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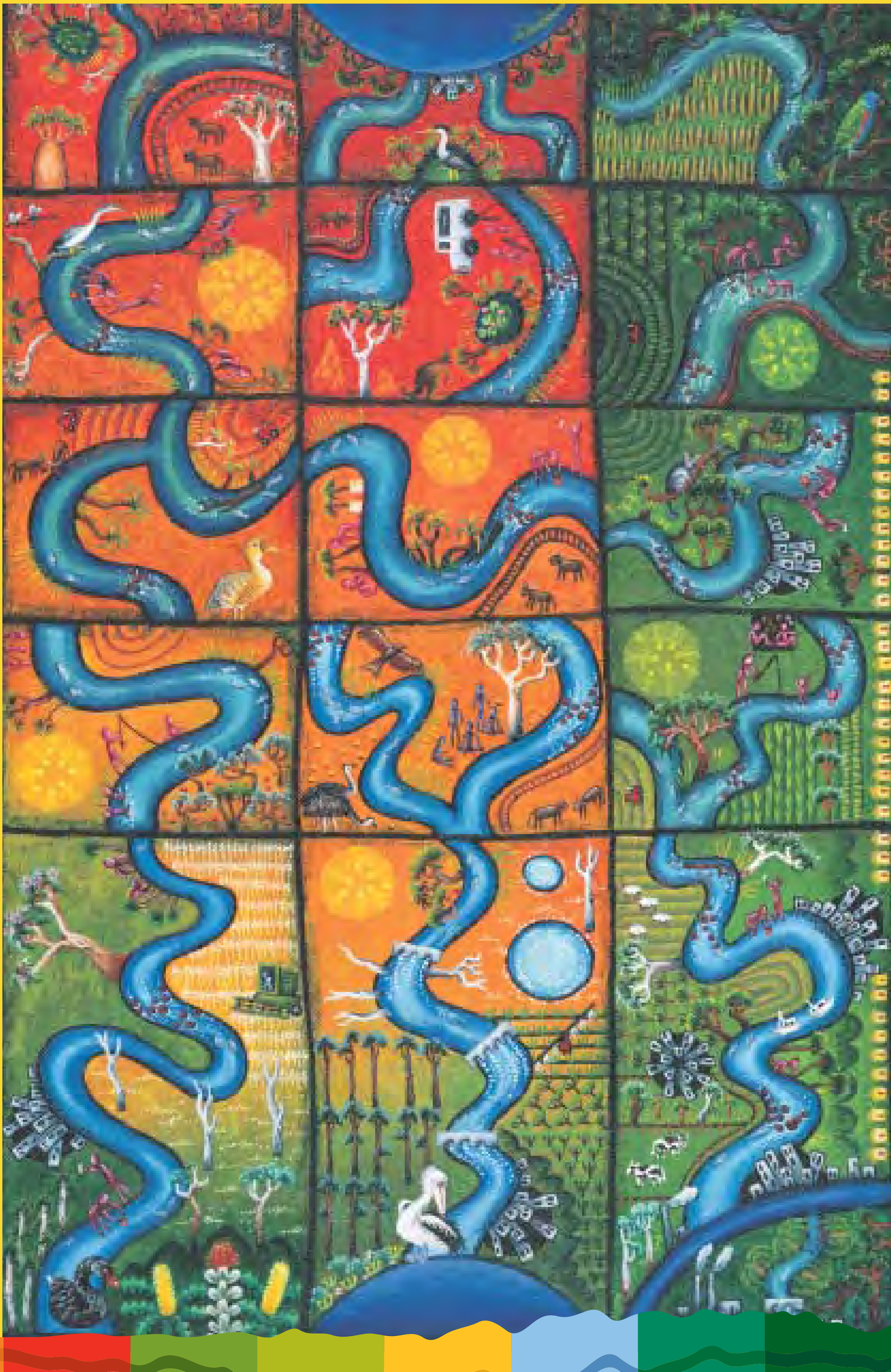
Principles for riparian lands management

