of vegetation affect different processes, so it is imperative to assess the dominant erosion process correctly so that appropriate species can be selected for stability. All of the erosion processes that act on banks can be grouped together into three erosion-domains. (1) Subaerial erosion (erosion caused by processes external to the stream such as cattle, or rain splash). (2) Scour (removal of individual sediment particles or aggregates by flow). (3) Mass-failure (slumps). An underlying philosophy of these guidelines is that the dominant bank erosion process changes downstream along a river due to changes in channel scale.

The guidelines stipulate minimum riparian zone establishment-widths. Minimum riparian zone widths are calculated individually for each site on the basis of the present site conditions (observed bank geometry) and the past erosion history (measured or estimated bank erosion rate). The *basic allowance* for the width of any riparian plantation designed for bank stabilisation should not be less than 5 m measured onto the floodplain from the bank crest. As banks become higher they become less stable. Hence, in addition to the basic allowance, we recommend that the width of riparian strips also include a *height allowance* not less than the height of the bank measured vertically from the bank toe to the bank crest. Time must be allowed for the plants to grow before they can begin to stabilise the bank, so where banks are actively eroding an *establishment allowance* should also be included in the final riparian zone width. The establishment allowance is determined by multiplying the erosion rate by the time required for the plantation to mature.

The material presented in this document is summarised and collated into a series of tables that can be used to guide and focus the practitioner's approach to planning riverbank stability works with vegetation. The report does not account for ecological, or sediment and nutrient filtering, or other criteria that may dictate specific riparian management regimes beyond those appropriate for bank stabilisation. The width and character of plantations designed for other criteria may be quite different than plantations designed for bank erosion control. Thus, these guidelines should be considered in the light of other requirements for riparian zone management.

Acknowledgements

The research, on which these guidelines are based, was funded by the Land and Water Resources Research and Development Corporation and the Cooperative Research Centre for Catchment Hydrology. Further funding from the Queensland Department of Natural Resources allowed translation of the original research to its present form.

Special thanks are due to the following individuals.

- Marek Komarzynski, Fiona Cavanagh and Kathryn Jerie (Cooperative Research Centre for Catchment Hydrology) for assistance with fieldwork.
- Allan Pedder and Richard Crook (Latrobe River landholders) for access to field sites.
- Ross Scott and Phil Taylor (Lake Wellington Rivers Authority) for loan of field equipment.
- Roy Goswell and Roger Doulis (Department of Civil Engineering, Monash University) for technical assistance with field and laboratory equipment.
- David Schmiede (Queensland Department of Natural Resources) for his helpful reviews of earlier drafts.
- John Amprimo (Queensland Department of Natural Resources) who initiated the guidelines.

1 Introduction

All streams erode but human impacts have accelerated the natural and essential processes of river channel adjustment, often to unacceptable levels. Riparian and in-channel vegetation can reduce stream erosion rates but it is unrealistic to expect revegetation to eliminate all erosion. By accepting some channel change as inevitable, a managed riparian zone provides space within which river form and processes can be allowed to adjust.

Managing the riparian zone to improve riverbank stability involves planting native (particularly indigenous) trees, shrubs, grasses and macrophytes in the stream, on the banks and on the stream margins. Stabilisation schemes that incorporate riparian plants are ecologically superior to hard engineered alternatives and generally provide satisfactory improvements to bank stability. Vegetation interacts with a range of geomorphological, geotechnical, hydrological and hydraulic factors to affect the type and extent of riverbank erosion (Abernethy and Rutherfurd, 1996; 1998a; 1998b). Riparian vegetation reduces flow velocities, directly reinforces riverbanks, intercepts and slows surface runoff, and limits access to the bank by stock. The enhanced lateral channel stability offered by well-vegetated riparian zones can also reduce the need for engineered stabilisation and heavy maintenance.

This document provides guidance for designing vegetated riparian zones intended for streambank erosion control. The guidelines are divided into a number of sections. As part of our introductory comments, Section 1 defines the purpose, scope and underlying principles of the guidelines along with some definitions of specific terms used throughout the document. Section 2 outlines our proposed technique for determining the width of the riparian zone to stabilise the riverbank under various conditions. Sections 3-6 provide background material that explains the interaction between riparian vegetation and bank erosion processes, how to assess the present condition of the riparian zone and considerations for plantation design. Maintenance regimes of riparian plantations and alternatives to stabilisation schemes that rely completely on vegetation are briefly touched on in Sections 7-8.

All of the material presented in this document is summarised and collated into a series of tables that may be used to guide and focus the practitioner's approach to planning riverbank stability works with vegetation. The five tables in Appendix A are presented in a top-down fashion that cover issues at various scales, from whole of catchment to regional to on-site, to provide context for design and on-site works.

1.1 Purpose of the guidelines

These guidelines will provide assistance in planning and implementing riparian revegetation works specifically designed to retard bank erosion rates to more natural levels. Our intention is to provide some general rules for deciding on the structure and width of vegetated riparian zones for bank erosion control. The width and character of plantations designed for habitat retention (Cummins, 1993), or for intercepting nutrients and sediment in runoff (Karssies & Prosser, 1999), may be quite different than plantations designed for bank erosion control. Thus, these guidelines should be considered in the light of other requirements for riparian zone management.

Readers should be aware of the following points.

a) These guidelines concentrate on the role of vegetation in riverbank erosion without considering other forms of erosion, such as gullies or channel incision.

b) The guidelines are intended for use in regions where water is extracted from streams for irrigation. While we recognise that these streams are typically large, meandering rivers, flowing through alluvial sediments, we also include guidance on revegetating smaller tributaries.

c) Bank erosion is a natural process. Given enough time, even fully vegetated, natural streams erode back and forth over their floodplains. Indeed, there is a growing body of evidence that some channel erosion is essential to the long-term health of stream ecosystems. A healthy, vegetated riparian zone should not be expected to provide absolute stability to a stream.

d) In degraded streams, there are many situations in which vegetation alone will not stabilise streams. One of the essential tasks for managers is to recognise such situations.

e) Finally, these guidelines do not discuss weeds in vegetated riparian zones. In Queensland, particularly, weeds are a critical management problem but, in some instances, they can also contribute to bank stability.

1.2 Principles of using vegetation for bank erosion control

The underlying philosophy of these guidelines is that the dominant bank erosion process changes downstream along a river due to changes in channel scale. Different types of vegetation affect different processes, so it is imperative to assess the dominant erosion process correctly so that appropriate species can be selected for stability.

Principle 1. *Bank erosion is the result of a number of different processes that all act to destabilise river channels.*

All of the erosion processes that act on banks can be grouped together into three erosion-domains. (1) Subaerial erosion (erosion caused by processes external to the stream such as cattle, or rain splash). (2) Scour (removal of individual sediment particles or aggregates by flow). (3) Mass-failure (slumps).

Principle 2. *Each of the three erosion-domains act throughout catchments but at any given location one of the groups dominates over the others.*

The dominant process varies down a stream system: subaerial processes tend to be more important on smaller streams, the effects of scour are most pronounced in mid-catchment reaches while mass-failure is increasingly important as bank height increases in lowland settings.

Principle 3. *The influence of vegetation over each of the processes remains relatively constant throughout catchments.*

Suitably selected and placed vegetation will reduce the rate of the bank erosion processes. The overstorey has a greater influence over the processes of mass-failure than do understorey, groundcover or macrophyte species. However, shrubs and grasses on the bank face, and macrophytes at the bank toe, are equally important for controlling sub-aerial erosion and scour.

Principle 4. *Know your erosion processes. The key to planting vegetation to control bank erosion is to know what the dominant erosion process is, and to know how each of the vegetation types will affect that process.*

For example, lowland riverbanks generally retreat by cyclical combination of fluvial scour of the bank toe followed by mass failure under gravity, followed then by removal of the failed material by further scour. All components of the cycle are affected to some degree by bank material loosening or weakening due to subaerial weathering processes. The subaerial mechanisms of weakening and weathering are generally controlled by climatic conditions, whilst fluvial processes are associated with channel flow hydraulics. Mass failure is usually triggered when a critical stability condition is exceeded, either by reduction of the internal strength of the bank (often due to subaerial processes) or a change in profile geometry (typically the result of scour). The rate at which material is transported away from a particular site ultimately controls the rate of bank retreat over time (Little *et al.*, 1982; Thorne, 1982; Chang, 1988; Alonso and Combs, 1990). Revegetation to stabilise a riverbank undergoing this kind of erosion must ensure that appropriate plants are established in appropriate places on the bank.