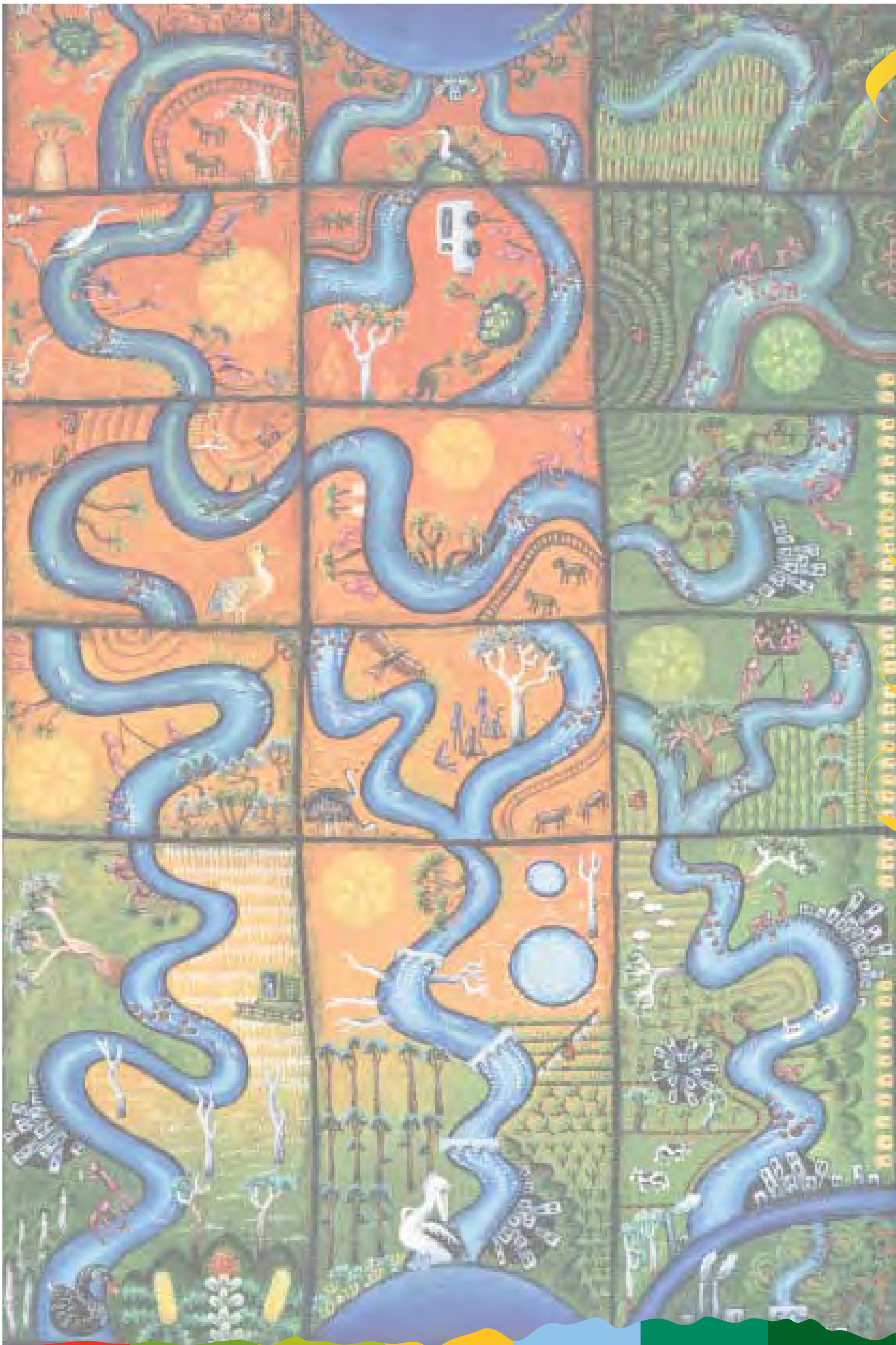


RiverLandscapes

Together...
we can restore, protect and enhance our river landscapes for present and future generations.

Principles for riparian lands management

Edited by Siwan Lovett and Phil Price



RiverLandscapes

Principles for riparian lands management

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Postal address: GPO Box 2182, Canberra ACT 2601

Office location: Level 1, The Phoenix, 86 Northbourne Avenue, Braddon ACT

Telephone: 02 6263 6000

Facsimile: 02 6263 6099

E-mail: Land&WaterAustralia@lwa.gov.au

Internet: www.lwa.gov.au

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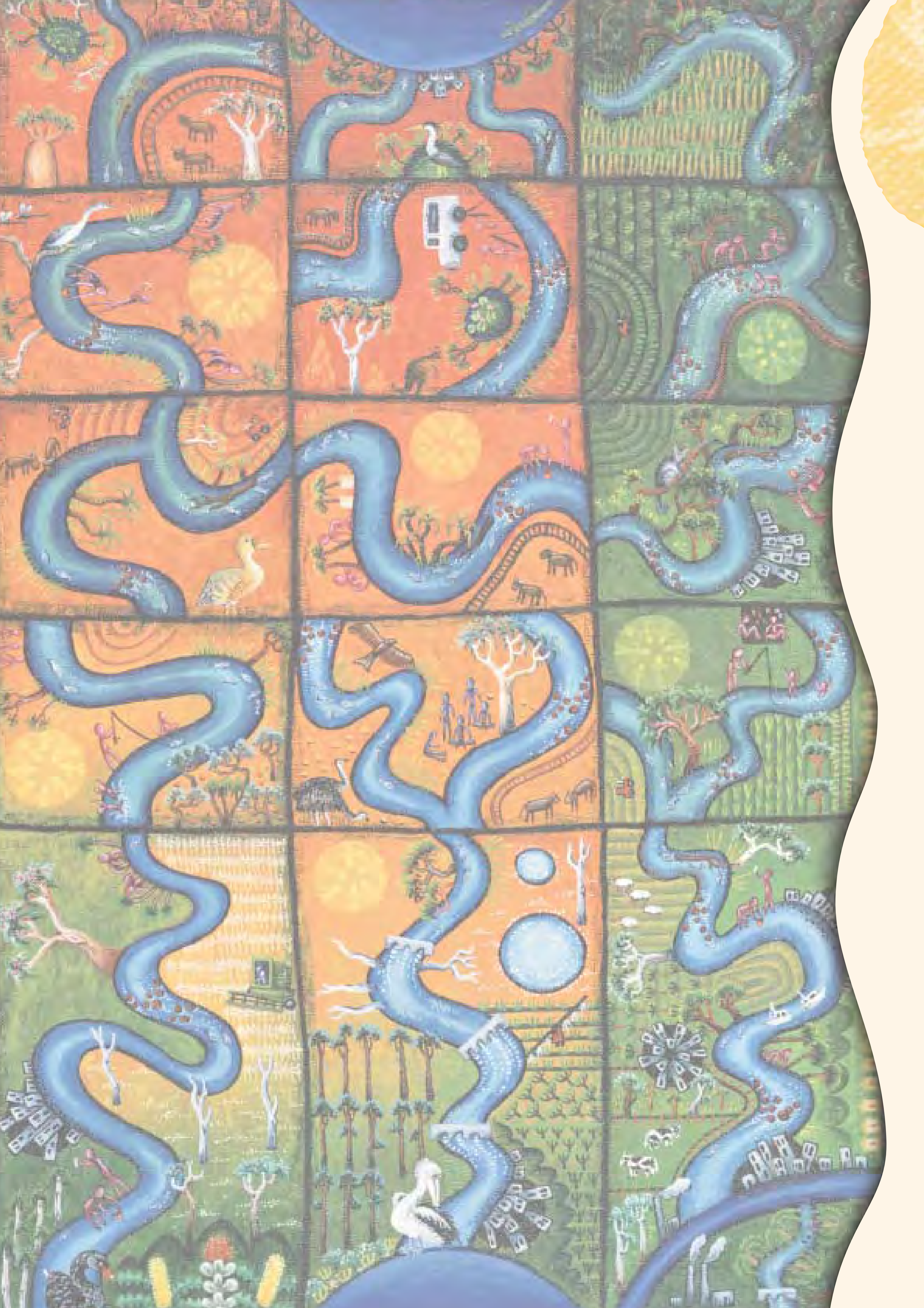


FOREWORD

In 1993, the Land & Water Australia Board (then the Land & Water Resources Research & Development Corporation) agreed to fund the National Riparian Lands R&D Program. This followed a study that showed although riparian zone processes were thought to be crucial for healthy rivers, there was very little published Australian data about these processes, or about how riparian land should be managed to maintain its key functions. Phase 1 of the Program ran for nearly seven years in total. It had three sub-programs, two based on scientific experimentation and one on practical application through a series of demonstration projects. Phase 1 had funding of $4.6 million from Land & Water Australia, $0.7 million from third parties (mainly state agencies) and $2.3 million from research organisations. It was guided by an advisory committee with representation from Commonwealth, state and territory agencies. This group played an important role in making sure the R&D responded to issues faced by river managers, and also in taking research results back into agency policy and programs. Phase 1 also started the strong communications effort that has characterised the entire Program, with a series of *River and Riparian Management Fact Sheets*, *River and Riparian Management Technical Guides*, and the *Riparian Land Management Technical Guidelines* (1999) which summarised both the scientific knowledge at the time and provided practical guidance in riparian management, as well as a summary of relevant legislation. These were complemented by the *RipRap* newsletter and establishment of the www.rivers.gov.au website.

Phase 1 provided for the first time a sound, scientific underpinning on which to base good riparian management. Land & Water Australia decided to fund a second phase of the Program to translate this research into management practices that could be used by agencies, rural industries, land holders and community groups. A series of workshops with agencies and industry bodies identified 11 management issues that have been the focus of work within Phase 2, which ran from 2000 until 2005, with a harvest year in 2006 to complete the synthesis and communication of new information. Funding for Phase 2 was $3.5 million from Land & Water Australia, $1.1 million from third parties, and $1.3 million from research organisations. The range of communication materials has been expanded and earlier editions updated, and several industry-specific guides on sound riparian management have been published through collaboration with the Sugar and Cotton R&D Corporations and Australian Wool Innovation.

This large, national investment, equivalent to $1 million per year over 13 years, has greatly increased the understanding and measurement of important riparian processes, enabling sound management practices to be developed and used with confidence. It has also been instrumental through its communication effort in lifting the profile of riparian and river management within rural communities and industries.

Principles for Riparian Lands Management reviews the science underpinning recommended management practices, and updates the *Riparian Land Management Technical Guidelines* published in 1999. The chapters are based on the main aspects of riparian land management, and summarise Australian R&D from within and beyond the National Riparian Lands R&D Program, as well as related findings from overseas. *Principles* has been developed to provide advisers and facilitators, state and territory agency, and local government staff, with information that will help them in working with groups and individual landholders to design and implement best-practice riparian management. The document is intended to have a national scope, but as Australia has a huge diversity of environments, it is not possible to be prescriptive about what to do in every region. The aim is to provide the science that will empower those with local knowledge to make appropriate local decisions.

The authors of the chapters are mainly the researchers who conducted the work, and we would like to acknowledge the immense contribution these people have made to the success of the National Riparian Lands R&D Program. We would also like to thank all those people across Australia who have been involved with our demonstration projects, used our products, contributed to our research and worked to protect and restore our riparian environments. It has been a pleasure and a privilege to work on the National Riparian Lands R&D Program and we hope *Principles for Riparian Lands Management* reflects the effort, insights and progress we have made together in better understanding and managing riparian lands across Australia.

Dr Siwan Lovett
Program Coordinator
National Riparian Lands R&D Program

Dr Phil Price
Technical Adviser
Mackellar Consulting Group Pty Ltd

CHAPTER 1

Structure and characteristics of riparian lands

Phil Price and Wendy Tubman[1]

Summary

~ Riparian land is defined here as 'any land which adjoins, directly influences, or is influenced by a body of water'. The body of water could be a creek or stream (even if it flows only occasionally), a river, a lake, or a wetland. There is no rule of nature that defines the 'width' of riparian land: the width of interest or concern is largely determined by the particular landscape and by management objectives.

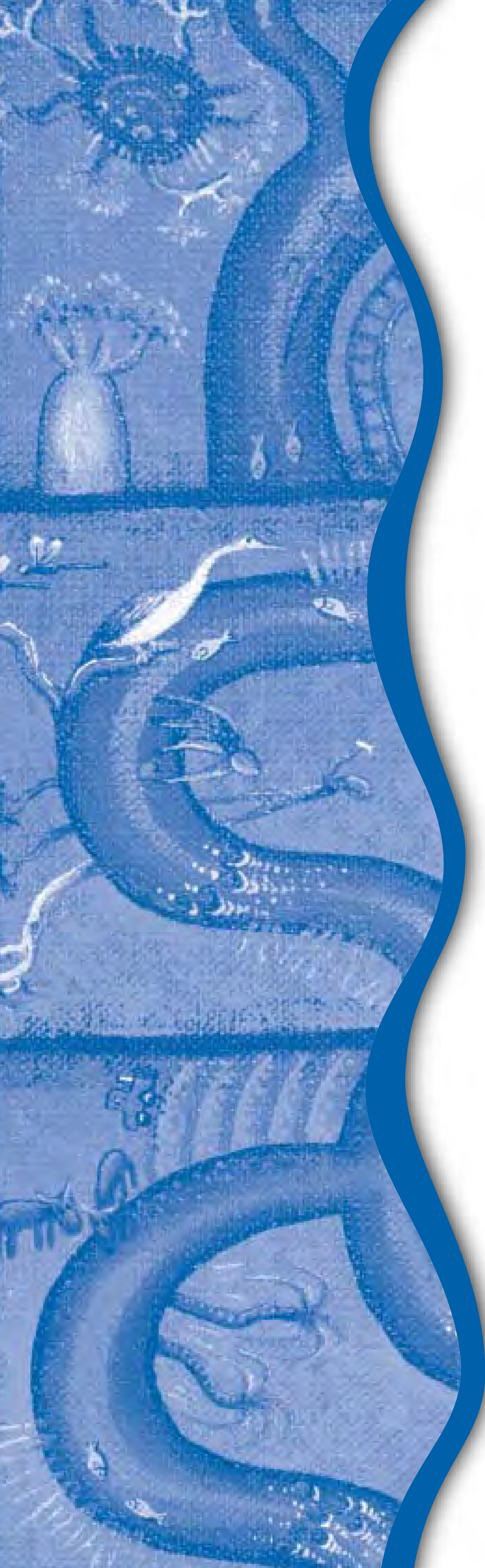
~ Riparian land is important because it is ecologically and economically productive.

~ Riparian land is vulnerable and is the 'last line of defence' for aquatic ecosystems against the impacts of land use elsewhere in the catchment.

~ Since European settlement, riparian land in Australia has been subjected to considerable degradation, much of which is associated with the clearing of native vegetation for agricultural or urban development, or with un-managed grazing by domestic stock or feral/native animals.

~ Fortunately, the importance of managing riparian land well is increasingly being recognised, and protection, rehabilitation and restoration work is being undertaken at local, regional, state and territory, and national levels.

1 Wendy Tubman was co-author of this chapter in the previous edition.



1.1 What is riparian land?

Riparian land can be defined in a number of ways — how it is defined in particular situations largely depends on why it is being defined. For example, for administrative or legal purposes riparian land has sometimes been defined as a fixed width alongside designated rivers and streams. For management purposes this definition is not very useful: in places, the band identified may be too narrow to include all the land influencing the stream; in other places, it may be wider than is necessary. It would clearly not be helpful to have the same riparian width designated for a small upland tributary as for the large, main stem of a river in its floodplain. Definitions based on land use are similarly of limited use for management purposes. This is because what the land is used for often pays little attention to protecting the natural processes fundamental to riparian land.

This publication aims to help people improve and protect the health of riparian land (including associated waterbodies). As a result, the definition used here is in terms of the roles — or functions — of such land.

Using the functional approach, riparian land is defined as:

> ‘any land which adjoins, directly influences, or is influenced by a body of water’.

With this definition, riparian land includes:

~ land immediately alongside small creeks and streams (even if they flow only occasionally), including the bank itself,

~ land alongside major rivers including the bank,

~ gullies and dips which sometimes run with surface water that finds its way into a nearby watercourse,

~ areas surrounding lakes, reservoirs, and large farm dams, and

~ wetlands on river floodplains which interact with the river in times of flood.