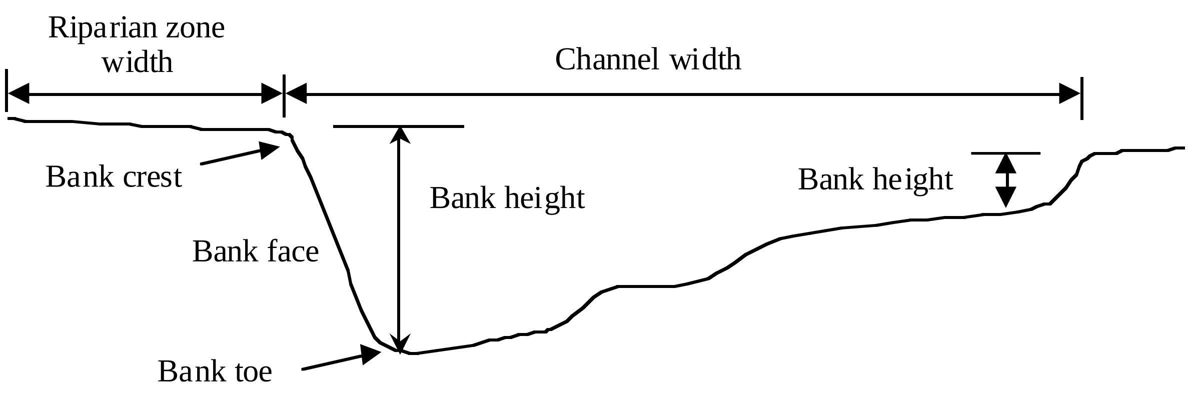


Figure 1: Description of features used in the guidelines

1.3 Terms

Riparian zone width (*Figure 1*) is the minimum width of riparian forest required for ongoing bank stability. It is measured from the bank crest away from the channel. The minimum width of the riparian zone varies with bank height and bank erosion rate (Section 2).

Bank height (*Figure 1*) is really a measure of near-bank channel depth measured vertically between the bank toe and bank crest. This will often be the local maximum depth of the channel and is likely to vary from bend to bend.

Bank crest (*Figure 1*) is the junction of the channel with the floodplain. In practice, this point can be difficult to identify. An alternative definition is the level reached by the flood that comes on average every one to two years, or the point above which you consider the river to be in flood.

Bank toe (*Figure 1*) is the junction of the bank with the bed of the channel. The bank toe is usually marked by a break in slope but often the transition from bank to bed is gradual and the toe is difficult to determine.

Stability is defined as a 'natural' rate of bank erosion. This does not imply absolute stability, but the rate of change that may have existed before European settlement. Thus, an unstable bank is a bank that is eroding at a faster rate than natural. You may be able to determine what the natural rate is by comparing your target bank with a nearby reach in near-natural condition.

Erosion rate is the rate at which the bank face moves (metres/year). This will be an average rate over at least 20 years so that the bank will have been subjected to some major floods. The erosion rate should be determined by existing evidence (aerial photos, distance from fence lines, etc.) but can be estimated as 1.6% of channel width per year (see Section 6.2).

Channel width *(Figure 1)* is measured from crest to crest.

Plantation maturity is defined as the time it takes the vegetation to have a major influence on the erosion rate (e.g. to a closed canopy). Plantations in the wet-tropics can mature within ten years but this could take up to 50 years in drier areas (see Section 6.2).

2 Guidelines for determining minimum riparian zone widths

The following procedure can be applied to short reaches of uniform stream. The higher and steeper the bank the more prone it is to erosion. As the bank becomes steeper and higher, the zone of influence of the erosion processes extends deeper into the bank (Sections 4.1 and 6.1). Slump blocks become larger and deeper and the portions of the bank profile vulnerable to scour and subaerial processes increase. So, as a rule the higher and steeper the bank profile, the wider the protective zone that should be replanted. Hence, applying the following technique to bank sections on the outside or the inside of meander bends or at inflection points will result in design criteria for riparian zones of varying widths. In those circumstances where the control of sediment/nutrient ingress to the stream is also desired, a grassed filter zone in addition to the riparian zone widths recommended here is also desirable (see Karssies and Prosser, 1999).

Note that vegetation condition is assessed in terms of the Raine and Gardiner (1995) 'traffic light' classification (see also Section 5). Other vegetation classifications, such as that developed by Luke Pen in Western Australia (Pen, 1994), could also be usefully adopted for this purpose. Staying with the Raine and Gardiner traffic light system, though, we define:

- 'green' vegetation to be a contiguous stand of mature riparian forest established at least the recommended minimum width for its location.
- 'Yellow' vegetation is a riparian forest that is not contiguous (compared to natural remnants or other local expert advice), is immature (perhaps a recent plantation), or does not meet the recommended width requirement.
- 'Red' vegetation lacks one or more structural elements (Section 3), is in a generally degraded condition and performs no stabilising role (Table 1).

For the purposes of bank stability, interspecies variation within structural groups, (see Section 3) are relatively small and unimportant. All deep-rooted species (overstorey) are more capable of reinforcing riverbanks against mass failure than shallow rooted groundcover. Trees should be planted around potential slump-block failure planes (Sections 4 and 6). However, understorey and groundcover species provide mid- and upper-bank sections with greater protection from scour. Lower bank sections that tend to remain wet throughout the year are best protected by macrophyte species where they can be established. All structural groups interact with and modify subaerial processes. Trees may dry the bank through transpiration and help resist the onset of piping, while smaller plants might reduce the affects of rainsplash or rill erosion.

Final design considerations (e.g. planting density and species makeup) tend to be controlled by ecological constraints. As a result, our only advice is to aim for a naturally diverse and dense vegetation community.

2.1 Recommendation

The minimum width of any riparian plantation designed for bank stabilisation should not be less than 5 m measured onto the floodplain from the bank crest. Wherever possible, plants established on the bank face should be integrated with the *basic allowance*. Also, macrophytes should be incorporated in the design where appropriate.

Table 1: Summary of vegetation condition assessment.
(✓ = attribute present, ✗ = attribute absent, ? = attribute either present or absent)

	Vegetation condition		
Attribute	Green	Yellow	Red
Native	✓	?	?
Mature / established	✓	?	?
Structural elements	✓	?	✗
Contiguous	✓	?	✗
Appropriate width	✓	✗	✗

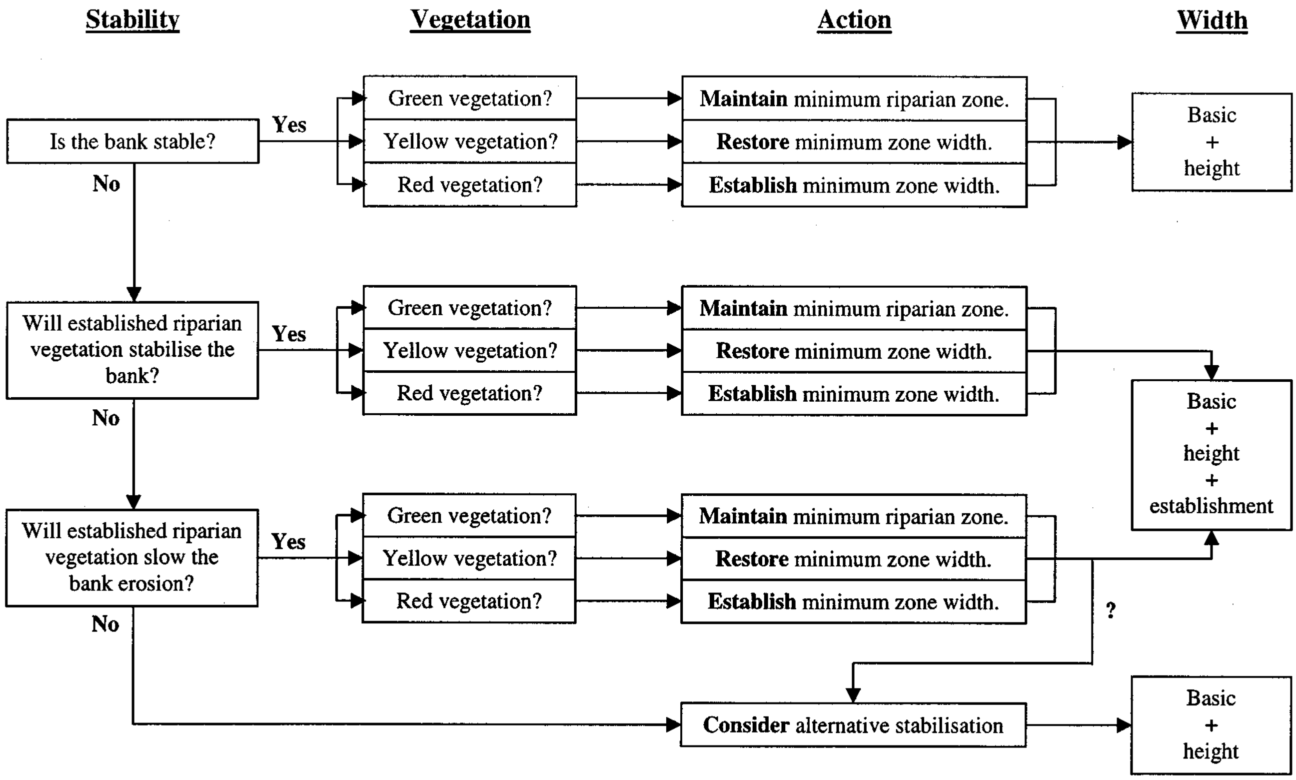


Figure 2: Decision tree for determining minimum riparian zone widths for bank stability (definitions are given in the text)

As banks become higher they become less stable. Hence, in addition to the (5 m) basic allowance, riparian strips must also include a width component that compensates for bank height. The *height allowance* should not be less than the height of the bank measured vertically from the bank toe to the bank crest (*Figure 1*).