It is important to remember that there is no single law of nature that defines the width of riparian land or of buffer strips within riparian land, as the width is determined largely by the particular landscape and by management objectives. For example, the riparian width required to trap sediment from upslope may be a fraction of that required for wildlife habitat, yet both are legitimate objectives for riparian management. One of the aims of

Photo courtesy North Central Catchment Management Authority.

Photo Michael Douglas.

Photo Siwan Lovett.

Photo Alex Meehan.

Photo courtesy NSW Murray Wetlands Working Group.

For more information about managing riparian land to achieve different management objectives

'Managing riparian widths', *River and Riparian Management Fact Sheet*, no. 13, Price, P., Lovett, S. & Lovett, J. 2005.

'Managing riparian land to achieve multiple objectives', *RipRap*, edition 23, Lovett, S. (ed.) 2003.

Managing riparian land for multiple uses — Robins, L. (ed.) 2002.

As well as specific industry guidelines on managing riparian lands to achieve multiple objectives in the cotton, sugar and wool industries. All these publications are available on the www.rivers.gov.au website.

this publication is to help people make informed choices about the riparian widths appropriate to their particular situation and management objectives.

Because of the complex interactions between land and water in riparian areas, this publication deals with both the land around water bodies (riparian land) and the water itself.

1.2 The importance of riparian land

Productivity and vulnerability

Riparian land is important because it is often the most fertile and productive part of the landscape, in terms of both agricultural production and natural ecosystems. It often has deeper and better quality soils than the surrounding hill slopes due to past erosion and river deposition and, because of its position lower in the landscape, often retains moisture over a longer period.

Riparian land generally supports a higher diversity of plants and animals than the surrounding hillslopes. This is a result of its wide range of habitats and food types, its proximity to water, its less extreme microclimate and its ability to provide refuge. Many native plants are found only, or primarily, in riparian areas, and these areas are also essential to many animals for all or part of their lifecycle. Riparian land provides a refuge for native plants and animals in times of stress, such as drought or fire.

The photos at left show different types of riparian land.

Intact riparian area with natural processes functioning to provide terrestrial and in-stream habitat for a range of organisms. Photo Mike Wagg.

From an aquatic perspective, vegetation on riparian land regulates in-stream primary production through shading (reduced light and water temperature); supplies energy and nutrients (in the form of litter, fruits, terrestrial arthropods and other organic matter) essential to aquatic organisms; and provides essential aquatic habitat by way of large pieces of wood that fall into the stream and through root-protection of undercut banks.

In addition to being productive, riparian land is often a vulnerable part of the landscape — being at risk of damage from cultivation or over-grazing and from natural events such as floods. The combination of productivity and vulnerability means that careful management of riparian lands is vital for the conservation of Australia's unique biodiversity, as well as for sustainable agricultural productivity.

The interaction between land and water

There are many types of interaction between riparian land and adjacent waterways. For instance, a tree on riparian land may fall into a stream, creating new aquatic habitat; riparian land can 'buffer' streams against sediment and nutrients washing off agricultural land; and riparian land can be a source of leaf litter and insects that fall into a stream and become food for aquatic organisms. Operating in the other direction, insects which spend much of their life in the stream may become food for land-based animals when they emerge. The interactions between land and water are depicted in Figure 1.1.

The use and management of riparian land

The important linkages between land and water in riparian areas were not well recognised in the past by Australian land users or governments. There was a widespread belief that streams and rivers could be used as drains — removing problems from the adjacent land. However, it is now understood that rather than being seen as drains, waterways should be likened to arteries supporting the land around them. Similarly, because of its position, riparian land can be seen as a 'last line of defence' for aquatic ecosystems against potential negative effects from surrounding land use.

In recent years, in recognition of the significant benefits that can be achieved, many landholders, community groups and government agencies have become actively involved in improving the management of riparian lands. They have recognised the capacity of riparian land to:

- trap sediment, nutrients and other contaminants before they reach the waterway and reduce water quality for downstream users,
- lower water tables,
- reduce rates of bank erosion and loss of valuable land,
- control nuisance aquatic plants through shading,
- help ensure healthy stream ecosystems,
- provide a source of food and habitat for stream animals,
- provide an important location for conservation and movement of wildlife,

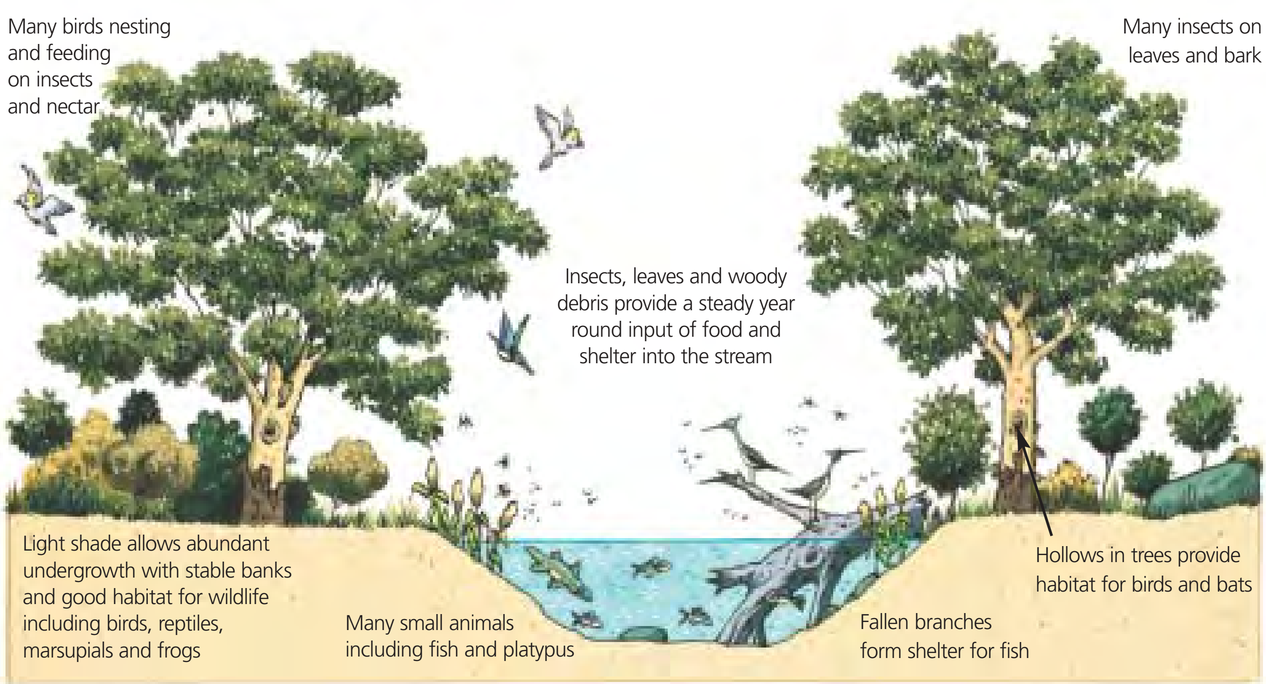


Figure 1.1. The benefits of native vegetation in riparian areas. **Below**: Significant effort is now going into rehabilitating riparian land. Illustration Paul Lennon. Photo Greening Australia.