Time must be allowed for the plants to grow before they can begin to stabilise the bank, so where banks are actively eroding an establishment allowance should also be included in the final riparian zone width. The establishment allowance will permit the components of the riparian zone planted for basic and height allowance to mature as the present bank-line erodes towards them. The *establishment allowance* is determined by multiplying the erosion rate (see Section 1.3) by the time required for the local riparian forest to mature (Section 6.2).

The above recommendation assumes certain things about bank material, bank hydrology and bank geometry. One assumption is that the riverbed is stable. Without bed stabilisation, it may not be possible to achieve bank stability with vegetation alone in excessively incised streams with high, steep banks and large failure blocks. Local conditions may dictate that the ultimate design for bank stability may require other treatments at the site. If, for example, rock toe-protection was used to prevent scour of the bank toe then the establishment allowance could be relaxed or avoided.

The last point is an extremely important caveat to all our recommendations. Onsite conditions vary enormously and preclude the use of overly-prescriptive guidelines. When seeking to stabilise riverbanks you must match erosion process and vegetation. Moreover, you must appreciate that both the erosion process and the effect of the vegetation will not remain static but will change over time. Find out what the dominant erosion process is, determine where on the riverbank it acts, measure or estimate the rate of bank retreat, determine the regional context (if any) for the problem (Section 5) - then choose species and planting strategies specifically for your local conditions, bearing in mind the minimum plantation widths.

2.2 Decision tree

The 'decision tree' shown in *Figure 2* illustrates the process of determining riparian zone widths. The decision tree begins with minimum requirements for the width of a vegetated riparian zone, and then progressively adds to that minimum for various circumstances. Note that the minimum requirement should in no way be seen as a licence to degrade a riparian zone that exceeds that minimum. In terms of bank stability, more vegetation is almost always better than less.

The following notes refer to different scenarios that could be followed through the decision tree; the list is not exhaustive. Supplementary information is detailed in Sections 5 and 6.

a) Stable bank - green/yellow vegetation

Any vegetated riparian zone less than 5 m wide is unlikely to be sustainable. Hence, the basic allowance provides a manageable zone for even small streams that have a trivial depth. As channels become larger, however, some account must be made for the decreased stability of their banks. The height allowance increases the width of the plantation to reflect the larger channel size. Stable banks with yellow vegetation require gaps in the cover to be planted out. Even stable banks with green vegetation require ongoing maintenance - occasionally monitor bank and vegetation condition.

b) Stable bank - red vegetation

In this case, there is no vegetation but the banks appear stable. Planting is still required because there is no guarantee that a stable bank will remain that way. Stable bank sections are in fact the ideal place to establish a plantation (from scratch) as the plants will have time to grow and provide increasing protection from future erosion pressures.

c) Unstable bank - red vegetation - revegetation will provide adequate stability

In this case, bank erosion is likely to be the result of a locally depleted riparian zone with nearby vegetated sections remaining stable. Along with the basic allowance and height allowance, an establishment allowance should also be included in the riparian zone design. The establishment allowance will create space for further short-term adjustment without compromising the long-term goals of the revegetation.

d) Unstable bank - green/yellow - revegetation will slow erosion rate

What is the rule if banks with good vegetation cover are still eroding? Clearly, the erosion forces are exceeding the resistance of the vegetation. Typically, this means that the erosion is related to major reach scale processes, particularly deepening, or increased rates of scour at the bank toe. In these circumstances, even if vegetation cannot reduce the instability to acceptable levels, the erosion rate is likely to be considerably slower than would be the case for cleared banks. Regardless of vegetation condition, it is important to establish and maintain an appropriate establishment allowance along with the basic and height allowances. Follow-up plantings may be required. It is often worth persisting with vegetation in these conditions as the processes of bank erosion continually shift and change, previously unstable banks will always stabilise with time. Where persistence with vegetation cannot be warranted due to continued high erosion rates, over long periods, artificial stabilisation techniques may need to be considered (Section 8).

e) Unstable bank - red vegetation - revegetation will not slow erosion rate

This scenario is one of serious riparian degradation. Perhaps the erosion rate is too high for an adequate width of riparian zone to be given over to managing channel stability. Perhaps unchecked bed degradation has heightened the banks beyond some critical value and tree roots are unable to penetrate deeply enough to reinforce failure planes. Whatever the case, if vegetation cannot be relied upon to stabilise the banks and bank stability is desired, alternative measures will need to be sought. Remember, though, that even young vegetation will tend to slow bank erosion if it can be effectively established. However, work here and overseas (*e.g.* Hemphill and Bramley, 1989; TRCRD, 1997) has demonstrated that structural reinforcement at the bank toe combined with vegetation on the upper portions of the bank provides a cheap and viable alternative to fully engineered options. With the toe fixed by structure the establishment allowance may be relaxed with the riparian zone width comprised of the basic and height allowance only.

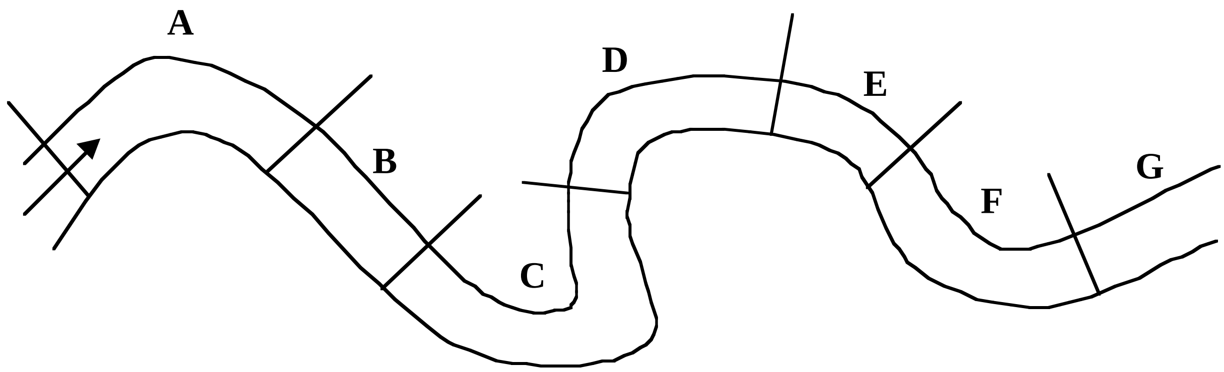


Figure 3: Hypothetical reach divided into sub-reaches for management according to the decision tree shown in *Figure 2*.

2.3 Worked example

A landholder owns one side of the 4 km reach of meandering river shown in *Figure 3*. The channel is moderately sized: about 30 m wide, with 5 m outer-banks. Remember, the landholder is only assessing the condition of his or her side of the stream. The reach consists of four bends with all erosion types - subaerial, scour, mass failure- active along the banks. Based on an assessment with the decision tree, the farmer decides that the reach should be divided into seven sub-reaches (A to G) for riparian management.

Mature vegetation that will control erosion is expected to take 25 years to establish. The farmer knows that sub-reach A has eroded 15 metres towards a tank his father built 30 years ago. Hence the establishment allowance for this reach is 25 (0.5 = 12.5 metres. This is about the same answer that he would have got using the 1.6% of width per year estimate for bends.

With reference to *Figure 3*:

Sub-reach A

Description: Steep outside bend, 5 m high.
Stability: Scour at the toe of the bank leads to continuing retreat of a steep bank face, with slumping seemingly un-controlled by the vegetation.
Vegetation: Green/yellow.
Action: Stabilise toe with rock riprap and plant out gaps in the riparian zone to give continuous cover at minimum width through the sub-reach. Because the rock stabilisation will prevent further scour at the toe, there is no need to include an establishment allowance in the final riparian zone width.
Riparian width: Basic plus height allowance (5 + 5 = 10 m).

Sub-reach B

Description: Inflection, 3 m high.
Stability: Banks are laid back and appear to be stable.
Vegetation: Yellow.
Action: Improve riparian zone to green vegetation condition.
Riparian width: Basic plus height allowance (5 + 3 = 8 m).

Sub-reach C

Description: Pointbar, <1 m high.
Stability: Stable. The pointbar is in reasonable condition, although it is prone to some stock damage. The stock are probably the cause of the plant loss in the riparian zone as well.
Vegetation: Yellow/red.
Action: General improvement of the vegetation condition, although stock access routes will be maintained. Perhaps some thought towards stock watering issues - although pointbars probably represent the best sites for on-channel watering.
Riparian width: Basic allowance (5 m).

Sub-reach D

Description: Steep eroding outside bend, 4 m high.
Stability: Continuing retreat of a steep bank face due to direct scour and slumping. A tall tree has been blown over in the past creating a point of localised erosion. Seepage through the bank appears to have assisted the tree loss by undermining the root system. Seepage remains a problem at the site.
*Vegetation:*Red.
Action: Farmer believes that the additional transpiration of a wide riparian zone may improve the seepage problem, thereby improving stability and

perhaps negating the need for structural intervention. After riparian planting, farmer will maintain watching brief and reassess the need for structure from time to time.
Riparian width: Basic plus height plus establishment allowance (5 + 4 + 15 = 24 m).

Sub-reach E

Description: Outside bend, 4 m high.
Stability: Eroding, but vegetation will reinforce against small slumps and reduce scour.
Vegetation: Red.
Action: Establish riparian zone.
Riparian width: Basic plus height plus establishment allowance (5 + 4 + 15 = 24 m).

Sub-reach F

Description: Pointbar, ~1 m high.
Stability: Essentially the same as Sub-reach C except in better condition.
Vegetation: Red.
Action: Revegetate and improve vegetation to green condition. The farmer has decided to extend this zone somewhat to build on the previous work of Sub-reach F and to match up with the wider requirement of Sub-reach E.
Riparian width: Extra plus basic plus height allowance (>5 + 1 = >6 m).

Sub-reach G

Description: Straight, 3 m high.
Stability: Stable. This is the farmer's best bit of frontage. Remnants, and additional plantings from some years ago, fenced and well established.
Vegetation: Green.
Action: Enjoy the view.
Riparian width: Basic plus height allowance (5 + 3 = 8 m).

The result of the above procedure is that the required riparian zone widths around the reach of river will vary from 5 m to about 24 m. The minimum riparian zone widths recommended here are intended for erosion control only. However, there may be many other good reasons to vegetate a wider riparian zone. It is also important to emphasise that this exercise will be much more useful if the landholder on the opposite side of the river adopts a similar methodology and revegetation occurs on both sides of the river.

The remaining sections provide background and supplementary material to the guidelines sketched out in this section. Much of the following material is also summarised in the Assessment Tables that are appended to the end of the document. It is important to emphasise that along with the many causes of bank erosion and the many different riparian species, there are many different sources of information. Often, material is locally based, incorporating valuable local knowledge that this document cannot provide. In Queensland, for example, QDNR have produced a series of river fact sheets that provide valuable information (available at http://www.dnr.qld.gov.au/fact_sheets/riverfacts.html). Other supporting information, that is directly relevant to Queensland streams can be found in publications such as O'Donnell (1998), or Kapitzke *et al*. (1998).

3 Riparian forest structure

The density and type of riparian vegetation cover strongly influence all aspects of riverbank erosion. Riparian forests are typically composed of overstorey, understorey, groundcover and macrophyte species. In some environments, some of the structural elements may be missing. This might occur in situations where for example stream velocities do not allow macrophyte establishment or where the groundcover is shaded out by the higher elements. The age and health of all plants also affect the stabilising effectiveness of any riparian forest. Structural elements are described here in terms of their bank stabilising attributes. We pass no comment on any ecological, biological, establishment or maintenance concerns.

3.1 Overstorey

The overstorey consists of emergent trees which, typically, grow to a height anywhere between 5 and 20 m (depending on species composition and local conditions). Tree-root networks are as variable as the above ground parts and are, thus, difficult to characterise. Most riparian species typically develop a central rootball or rootplate of dense roots that can usually be considered as half a sphere below the surface that has a diameter of about five times the diameter of the trunk. Root density declines rapidly beyond the rootball, with both lateral distance and with depth. For reinforcement purposes, there are usually few roots beyond the canopy dripline or below about 2 m under the bank surface. High water tables and/or heavy textured sediment affect the extent of the root network and give rise to shallow root systems as the roots grow laterally to avoid the saturated and/or hard material.

3.2 Understorey

The riparian understorey ranges from nothing, to a complex array of shrub species. For the purposes of bank stability, the shrubs of the understorey act the same as small trees. Generally, the understorey grows to a height of between 1 m and 5 m, with a rooting depth less than that of trees but still down to over a metre. As with trees, the lateral extent of the root mass is about that of the dripline and the root density quickly diminishes with depth and distance from the trunk.

3.3 Groundcover

Riparian groundcover is typically less than 1 m high. Groundcover species can include prostrate shrubs, grasses, sedges and forbs. Groundcover is usually quick to establish on a bank, but susceptible to trampling and other grazing pressures. Although the roots of grasses can be seen at depths of over a metre on exposed bank profiles, their reinforcement potential is negligible at depth. For the purposes of bank reinforcement, the maximum zone of influence of groundcover is probably constrained to about the top 30 cm. Regardless of the exact depth, the effective rooting depth of grasses will be fairly shallow and may vary between species and between sites. The main advantages of groundcover are that it densely covers the bank surface (except for vertical banks) and has a dense (if shallow) root mat. A disadvantage of many groundcovers is that they will not grow below the low-flow waterline.

3.4 Macrophytes

Emergent aquatic macrophytes, such as some sedges, rushes and reeds, are shallow-rooted species which grow at the margins of the mean water level. They readily colonise wet areas where terrestrial plants do not establish. Macrophytes will generally not survive for long periods of time in water that is more than 0.5 m deep. They flourish in conditions of low velocity (about 0.2 m/s) but will withstand the short periods of inundation and high velocity, which occur when the stream is in flood.

4 Riparian vegetation and streambank stability

Alluvial rivers change through time as the channel evolves naturally or responds to the morphological impacts of imposed management. The cause of local bank instability can be difficult to isolate and identify. Problems may result from a wide variety of geomorphological processes, some operating locally, others at reach scale, and some associated with catchment-wide adjustments to changes in hydrology or sediment yield. Regardless of the wider geomorphological context, the nature and extent of local bank erosion at some specific point along a riverbank are controlled by:

a) local discharge;
b) channel shape (cross-section and planform);
c) location of eroding bank section (*e.g.* inner or outer bank);
d) bank geometry;
e) bank geotechnical properties;
f) bank hydrological properties; and
g) vegetation.

With the exception of vegetation, each of the above factors are very much dependent on local conditions. However, generalised descriptions usefully identify the broad interactions of vegetation with each of the three erosion process groups: mass failure, fluvial scour and subaerial preparation.

4.1 Mass failure

Mass failures occur when whole blocks of material slide or topple from the bank into the water. The shape and extent of mass failures are a function of the geometry of the bank section, the physical properties of the bank material, and the type and density of vegetation. Trees, in particular, have been attributed a number of influences over slope processes (Gray and Leiser, 1982; Bache and MacAskill, 1984; Barker, 1986; Greenway, 1987; Coppin and Richards, 1990; Styczen and Morgan, 1995; Gray and Sotir, 1996). Reinforcement of the bank sediment by roots, transpiration and improved bank drainage all act to enhance the riverbank stability. On the other hand, windloading and the additional weight of riparian trees have often been implicated in the failure processes of bank sections within vegetated reaches. The destabilising effect of the weight, or surcharge, of trees is dependent on local bank geometry, bank geotechnical properties and the tree position. That all of the effects vary seasonally and with plant development makes it difficult to incorporate them into bank stability analyses.

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 and act in much the same way as steel reinforcement in concrete. Groundcover species do not generally contribute to the mass stability of banks because of their limited root depth.

The extent to which vegetation acts as reinforcement depends on a number of root properties. Probably the most important are the root tensile strength and root density. Root strength depends on the species, size, age, and condition of the root. Generally, smaller roots are the main contributors to additional soil strength because many small roots provide more effective reinforcement than one or two large ones. This can be thought of as following the same principle as ropes: many small fibres provide a much stronger structure that a single strand of like diameter.

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. Work overseas suggests that small roots of Northern Hemisphere species can increase cohesion by an average of 20%, although this can be up to 50% (Greenway, 1987; Coppin and Richards, 1990; Shields and Gray, 1992). Our work suggests that the effect of tree roots may be even greater than this, with perhaps up to a ten-fold increase in cohesion close to the trunks of riparian trees, falling to about a two-fold increase under the dripline. Longer and more firmly anchored roots provide greater reinforcement than do their shorter and loosely anchored counterparts. Mature trees thus provide more reinforcement than younger trees.

Roots also enhance bank stability by inhibiting the development of tension cracks (Thorne and Lewin, 1979). Tension cracks that run parallel to the riverbank are often observed on the surface before failure. The eventual failure surface will normally follow such cracks, and their position will indicate the approximate extent of any potential failure (Hemphill and Bramley, 1989). In cases where the potential depth of the tension crack is large in proportion to the total depth of the slope, the failure surface may be significantly affected by the tension crack.

Bank hydrology modification

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, transpiration, and increased drainage through the soil. Annual evaporation from eucalypt 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 within the soil.