~ help to maintain agricultural productivity and support mixed enterprises,
~ provide recreation and maintain aesthetically pleasing landscapes, and
~ provide cultural and spiritual enrichment for people.

The range of benefits provided by riparian land can be referred to as 'ecosystem services'. Ecosystem services are the benefits to humans that come from plants, animals and micro-organisms in nature interacting together as an ecological system, or 'ecosystem'. The functioning of natural ecosystems provides 'services' that are essential for human health and survival. Examples of the kinds of services we receive from nature are those listed above, as well as water filtration, maintenance of soil fertility, pollination and pest control. Despite providing these benefits, however, many of the ecosystems that deliver them in Australia are in decline. Riparian areas are particularly important because they are where land and water meet in the landscape and, as a result, support a diversity of terrestrial and in-stream ecological processes.

For more information on ecosystem services

'Riparian ecosystem services', *River and Riparian Management Fact Sheet*, no. 12, Lovett, S., Price, P. & Cork, S. 2004.

'What are ecosystem services', *RipRap*, edition 21, Lovett, S. (ed.) 2002.

Both publications are available at www.rivers.gov.au

Flood and fire are natural disturbances to riparian land, although their frequency may have changed since European settlement in Australia.
Photos: (left) Angus Emmott, (right) Tim Le Roy.

1.3 Degradation of riparian land

Because riparian land is a particularly dynamic part of the landscape, it can change markedly — even under natural conditions. Fires, unusually severe frosts, cyclones, and major floods, can all have huge impacts on riparian land and result in major changes to channel position, shape and associated riparian vegetation. Although relatively infrequent, these events can cause large changes to riparian land.

In contrast, human impact since European settlement has been at a lower intensity than these extreme natural events, but it has been continuous over time and has resulted in widespread and large-scale degradation of riparian areas. In southern Australia, the degradation has been largely as a result of the wide-scale removal or non-regeneration of riparian vegetation due to clearing and un-managed grazing of domestic stock. In northern Australia, feral animals and plants have also had a major impact on riparian areas.

The nature of the problem

The degradation of riparian land, especially in southern Australia, is often associated with the removal of vegetation for agricultural or urban development within a catchment. The major impacts of this are summarised below.

~ Removing riparian trees increases the amount of light and heat reaching waterways. This favours the growth of nuisance algae and weeds.

~ Clearing native riparian plants removes the natural source of leaves, twigs, fruit and insects that underpins the aquatic food web.

~ Under natural conditions, trees would occasionally fall into the river, and the large woody pieces provide important habitat for aquatic organisms. Removing riparian vegetation takes away the source of large branches and trunks and disrupts aquatic ecosystems.

~ Continuing agriculture to the top of stream banks by cropping or unrestricted stock access increases the delivery of sediments and nutrients to streams. Large volumes of fine-grained sediment smother aquatic habitat, while increased nutrients stimulate weed and algal growth. Increased nutrient load also affects estuaries and marine life beyond the river mouth.

~ Removing riparian vegetation destabilises stream banks, often resulting in massive increases in channel width, channel incision and gully erosion. This erosion of the channels often delivers more sediment to streams than does human activity on the surrounding land.

~ Removing vegetation along channels, and of large wood in channels, can allow water to travel downstream at a faster rate, sometimes contributing to increased flooding and erosion of lowlands.

~ Removing vegetation throughout the catchment can lead to raised water tables and salinisation of land which, as salt-saturated water drains into rivers and streams, ultimately results in saline waterways.

Examples of factors other than clearing that also degrade riparian land. Photos: (top left) Siwan Lovett, (top right) Jenny O'Sullivan, (bottom left) Gary Caitcheon, (bottom right) Lizzie Pope.

However, removal of native vegetation is not the only human impact that adversely affects riparian land, other impacts include:

~ altering water regimes (through the construction of dams and weirs, and from pumping) that can severely affect aquatic populations and the capacity of the waterways to carry flow,
~ removing sand and gravel and straightening channels can result in channel incision and head cutting, which in turn influence bank height and shape and lead to increased erosion rates,
~ uncontrolled access of stock can lead to over-grazing and trampling of vegetation, breakdown of soil structure and contamination of the water with nutrient-rich urine and faeces,
~ altering fire regimes and invasion by exotic weeds can further degrade riparian land.

It is important to recognise that the impacts of these disturbances are not just cumulative; they often exacerbate each other. For example, clearing riparian vegetation from upland streams multiplies, many times, the impact of increased nutrients from surrounding land use. This is because clearing also results in extra light and higher water temperatures, conditions needed to enable nuisance weeds and algae to flourish and dominate the aquatic ecosystem.

The National Land and Water Resources Audit publication *Catchment, River and Estuary Condition in Australia* (2002) lists the following as key management actions required to improve the condition of rivers and wetlands:

~ protective management of good condition riparian lands and wetlands,
~ revegetation of disturbed riparian lands,
~ reduction in the barriers to fish passage,
~ rehabilitation and re-establishment of wetlands, and
~ provision of environmental flows.

Publication available at www.nlwra.gov.au

These images show the changes that have occurred along the riverbank as a result of stock exclusion. In the photo at right, the bank is now stable, water quality has improved, and the riparian vegetation is regenerating. Photos Bruce Mundy.

The extent of the problem

The following statistics, drawn from the National Land and Water Resources Audit 1997–2002 and earlier State of the Environment reports, give some indication of the magnitude of the land and water degradation problem in Australia. As riparian land is often the 'last line of defence' in protecting waterways and water quality, problems arising elsewhere in a region or catchment usually affect riparian land.

~ It is estimated that since European settlement, about 40% of all native tree cover (an area over one and a half times the size of Tasmania) has been completely removed, and a further 35% of all native tree cover has been subjected to harvesting — this includes past clearing and harvesting adjacent to waterways, (there are now regulations and codes of practice in most states to govern such activity).

~ Out of the 14,500 river reaches assessed for the Audit, about one quarter were found to be extensively modified and extremely impaired in comparison with reference (natural) reaches, a further 50% were either severely or moderately affected, and only around 25% were largely unmodified and found to be in natural condition. In the Northern Territory, around two thirds of total river length assessed was largely unmodified, while in all other states and the Australian Capital Territory, except for Tasmania, 80% of the total river length assessed was substantially or moderately modified from natural condition. The Audit identified loss of native riparian vegetation as a major driver of river degradation.