Surcharge

The extra weight, or surcharge, of trees on a riverbank is often thought to encourage the banks to collapse. However, the location of trees on a bank will affect the degree to which they influence the balance of forces (Gray, 1995; Gray and Sotir, 1996). The surcharge of trees growing at the bottom of a bank prone to rotational failure mechanisms is likely to increase, not decrease, overall bank stability (Coppin and Richards, 1990). However, the weight of trees at the top of the same bank profile might destabilise the bank sections.

Trees are often restricted to the floodplain beyond the bank crest on actively eroding riverbanks, as they are not able to establish successfully on an actively eroding bank face. Tree surcharge on the top of the bank is especially pronounced when the trees lean over the channel as a result of growth asymmetry, grazing on the bankward side only, or wind loading (Thorne, 1990). However, our work on the Latrobe River (Abernethy, 1999) shows that the effect of tree surcharge on bank stability, even those that appear to be detrimental, is marginal.

Windloading

Styczen and Morgan (1995) demonstrated that the pressure exerted on a tree by wind can be transmitted to a bank as increased loading. This reduces the bank's resistance to failure. The transmission of the forces to the soil is by virtue of the root system with roots held in tension or compression. The stronger the soil and root-soil bond and the greater the root surface area, the larger the uprooting force that can be resisted (Coutts, 1983; Fitter and Ennos, 1989; Ennos, 1993).

4.2 Fluvial scour

Scour occurs when the force applied to a bank by flowing water exceeds the resistance of the bank surface to withstand those forces. Vegetation on the bank face reduces scour by directly strengthening the banks. Dense root mats protect the bank face with the finer roots particularly useful in holding the bank material together. The root mats of species such as She-oak (*Casuarina cunninghamiana*), Bottlebrushes (*Callistemon spp.*), Paperbarks (*Melaleuca spp.*) and Tea trees (*Leptospermum spp.*) have been found to be useful in this regard.

Vegetation also creates backwaters that slow flow against the bank face and weaken secondary circulation in bends (Thorne and Furbish, 1995). Slowing the flow against the bank greatly reduces the ability of the flow to scour bank material. 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 erosion. 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 (Kouwen, 1988).

Trees are not as effective as grasses and shrubs at retarding flow velocities near the bank when the flow is slow. At high velocities, however, the much stiffer trunks of trees are useful to retard the flow close to the bank. The Japanese Technology Research Centre for Riverfront Development (TRCRD, 1997) has conducted extensive research on many of the hydraulic aspects of riparian trees. They find that flow within stands of trees is markedly slower than flow against unprotected banks. However, for effective reductions in flow attack on the bank, planting densities where the crowns begin to intermesh are the minimum for hydraulic effect. Isolated clumps of trees on banks should also be avoided in revegetation strategies as they can act as hardpoints that can be outflanked by the flow in some circumstances.

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 absorb wave energy. A reed-bank 2 m 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*.

4.3 Subaerial preparation

Streambank segments exposed to air are subject to subaerial preparation from a variety of processes that are largely external to river processes. These include the effects of windthrown trees, piping, desiccation, rainsplash, rill erosion, and stock trampling which are all discussed below. Some directly cause erosion, while others render banks more susceptible to erosion. Subaerial processes are active on all exposed banks but are usually only apparent when scour and mass failure are limited. One way to see if subaerial processes are important on a given stream is to look at the erosion processes that are active on banks isolated from the main flow, such as cutoff meander bends or old abandoned channels.

Windthrow

Windthrown trees directly deliver sediment into the flow when their rootballs detach from the bank. The resultant debris dams often redirect flow against the bank and the scallops formed in the bank after the trees fall present ideal places for concentrated erosion. Windthrow problems are exacerbated when trees occur in a single line along the top of the bank; hence, a wide stand of trees is preferable in terms of their impact on bank stability (Thorne, 1990).

Piping

A common cause of bank undermining is seepage of water through the bank that leads to leaching and softening of the bank material or in extreme cases, pipe erosion (Hagerty, 1991). In some areas, irrigation may contribute to seepage as excess water drains towards the channel through the bank profile. Tension crack development can allow surface flows to drain into the bank, increasing seepage force and further reducing the stability of the affected bank (Simons and Li, 1982). The effects of vegetation on piping are both positive and negative. The casts left by dead roots may leave pathways for piping through the bank while evapotranspiration may delay or mitigate the onset of saturated flow within the bank.

Desiccation

Dry and cracking bank material is highly erodible. In fact, desiccation sometimes has a greater influence on erodibility than does the composition of the bank material itself (Knighton, 1973). Vegetation can reduce desiccation by binding bank material together, while shade from trees, grass and leaf litter reduce drying.

Rainsplash and rill erosion

During storms, rainsplash and rill erosion can detach material directly from a degraded bank and wash it into the channel. Well-established bank vegetation will reduce the rate of surface erosion by one to two orders of magnitude (Kirkby and Morgan, 1980). Thorne (1982) maintains that overland flow on well-vegetated banks can be ignored in determining bank stability over engineering time scales of 10 to 100 years.

Stock trampling

Livestock reduce the resistance of the riverbank to erosion by reducing the vegetation cover and exposing otherwise protected bank material. Trampling also directly breaks down banks, and transfers large quantities of bank material straight into the flow (Trimble and Mendel, 1995).

5 Assessment of existing riparian condition

The existence and extent of the riparian corridor is an important indicator of channel condition, sensitivity to change and management status. Knowledge of the existing vegetation assemblage on the floodplain and its influence on the present hydrological, hydraulic and sediment processes is useful for any assessment of the potential for instability induced by changes in vegetation, land use or floodplain management. The purpose of this section is to highlight factors that should be considered in any on-site assessment of riparian condition. The following discussion draws on various methodologies that have been developed around the country (*e.g.* Raine and Gardiner, 1995; Kapitzke *et al.*, 1998) and oversees (*e.g.* Thorne, 1998).

Because QDNR have already shown a preference for the Raine and Gardiner (1995) Rivercare methodology (River Fact Sheet R34) we will begin the discussion with reference to Raine and Gardiner's 'management style' approach. The 'yellow' vegetation condition is the minimum standard that could be expected to provide any stabilising influence to a riverbank. However, it is difficult (perhaps impossible at some sites) to establish riparian vegetation where the banks are actively eroding, i.e. the 'red' channel condition. At sites where the bank is actively eroding, assessment of the bank condition should consider alternatives for stabilisation. Alternatives might include: hard engineering options; wider riparian zones that include some leeway for future erosion while the plantation matures; a catchment-wide plan of river rehabilitation (*e.g.* Rutherfurd *et al.*, 1999); or a combination of approaches.

5.1 Reach assessment

To get the feel for the geomorphological characteristics of the problem, a wider view beyond the bank section at hand is required. Use should be made of stream condition surveys, undertaken by the local stream-management agency, where they exist. Where they do not exist, a field assessment of the channel planform, hydraulic geometry and erosion/deposition history of the river reach in the vicinity of the site should be conducted. This will assist in identifying current or future pressures on bank stability at the site.

The reach assessment provides context for a particular site in terms of a broader reach-length perspective. During assessment of the reach, assessors should try to get a feel for the form and processes that currently occur in the river. It should always be remembered, however, that all alluvial channel forms are transient and will continue to change. What you see today may not exist tomorrow. The following are about the minimum that should be considered during this part of the assessment.

a) Historical channel change
   - Look for bed degradation/aggradation (bridge piers provide good indicators).
   - Look at the channel planform - is it stable? (Air photos will indicate erosion extent and rate).

b) Stream hydrology
   - How big are the floods? When do they occur? How long do they last?
   - Do floods strip or deposit sediment from or onto the floodplain?

c) Channel hydraulics
   - Look for channel obstructions, particularly those that redirect flow against the banks.
   - Look for channel bars that concentrate flow (particularly those that are vegetated).

d) Channel form
   - Look at the bank shape around bends and along straights.
   - Measure the width and depth of the channel at various points to compare with your site.
   - Look for any incidence of erosion.
   - Pay particular attention to the size and shape of failures.
   - Look for undercutting or other evidence of scour (*e.g.* floodplain stripping).
   - Look for seepage through the bankface (particularly adjacent to irrigation).

5.2 Bank assessment

Following the broader reach investigation, attention should then be focussed on the bank section(s) where the work is planned. First, an assessment of the current bank condition should be made. This should include consideration of (at least) the following.

a) Rate of bank retreat (aerial photographs, if available, or some other means).

b) Bank geometry (*cf.* other bank sections in adjacent reaches).

c) Signs of bank slumping (failed material along the toe, tension cracks, steep or undercut profiles, bare patches of soil on the bank face).

d) Bank material (structure, stratification, strength, hydrology).

e) Desiccation cracks.

f) Windthrown trees.

g) Seepage through the bank face.

h) Stock tracks.

In those circumstances where the bank condition does not correspond to at least the yellow score overall, engineering strategies to remedy individual problems may need to be adopted in conjunction with revegetation. If the current bank condition relates to a yellow or better score, and the reach-length survey did not identify any future pressures, then it is probable that the planned revegetation can be established. Revegetation works should endeavour to make use of any native vegetation that is already growing at the site.

5.3 Vegetation assessment

The next part of the process is to assess the condition of the local riparian community. In general, the assess-ment is conducted by comparing the *in situ* vegetation with nearby remnant stands of riparian forest. The vegetation assessment should consider the following points.

a) Structure
  - Look for species in all of the structural elements typical of the bio-geographical region, *e.g.* in some regions groundcover may be missing due to overstorey shading.

b) Species
  - Look for species with extensive root networks.
  - Look for a diversity of species - this implies a mature state that is stable and well-established.

c) Density
  - Continuous covers of all structural elements are preferable for bank stability.

d) Location
  - Look for plants established near potential failure planes either near the bank toe or on the floodplain some distance back from the bank-crest.
  - Plants with deeper and more extensive root systems are better in these locations as the possibility of roots intersecting and strengthening potential failure planes is increased.

For those sites that score a green vegetation condition, no further planting is required. Sites with yellow or red vegetation scores require revegetation works.

6 Riparian plantation design

The main consideration when designing riparian revegetation works for bank stability is continuity of cover. Spacing the overstorey to allow development of an extensive and intermeshed root network will do much to stabilise the bank section. The information in this section relates specifically to stabilising banks against mass failure by planting deep-rooted trees. However, associated planting of understorey, groundcover and macrophyte species will assist in controlling erosion by other mechanisms and ensure the ongoing stability of the site. Understorey and groundcover elements tend to be more important in resisting subaerial processes as they provide protection much closer to the soil surface. For protection against fluvial scour, groundcover and macrophytes are important as they slow the flow close to the bank. It should also be remembered that plants cannot provide instant reinforcement: their stabilising properties will improve with age.

6.1 Background

The ideas presented below are based on the results of a physically based computer model of bank erosion processes and the effect on bank stability of tree root reinforcement. Further information on the model and its previous applications can be found in Abernethy and Rutherfurd (1999; subm.-a; subm.-b). The model has been successfully applied to and calibrated with bank conditions along the Latrobe River in Gippsland. We assessed the effect of vegetation on bank stability by analysing the tree root reinforcement of individual River Red Gums (*Eucalyptus camaldulensis*) and stands of Swamp Paperbark (*Melaleuca ericifolia*). The lateral position of the River Red Gum was allowed to vary while the Swamp Paperbark stands were maintained on the bank face - extending from the summer baseflow level over the bank-crest to about 1 m onto the floodplain.

Numerical modelling of bank stability requires detailed inputs of bank material strength properties, pore-water pressure distributions, channel drawdown conditions, bank geometry data and an assessment of the strength and distribution of root reinforcement throughout the bank profile. The level of detail required to fully parameterise our model is beyond the scope of the type of stability assessment required here. Hence, the following broad recommendations are the product of a generalised application of the results of detailed analyses conducted on the Latrobe River.

The size and type of any mass failures observed during the site assessment phase will indicate the extent of bank instability at the site. We found that planting trees at locations where potential failure planes were likely to intercept the profile surface provided the greatest resistance to failure. Failure planes typically intercept the profile surface somewhere near the toe of the bank and somewhere on the floodplain surface behind the bank crest. For example, the location of the failure plane of a deep-seated rotational failure on a 6 m high bank was some 5 m behind the bank crest on the Latrobe River. With no vegetation to reinforce this particular bank profile, our model predicted that the bank section was inherently unstable. The addition of a single mature River Red Gum, located at the failure plane on the floodplain, effectively stabilised the bank section (the factor of safety rose from 1 to 1.6).

Our modelling work indicated that many unstable degraded banks along the lower Latrobe River could be stabilised with vegetation. For the range of bank heights along the river, planting vegetation meant that the banks would have to become undercut before they failed. For example, our modelling showed that a 5 m high bank supporting no vegetation would fail when steepened to 70º by scour at the bank toe. However, further model simulations indicated that the same bank reinforced by mature tree roots would remain stable even when vertical. Undercutting was required to destabilise the bank.

Vegetated banks subject to bed-degradation without undercutting were stable up to some 2 m higher than vegetation-degraded bank sections. For example, a bare bank standing at 59º is stable until bed scour increases its height above 6.2 m. Reinforcing the bank with a mature root system improved stability such that with vegetation the bank is stable until its height exceeds 8.9 m. That there are no bank profiles on the lower Latrobe that are this high indicates the importance of undercutting and reinforcement by vegetation in controlling bank erosion along that river.

Table 2: Estimating the design establishment width of the riparian zone for a 40 m wide channel with differing maturation rates.

	Time for plantation maturity	
	Twenty years	Fifty years
Current erosion rate	0.5 m/year	0.5 m/year
Design establishment width	10 metres	25 metres
Estimated erosion rate	.016 x 40 = 0.64 m/year	.016 x 40 = 0.64 m/year
Design establishment width	13 metres	32 metres

6.2 Site considerations

The first step to consider is the environment in which a plant can or cannot thrive, for without ecological stability the mechanical advantages of the plantation cannot be assured. For final choice of species, reference should be made to published works or other local expertise. As a matter of course, plantations should mimic the natural lateral-zonation of species. Other aspects of vegetation/erosion interaction should also be considered in the final design. For example, a single line of trees established along the top of the bank could predispose some banks to failure induced by windthrow. Hence, planting wider riparian strips will not allow preferred lines of stress to develop in the bank.

Vegetation will not prevent all bank erosion from occurring. Even with an established and vigorous riparian forest, some bank adjustment will continue to occur. The riparian forest should be wide enough to allow some channel adjustment to take place without interrupting any agricultural activities occurring beyond the forest zone. Hence, the width of revegetation works must allow for the stabilisation of the present bank profile and for future bank adjustments.

Where the site assessment indicates that the bank is actively eroding, riparian zone design should allow for a period of maturation so that the reinforcing root networks of the dominant species may develop fully. In these circumstances, the riparian zone must be wide enough to allow the vegetation away from the bank line to mature by the time the erosion front reaches that point. If all of the vegetation is planted at the one time, the erosion front will meet progressively more established vegetation as it migrates back. The result will be a progressive decrease in the erosion rate. The width of this zone can be calculated as the time it takes the plantation to mature, multiplied by the erosion rate (Section 1.3). Immature plants do provide some erosion resistance that increases as the plants grow. This increasing resistance tends to slow the erosion rate as the bank-line moves through the aging plantation. However, for the guidelines to be generally applied into an unknown future we stress that the full allowance (based on contemporary erosion rates) should be adopted in plantation design.

As an example (see also Table 2), if a plantation matures in 20 years, and the bank erosion rate is 0.5 m/year, then a minimum of 10 m additional riparian zone width is required before vegetation can control erosion in the long-term. Note that bank migration rates of 3 m per year have been measured in cleared Queensland rivers (*e.g.* Russell River). If you do not know the erosion rate for a migrating outside bend, then a rough rule-of-thumb is 1.6% of channel width per year. This is the median value from an unpublished data-set of 100 rivers (Cooperative Research Centre for Catchment Hydrology). Thus, a 40 m wide meandering channel, in an environment where the maturation of vegetation takes 50 years, will need 32 m of additional riparian zone (0.64 m/yr for 50 years).

The bank material on which we based our original modelling was a relatively homogenous silty loam with moderately low strength values when compared to those of typical cohesive riverbanks. For banks formed in cohesive clays, the riparian width calculation is likely to be somewhat conservative because the strength of the bank material itself will support higher and steeper bank profiles. The plantation width may be similarly conservative for banks formed in non-cohesive materials. For these bank types, groundcover species on the bank face (and macrophytes at the bank toe) are likely to provide most of the direct protection. However, other plant types will continue to perform stabilising roles, such as modifying the bank hydrology to prevent high pore-water pressures.

The procedure outlined in Section 2 suggests a minimum width that can be generally applied. However, the results of our modelling on the Latrobe River suggest that individual trees even 15 m from the bank can still provide reinforcement to otherwise unstable bank sections. Hence, even trees at the margins of “over-wide” riparian strips will function as a bank stability agent. Even so, final design choices should be coloured by the results of the geomorphological, geotechnical, hydrological and hydraulic assessments of local conditions and the effect of these factors on bank overall bank stability. The bank geometry and the nature and rate of bank erosion (if any) will indicate any additional width, or special treatment, required and species make-up of the planned revegetation work.

7 Maintenance regimes

There is a growing body of locally based information on appropriate species for riparian planting and their maintenance requirements. Reference should be made to works such as the QDNR River Facts Sheets, O'Donnell (1998) or Kapitzke *et al.* (1998). Regardless of their final makeup, riparian revegetation schemes should consider the following construction and maintenance principles.

a) Consult local tree planting groups for advice on suitable species.
b) Determine availability of suitable local plant stock.
c) Ensure correct zonation of species and structural and floristic diversity.
d) Plant to allow vegetation to establish before seasonal flooding.
e) Plant in high density, if necessary, to maintain riparian zone integrity while immature.
f) Thin selectively or provide secondary planting (as necessary) as plantation matures.
g) Provide short-term stabilisation during early growth, as required.
h) Temporarily irrigate to establish plantation, as required.
i) Weed, as necessary (mulch is commonly used to provide initial weed control and reduce evaporation).
j) Fence and/or manage stock to preserve corridor continuity.
k) Follow suitable guidelines for planting.