~ The Audit found that there was a strong relationship between loss of natural condition and ecological impairment, and the intensity of catchment development — catchments and waterways in poorer condition form a crescent running from Western Australia through the southern states and into Queensland, all areas with a history of high intensity land uses. The catchments in better condition lie in Tasmania, the Northern Territory and northern Queensland.

~ The Audit showed that rivers with the most degraded reaches are located in the Murray-Darling Basin, the Western Australian wheatbelt, western Victoria, and South Australian agricultural regions. These

Examples of severely degraded riparian lands and waterways. Photos: (top left) Samantha Burt, (top right) Nicky Taws, (bottom left) Gary Caitcheon, (bottom right) Peter Davies.




reaches generally have highly modified (developed) catchments, are subject to high loads of suspended sediment and nutrients, have lost much of their riparian vegetation, and have dams and levees that disrupt natural water flow and the movement of material and biota into and from the river.

~ Drainage in South Australia has reduced that state's wetlands to 11% of their former area.

~ Estuaries have generally fared better than fresh-water bodies. Of the 980 estuaries and coastal waterways assessed by the Audit, three quarters were either in near pristine condition or largely unmodified, while about 20% were in modified condition and 10% extensively modified.

The State of Environment reports provides numerous examples of research which has shown the extent of degradation of Australia's waterways. For example:

~ of New South Wales lakes, 38% were degraded by nutrient enrichment and only 18% were considered to be in a 'good' ecological condition (Timms 1992);

~ of 27 Victorian river basins, only 44% had more than half of their stream length in an excellent or good environmental category (Mitchell 1992).

Some of the other impacts of catchment development and changed land use are demonstrated in the following statistics.

~ Soil and water degradation is estimated to cost Australia about $2 billion each year, made up of potential agricultural production foregone, the costs of rehabilitating degraded land, repairing effects on infrastructure (for example the effects of rising salinity on roads, houses and underground services), and in direct treatment costs (for example, to treat poor quality water to the standard required required for human consumption).

~ Around 14 billion tonnes of Australian soil are moved by sheet and rill erosion each year — representing about 19% of global soil movement. Much of this finds its way into water bodies, mainly through hillslope erosion in the north, and through erosion of gullies and river banks in the south.

~ Of the approximately 1900 plants introduced since European settlement, 220 are now declared noxious weeds, and weed control costs about $3.3 billion annually. Many of these weeds have infested riparian areas, where control will be difficult and expensive.

Some of the consequences of allowing riparian land to degrade. Photos: (top left) Phil Price, (top right) Angus Emmott, (bottom left) Roger Charlton, (bottom right) Phil Price.

1.4 Improving riparian management

Catchment and landcare groups, as well as individual landholders, are recognising that many of the recent and current management practices employed on riparian lands (practices often derived from very different northern hemisphere environments) are unsustainable. Fortunately, it is also being recognised that often environmental and agricultural objectives can be achieved simultaneously. Research has established that those land-use practices and techniques that are attuned to prevailing environmental characteristics are more sustainable in the long term, and with careful planning at the whole-property level they can be more profitable as well. As a result, increasing attention is now being paid by individuals, community groups, rural industries and governments at all levels to halting and reversing the processes of degradation which these practices have caused and, in many places, are continuing to cause. For example, promoting natural regeneration and active revegetation are now widely accepted as cheap and effective means of erosion control and bank stabilisation in many situations. Native species are seen as more appropriate than exotic species such as willows. The distinctive riparian vegetation is being recognised as an important ecosystem, itself worthy of preservation and significant as a wildlife corridor. Healthy riparian land is being recognised for the key role it plays in aesthetic appreciation of the landscape. Some actions have been taken by individual landholders, but in many cases it is more effective for neighbours to work together, in collaboration with local and state governments, to achieve improved management along a waterway reach that may be 10 to 30 kilometres long.

Sound riparian management is not a substitute for good land management elsewhere in the catchment. Rather, it should be seen as one part, albeit a very important part, of sound management throughout the property or catchment. Even the best management of riparian lands will not overcome management practices elsewhere that lead to excessive soil erosion, or off-site loss of nutrients or other contaminants. This publication is intended to help practitioners understand the scientific principles that underpin sound management of riparian land. Although not exhaustive, the chapters bring together a wide range of information and research results to describe the crucial riparian processes that are important in Australia.

The material in this volume concentrates on specific natural processes that dictate how riparian areas 'work' and which need to be taken into account if management decisions are to be informed and responsible. Guidelines to assist in diagnosis of problems and determining the best management response, have been published separately by Land & Water Australia as a series of River and Riparian Technical Guidelines. These are listed at the end of this document, together with information about how to obtain them.

Landholders, community groups and agencies are leading efforts to rehabilitate riparian land. Photos: (top left) courtesy Greening Australia ACT & SE NSW, (top right) Rae Glazik, (bottom left) Lizzie Pope, (bottom right) Phil Price.