8 Alternatives to vegetation

Where high levels of stability are required to protect infrastructure such as bridges or buildings, or where the erosion rate is such that riparian plants cannot be established, alternative schemes should be considered before deciding on a bank stabilisation program. Alternative schemes should always be evaluated against the guideline objectives. Kapitzke *et al.* (1998) detail a number of alternative treatments, some of which include:

a) rock revetment;
b) bank profile battering
c) groynes and retards; and
d) combination of either or some of the above with vegetation.

9 Bibliography

Abernethy, B., 1999. *On the Role of Woody Vegetation in Riverbank Stability*. PhD Thesis, Monash University, Melbourne.

Abernethy, B. and I.D. Rutherfurd, 1996. Vegetation and bank stability in relation to changing channel scale. In I.D. Rutherfurd and M. Walker (eds.), *Stream Management '96, Proceedings of the First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, Melbourne, 213-9.

Abernethy, B. and I.D. Rutherfurd, 1998a. Scale analysis of bank stability: targeting river reaches for riparian revegetation. In H.O. Hansen and B.L. Madsen (eds.), *River Restoration '96 - Session Lectures Proceedings. International Conference Arranged by the European Centre for River Restoration, 9-13 September, 1996, Silkeborg*. National Environmental Research Institute, Silkeborg, 50-6.

Abernethy, B. and I.D. Rutherfurd, 1998b. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology*, 23(1): 55-75.

Abernethy, B. and I.D. Rutherfurd, 1999. Riverbank reinforcement by riparian roots. In I.D. Rutherfurd and R. Bartley (eds.), *The Challenge of Rehabilitating Australian Streams, Proceedings of the Second Australian Stream Management Conference, Adelaide*. Cooperative Research Centre for Catchment Hydrology, Melbourne, 1-7.

Abernethy, B. and I.D. Rutherfurd, in press. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes*.

Abernethy, B. and I.D. Rutherfurd, subm.-b. The effect of riparian tree roots on riverbank stability. *Earth Surface Processes and Landforms*.

Alonso, C.V. and S.T. Combs, 1990. Streambank erosion due to bed degradation - a model concept. *Transactions of the American Society of Agricultural Engineers*, 33(4): 1239-48.

Bache, D.H. and I.A. MacAskill, 1984. *Vegetation in Civil and Landscape Engineering*. Granada Publishing, London.

Barker, D.H., 1986. Enhancement of slope stability by vegetation. *Ground Engineering*, 19(3): 11-5.

Bonham, A.J., 1980. *Bank Protection Using Emergent Plants Against Boatwash in Rivers and Canals*, Report IT206. Hydraulics Research Station, Wallingford.

Chang, H.H., 1988. *Fluvial Processes in River Engineering*. Wiley and Sons, New York.

Coppin, N.J. and I.G. Richards, 1990. *Use of Vegetation in Civil Engineering*. Construction Industry Research and Information Association / Butterworths, London.

Coutts, M.P., 1983. Root architecture and tree stability. *Plant and Soil*, 71: 171-88.

Cummins, K.W., 1993. Ecology of Riparian Zones. In S.E. Bunn, B.J. Pusey and P. Price (eds.), *Ecology and Management of Riparian Zones in Australia*. Land and Water Resources Research and Development Corporation, Occasional Paper No. 05/93, Canberra, 5-20.

Ennos, A.R., 1993. The scaling of root anchorage. *Journal of Theoretical Biology*, 161: 61-75.

Fitter, A.H. and A.R. Ennos, 1989. Architectural constraints to root system function. *Aspects of Applied Biology*, 22: 15-22.

Frankenberg, J., W.K. Tennant and W. Tilleard, 1996. Mechanisms of streambank erosion. In I.D. Rutherfurd and M. Walker (eds.), *Stream Management '96, Proceedings of the First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, Melbourne, 93-8.

Gray, D.H., 1995. Influence of vegetation on the stability of slopes. In D.H. Barker (ed.) *Vegetation and slopes: stabilisation, protection and ecology, University Museum, Oxford*. Telford, London, 2-25.

Gray, D.H. and A.T. Leiser, 1982. *Biotechnical Slope Protection and Erosion Control*. Van Nostrand Reinhold Company, New York.

Gray, D.H. and R.B. Sotir, 1996. *Biotechnical and Soil Bioengineering Slope Stabilisation: a Practical Guide for Erosion Control*. Wiley, New York.

Greenway, D.R., 1987. Vegetation and slope stability. In M.G. Anderson and K.S. Richards (eds.), *Slope Stability*. Wiley, Chichester, 187-230.

Greenwood, E.A.N., L. Klein, J.D. Beresford and G.D. Watson, 1985. Differences in annual evaporation between grazed pasture and *Eucalyptus* species in plantations on a saline farm catchment. *Journal of Hydrology*, 78: 261-78.

Hagerty, D.J., 1991. Piping/sapping erosion. I Basic considerations. *Journal of Hydraulic Engineering*, 117(8): 991-1008.

Hemphill, R.W. and M.E. Bramley, 1989. *Protection of River and Canal Banks, a Guide to Selection and Design*. CIRIA Water Engineering Report, Butterworths, London.

Kapitzke, I.R., R.G. Pearson, S.G. Smithers, M.R. Crees, L.B. Sands, S.D. Skull and A.J. Johnston, 1998. *Stream Stabilisation for Rehabilitation in North-East Queensland*. Land and Water Resources Research and Development Corporation, Occasional Paper 05/98, Canberra.

Karssies, L.E. and I.P. Prosser, 1999. *Guidelines for Riparian filter Strips for Queensland Irrigators*. CSIRO Land and Water Technical Report, 32/99. CSIRO, Canberra.

Kirkby, M.J. and R.P.C. Morgan, 1980. *Soil Erosion*. Wiley, Chichester.

Knighton, A.D., 1973. Riverbank erosion in relation to streamflow conditions, River Bollin-Dean, Cheshire. *East Midland Geographer*, 5: 416-26.

Kouwen, N., 1988. Field estimation of the biomechanical properties of grass. *Journal of Hydraulic Research*, 26(5): 559-68.

Little, W.C., C.R. Thorne and J.B. Murphey, 1982. Mass bank failure analysis of selected Yazoo Basin streams. *Transactions of the American Society of Agricultural Engineers*, 25: 1321-8.

O'Donnell, S., 1998. *Management of River and Creek Bank Plantings in Sub-tropical Coastal Riparian Rainforest*. Mary River Catchment Coordinating Committee, Gympie.

Pen, L.J., 1994. *Condition of the Kalgan River Foreshores 1992/93*. Draft Report to the Albany Waterways Management Authority, Oyster Harbour Catchment Group and the Department of Agriculture WA. Waterways Commission, Perth.

Raine, A.W. and J.N. Gardiner, 1995. *Rivercare: Guidelines for Ecologically Sustainable Management of Rivers and Riparian Vegetation*. Land and Water Resources Research and Development Corporation, Occasional Paper Series No. 03/95, Canberra.

Rutherfurd, I.D., K. Jerrie and N. Marsh, 1999. *A Rehabilitation Manual for Australian Streams*. On line: http://www.lwrrdc.gov.au/v1srm.htm, 1 September, 1999. Text and figures.

Shields, F.D. and D.H. Gray, 1992. Effects of woody vegetation on sandy levee integrity. *Water Resources Bulletin*, 28(6): 917-31.

Simons, D.B. and R.-M. Li, 1982. Bank erosion on regulated rivers. In R.D. Hey, J.C. Bathurst and C.R. Thorne (eds.), *Gravel-Bed Rivers: Fluvial Processes, Engineering and Management*. Wiley, Chichester, 717-47.

Styczen, M.E. and R.P.C. Morgan, 1995. Engineering properties of vegetation. In R.P.C. Morgan and R.J. Rickson (eds.), *Slope Stabilisation and Erosion Control: A Bioengineering Approach*. E & FN Spon, London, 5-58.

Technology Research Centre for Riverfront Development (ed.), 1997. *Proposed Guidelines on the Clearing and Planting of Trees in Rivers*. Sankaido Book Publishing Co. Ltd., Tokyo.

Thorne, C.R., 1982. Processes and mechanisms of riverbank erosion. In R.D. Hey, J.C. Bathurst and C.R. Thorne (eds.), *Gravel-Bed Rivers: Fluvial Processes, Engineering and Management*. Wiley, Chichester, 227-71.

Thorne, C.R., 1990. Effects of vegetation on riverbank erosion and stability. In J.B. Thornes (ed.), *Vegetation and Erosion*. Wiley, Chichester, 125-43.