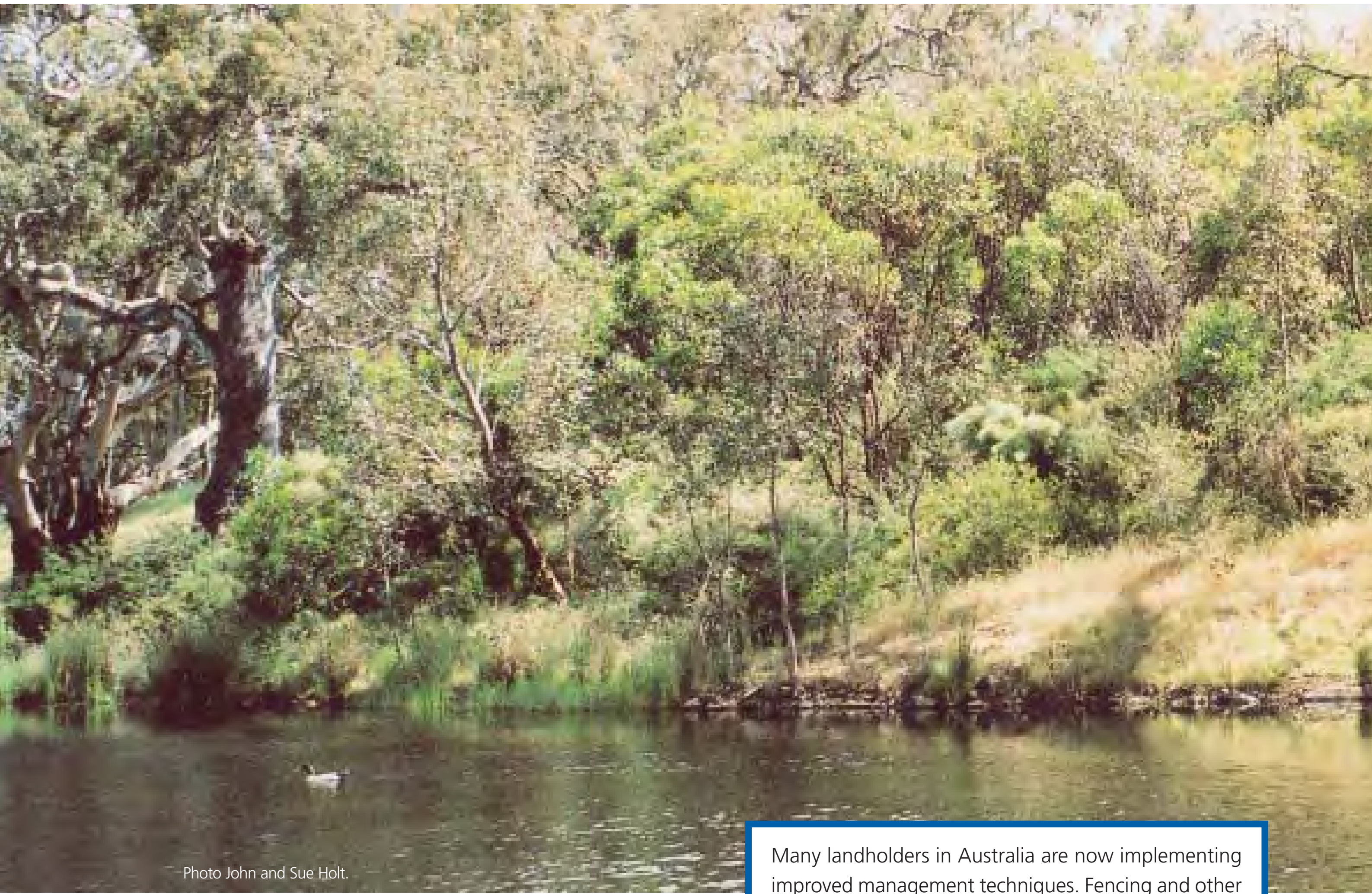


Photo John and Sue Holt.

Above: Riparian land in excellent condition. Below: A riparian area fenced to control access by stock. Bottom: Off-stream watering will discourage stock from using riparian areas.

Photo Mike Wagg.

Photo Roger Charlton.

Many landholders in Australia are now implementing improved management techniques. Fencing and other methods used to control and manage the access of stock to riparian areas are a high priority in many parts of the country. Landholders are reporting that the cost of fencing and off-stream watering can be more than recouped over time because, for example, fenced riparian land can be used for growing higher value crops, because grazing can be managed to improve pasture composition and production, or because the health and productivity of animals grazed there is improved due to reduced disease transmission and improved water quality. In recognition of the fact that improved riparian management provides public as well as private benefits, there are now many forms of community and government support available to help defray the cost of durable riparian fencing.

For information contact your local Department of Agriculture, Department of Natural Resources, or local catchment management agency.

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Mitchell, P. 1990, cited in State of the Environment Advisory Council 1996, *Australia: State of the environment 1996*, CSIRO Publishing, Melbourne, pp. 7–27.

Timms, B.V. 1990, cited in State of the Environment Advisory Council 1996, *Australia: State of the environment 1996*, CSIRO Publishing, Melbourne, pp. 7–26.

Australia's Natural Resources 1997–2002 and beyond, and related reports, 2002, National Land and Water Resources Audit, Canberra.

CHAPTER 10

Monitoring and evaluation in riparian land management

Phil Price

Summary

~ Monitoring and evaluation (M&E) should be seen as an integral part of any riparian management project.

~ M&E at a project or output level is straightforward, and methods for this are well developed. M&E at the outcome level, to determine whether, and the extent to which the project has met its objectives, is a more complex proposition and is likely to be expensive to undertake properly.

~ Effective evaluation requires consideration of the scale and frequency of measurement, and potential difficulties of separating treatment effects from natural variability. Statistical comparison with control or reference sites is the preferred approach, but is not always possible. A before-and-after (BACI) approach requires adequate baseline data before treatments are imposed.

~ Selection of indicators for monitoring programs should reflect the questions being asked in the evaluation, and the level of accuracy and precision therefore necessary.

~ Methods for the rapid appraisal of riparian condition have been developed to meet the increasing need to assess whether riparian management is being effective, and to further adapt it if not.

10.1 The importance of monitoring and evaluation

Monitoring and evaluation (M&E) should be considered as integral components of any riparian land management project or program (Ladsen et al. 1999), and be funded and resourced accordingly. It is often claimed that 'you cannot manage it if you cannot measure it', and it is certainly difficult to be confident that management is effective if there is no supporting evidence. As well as helping to show whether management is achieving its objectives, M&E also provides a basis for adaptive management and continued improvement, and can assist in identifying priorities when resources are limited.

Despite this, the history of natural resource management in Australia (including river and riparian management) has involved little or no effective M&E activity, even for programs that involve the expenditure of substantial public funds (Australian National Audit Office 2001). Much overseas experience is similar (for example Lovett 2004), although there are also a few examples of well-developed M&E programs (United States Department of Agriculture 2001). M&E activities can be long-term and expensive, and should be designed to be commensurate with the scope and scale of the riparian management itself. There are also pitfalls to be avoided as described below. Despite these caveats, there is much to be gained for existing and future riparian land management work by including M&E as an integral component.

M&E programs should meet several essential criteria if they are to be successful and justify the resources committed to them. They must have a defined purpose and clear objectives, otherwise it will be difficult to decide what data should be collected and how often over what period. There should be an effective link between the program and the decisions it is to influence, for example

Using transects and quadrats to monitor regeneration of riparian vegetation. Photo Michael Askey-Doran.

through public reporting of the results and presentation to users. The design of the program must have the potential to detect changes and differences at the spatial and temporal scales anticipated. The attributes to be measured must reflect the outputs and outcomes to be achieved by the project, preferably linked via a conceptual model of riparian zone functions. There should be consistent and reliable protocols for measurement. Finally, the program must be funded adequately as there is little to be gained from ineffective M&E.

Before proceeding we must distinguish monitoring, which is the collection of information to demonstrate continuity or change (for example following treatment or over time), from evaluation, which is the assessment of whether aims, objectives or preferences are being achieved. The purpose of the evaluation will, in general, guide the type of monitoring required, and is therefore discussed first.