Thorne, C.R., 1998. *Stream Reconnaissance Handbook*. Wiley, Chichester.

Thorne, C.R. and J. Lewin, 1979. Bank processes, bed material movement and planform development in a meandering river. In D.D. Rhodes and G.P. Williams (eds.), *Adjustments of the Fluvial System*. Kendall/Hunt, Dubuque, 117-37.

Thorne, S.D. and D.J. Furbish, 1995. Influences of course bank roughness on flow within a sharply curved river bend. *Geomorphology*, 12(3): 241-57.

Trimble, S.W. and A.C. Mendel, 1995. The cow as a geomorphic agent - a critical review. *Geomorphology*, 13: 233-53.

Appendix A: Assessment tables

Table A1: Catchment level assessment

Question	Evidence/information source	Planning outcome
How has landuse in the catchment altered?	Urbanisation, forestry, agriculture, irrigation, regulation, extraction	Changed catchment hydrology from altered landuse is generally reflected in channel adjustment. It may be that your site has yet to be affected by these adjustments but your plan should account for impacts such as a knick-point moving through the site, deepening the channel. Or weed infestation causing maintenance problems. The key is to be aware of current and potential pressures that may be the result of activities elsewhere in the catchment.
Has the flow regime changed?	Banks inundated longer, changed flood cycles, aggradation/ degradation	
Has the sediment load changed?	Floodplain stripping, overbank deposition, gully erosion, sand slugs	
Has the channel changed?	Channelisation, extraction, knick-point migration	
Are there any weed sources?	Weed infestations	
Are there other individuals or groups that can help?	Federal, State, Local Government Landcare, Greening Australia, etc. Catchment groups Neighbours	Don't try to reinvent the wheel. Look at all the available sources of information and use whatever is useful or appropriate for your site. Useful documents might include catchment management plans where they exist, or other LWMP's. You should also try to inspect other sites that have undergone stability works. Critically appraise them and adapt/adopt the successful ideas.

Table A2: Reach level assessment.

Question	Evidence/information source	Planning outcome
What is the catchment context of your site?	Catchment area, discharge, channel size	Expect dominant erosion processes to change with position in the catchment. As catchment area, discharge and channel size increase, the dominant erosion process will change from subaerial to scour to mass failure. The stabilising effect of vegetation will change with changing scale.
What is the channel form?	Channel form relies to some extent on position in the catchment	The object of this exercise is to assess the channel form around your site. With a clear picture of what the river looks like, you will be able to detect anomalies at your site. These may indicate specific problems that should be addressed. Be aware that outside banks naturally erode preferentially and that the width/ depth of bends and inflections will differ. Locally steep channel sections may be more prone to erosion. Remnant patches of riparian vegetation will help guide your choice of revegetation species.
Freedom to migrate?	Channel constrained by hillslopes or bedrock, or unconstrained by open floodplain	
Sinuosity?	Inspect planform from maps/air photos	
Width/depth?	Measure cross-sections in the field	
Gradient?	Measured channel length between contours on topographic maps	
Bed and bank material?	Field inspection – shear strength increases from gravel to sand to silt to clay	
Vegetation?	Assess condition of riparian vegetation – pay particular attention to native remnants	
What is the channel history?	Mainly applicable to floodplain reaches	The object of this exercise is again to provide a wider context for the pressures acting on your site. Knowing the pressures helps to predict the likely channel response and allows for appropriate planning. It is cheaper and more effective to be proactive rather than reactive.
Has the channel avulsed?	Look for billabongs on maps or on the ground	
Is there active meander migration?	Inspect sequential air photos	
Is the channel bed degrading, aggrading or stable?	Bridge piers can often be used to assess long-term bed movements	
Has channel been directly disturbed by human activities?	Extraction, meander cutoffs, snagging, riparian clearing, etc.	
Is there any incidence of erosion?	Only answered by field inspection	A critical evaluation of the nature, typical location and extent of all erosion processes operating throughout the reach will help your site evaluation enormously. Pay particular attention to other works in the reach and try to determine
What is the dominant erosion process?	Look for slump-blocks, undercutting, seepage on the bankface etc.	
Is it widespread?	Inspect the reach and note where the erosion occurs: outside banks, inflections, inside banks, or on vegetated bank sections	
Can it be controlled with vegetation?	Determine if vegetated sections are as prone to erosion as cleared sections.	
Has any stability work been undertaken?	Ask your neighbours. Contact your local Council. Go and inspect the sites.	

Table A3: Site level assessment.

Question	Evidence/information source	Planning outcome
What are the local channel influences?		Identifying local channel influences will highlight immediate potential for future instability. Some of these may present problems for establishing plants and will need to be treated prior to any other work.
Planform?	Bend, inflection, straight	
Width/depth	Compare with elsewhere in reach	
Hydraulic?	Bars, snags, tributaries	
Bed?	Bed material, bed control structures	
What is the bank form?	Compare with banks in similar positions along the reach	The current bank form will tell you much about the immediate short term stability of the bank. Look at the bank carefully.
Geometry?	Height, angle, shape (undercut, convex, concave)	
Material?	Cohesive clays, non-cohesive sands	
Bank margins?	Hillslope, floodplain	
What is the bank history?	Compare with reach assessment	The history of the bank along with knowledge of its present form will indicate much about the processes at work on the bank. Sometimes, banks that appear stable are seen to be actively eroding when their history is reviewed.
Stable?	No sign of erosion and air photos do not indicate retreat	
Steepening?	Progressive slumping leading to steep bare banks, concentrated scour at base of bank	
Heightening?	Local channel incision, compare with reach	
Parallel retreat?	May be hard to detect, examine air photos carefully	
What is the erosion process?		Correct identification of the type, extent, and magnitude of the active erosion process is paramount to successfully stabilising a riverbank with vegetation. Great care should be taken to assess all of the available evidence.
Mass failure?	Slump-blocks, tension cracks	
Fluvial scour?	Undercutting, scour around trees, slump-block removal	
Subaerial preparation?	Seepage on the bank face, dry and cracking bank material, fallen trees, rill development	
What is the riparian condition?	Compare with some benchmark – either remnant stands or seek expert advice	This is the starting point for your revegetation strategy. Take care to identify future pressures on the plants. If necessary, allow for season, recent floods and droughts etc. when you inspect the site.
Structural elements?	Compare existing elements with benchmark	
Species mix?	Identify useful/harmful species and identify species zonation	
Percent cover?	Estimate cover of all structural elements	
Pressures?	Pressures may be grazing, or weeds, etc.	
What is the landuse at the site?	Cropping, irrigation (flood, spray etc.), grazing, residential, shed, etc.	The landuse at the site may call for a modification to the design of the strip. Be sure to seek advice before ruling some species in and some out. Be aware that terrestrial activities as well as fluvial can affect the riparian zone.

Table A4: Intervention.

Question	Evidence/information source	Planning outcome
Do the assessments suggest that revegetation is required?	Cleared banks bare of any vegetation	If all the preceding assessments indicate that the site can be stabilised with vegetation care must be taken to ensure establishment. Pick your planting season, exclude stock and use appropriate species. Advice on planting techniques should always be sought if you have no experience. Allow for the appropriate width requirements of the plantation. Be aware that floods or droughts early in the life of the plantation might require additional maintenance.
Required width of plantation?	See Section 2	
Species?	Seek local advice, look at remnants	
Other considerations?	Fencing, mulch, access, etc.	
Do the assessments suggest that engineered options are required?	Widespread erosion, including vegetated sites	Vegetation will not stabilise all sites. Where the erosion process and rate do not allow for plantation establishment, seek alternatives. Experience throughout Australia and overseas suggests that many sites can be adequately protected with vegetation once the toe has been stabilised with engineered structure. The design of the structure will depend on the type and extent of the erosion and other local con-siderations. Wherever possible incorporate vegetation with structure. Seek advice.
Structure?	Cause of the erosion, discharge, flood frequency/magnitude, bank material, bank geometry	
Placement?	Cause of erosion, channel geometry, channel hydraulics	
Longevity?	Design life, erosion rate, hybrid designs	
What is the best design for longterm stability?		By this stage, you should be fairly clear on the final design. Weigh initial costs against on-going costs and account for the value of the asset you are protecting. Revegetation requires maintenance – plan for it. Good luck!
Cost?	Initial, ongoing	
Confidence?	Value of protection – land, other assets	
Maintenance?	Thinning, weeding, fencing, etc.	

Table A5: Reassessment.

Question	Evidence/information source	Planning outcome
Did you get it right?		Establish benchmarks against which different facets of the project can be assessed. These might include a known location to measure the bank crest against, or survival rate of trees, or number of curious visitors to the site. Keep a record of your practices, and how they may have changed during the project, so that others might learn from your experience. Photographs before, during and after plantation establishment provide an easy comparison.
Stability?	Measure against benchmarks	
Plantation survival?	Measure against benchmarks	
Structure survival?	Measure against benchmarks	
Are your neighbours impressed?	Measure against benchmarks	