10.2 Evaluation

Riparian management projects, including on-ground works, can be evaluated at two levels. The first is what might be called project or **output** evaluation. This type of evaluation is used to show whether the project is following its agreed (or contracted) schedule, whether key stages (milestones) have been completed, and whether it is delivering or has delivered its outputs (specified products or services). This follows the standard form of project evaluation, primarily for purposes of accountability and reporting. There is a large literature available about how to undertake this type of evaluation and what sort of things to measure and record (what to monitor). This could include the reporting of achievement of process milestones by the required dates (e.g. appointment of staff, completion of fencing or replanting), the time taken or funds expended to reach these stages in the project, the delivery of outputs (e.g. length of fencing erected, number of trees planted, number of landholders engaged in the project), or some comparison (benchmarking) with equivalent projects. Projects can also be evaluated in this way for the extent to which they have met broader program goals.

This type of evaluation is straightforward, and should be considered as part of the minimum requirements for good project management. However, it tells us little about whether the project achieved its purpose and wider objectives, i.e. the **outcomes** sought. To do this requires a different approach to evaluation, one that is capable of measuring over time whether the required changes in condition (e.g. less bank erosion, lowered water temperature, increased in-stream habitat) have been achieved, and, just as importantly, whether they are the result of the project and the work undertaken. This type of evaluation is more complex and difficult, and as a result is rarely undertaken. Its difficulties include:

~ **Timescale**. The primary outcome sought from many riparian management projects is some change in physical, chemical or biological condition of a riparian area and/or of the stream. This may take many years to become apparent, even to fine-scale monitoring. For example, replanting an eroding streambank (even if it is the correct response) will require time for new plants to grow and extend their root system, and if the original bank erosion was due to infrequent flood events, it could be many years before treatment effects can be demonstrated with confidence, even with careful longitudinal and cross–section surveys. This timescale is well beyond the funding cycle of riparian projects (generally three years at most), and would require some form of long-term periodic monitoring to be maintained.

The area fenced and replanted or number of trees established could be used in output valuation of this project in Tasmania. Photo Michael Askey-Doran.

- **Spatial scale**. Many outcomes (e.g. improved water quality, increased fish numbers) relate to factors that integrate riparian management over large areas, often the entire upstream network. A localised project could therefore be successful in dealing with some aspects of local condition, but have little or no effect on broader objectives. Spatial scale must be considered in designing both the project itself and for the effective monitoring of treatment effects.
- **Signal to noise ratio**. Given the large climate variability found over much of Australia, it can be difficult to distinguish treatment effects from the (often much larger) effects of climate mediated through rainfall, seasonal conditions for plant growth or animal breeding, flood, frost, or fire. This must be considered when designing the spatial and temporal scales for a monitoring program.
- **Frequency of measurement**. Several of the indicators that might be measured to demonstrate the effectiveness of riparian management (e.g. sediment and nutrient loads and concentrations) are driven by infrequent events, mainly related to flood flows. To be able to evaluate project effects on these attributes, it will be vital to capture information during the short period of such events, and this has implications for the type and expense of the monitoring system required.
- **Lack of baseline data**. Although some baseline data about streams and riparian areas can be captured from historical sources (maps, aerial photographs and stored satellite images), the general lack of detailed condition data means that for most projects there will be at best only a short period of 'before treatment' data that can be used for later comparison. This problem is compounded by the spatial and frequency issues listed above, and by the short timescale available for most riparian projects. Even with adequate post-treatment monitoring, it is difficult to draw firm conclusions in the absence of an adequate set of 'before' data, except in the rare case where there are control (matched and untreated) sites available.
- **Multiple variables**. In most riparian projects there are a mix of treatments aimed at addressing several identified problems at the same time, for example fencing to control stock access, replanting with native plant species, inclusion of trees to shade the stream, and possibly some reinforcing of the toe of the bank. It is then difficult to be sure about which of these treatment components is the cause of particular effects detected in the future.

These problems, and others outlined in Rutherfurd, Ladson and Stewardson (2004), help to explain the paucity of good evaluations of riparian management projects. The size of many projects would not warrant the expense of effective evaluation, but without such assessments it will be difficult to learn from past successes and failures in order to improve the effectiveness and efficiency of future projects. Evaluation, and the associated monitoring, must be incorporated into project design; it is rarely possible to return to past riparian projects and assess their success in achieving outcomes, for the reasons described by Rutherfurd, Ladson and Stewardson (2004).

One means of helping to overcome this apparent impasse would be to identify a small number of indicators of riparian condition (including surrogate indicators) that can be assessed easily and cheaply. These may not be suitable for all components of riparian management, but they can demonstrate at least the trend of changes following treatment, and they may be suitable for repeated assessment by non-technical people who have completed a short period of training. They may also enable some level of statistical analysis of the monitoring data to test for operator error and repeatability. Two examples, developed within the Riparian Lands Research and Development Program are listed later in this chapter.

Measuring change in ecosystem function (here, in-stream production and respiration) before and after rehabilitation can provide evidence about whether project objectives have been met. Photos Peter Davies.

10.3 Monitoring

Monitoring for project or 'output' evaluation of riparian management is fairly straightforward and can be based on published methods for project accountability and reporting. This discussion is more concerned with monitoring, that is the collection and analysis of information, which will enable an 'outcomes' evaluation to be undertaken.

The first question is "what type of monitoring system will best provide the data required?". The main requirement is to be able to detect change from the baseline condition, and to separate project or treatment effects from those due to natural spatial and temporal variability (Parr et al. 2003). It may be difficult to identify 'natural condition' if all local riparian areas have been affected to some extent by human disturbance. The effects of past changes (natural or human) may also be working through the system so that riparian zones are in transition rather than some stable equilibrium state.

Information (mainly field data) could be collected to demonstrate change over time, change from the base condition prior to treatment, change in relation to untreated control sites or to adjacent reference of 'natural condition' sites. Each approach can be valid depending upon the purpose of the riparian management and the resources available for monitoring. Statistically designed comparison of treated and control sites over an adequate timescale is the best option (the gold medal of Rutherfurd, Ladson & Stewardson 2004), but in practice has been uncommon. For many riparian rehabilitation projects, the emphasis will be on measuring change from the initial condition considered to be degraded or unsatisfactory, to one considered closer to natural or at least preferred. In the absence of a matching but untreated control site, comparison to an adjacent reference site is valuable to help distinguish treatment effects from natural background variability (the signal to noise issue discussed above).

Monitoring sites must be located to ensure that you can assess whether the project objectives have been achieved. Photo courtesy Tasmanian Department of Primary Industries and Water.

Where no comparison with other sites is possible, the collection of adequate baseline data from the treated site becomes paramount. Some type of before-after-control-impact (BACI) sampling design should be considered, with randomised or gradient sampling to take account of local spatial variability (Ellis & Schneider 1997). BACI monitoring systems are commonly used in environmental impact assessments, and for detecting the impacts of anthropogenic change. The length of the 'before' monitoring should be sufficient to provide information about the scale and direction of natural variability, and to capture the effects of significant natural events such as flood flows. In practice this is difficult due to the timing and funding processes for most riparian projects, although use may be made of local knowledge, oral histories, and past photographs or imagery.

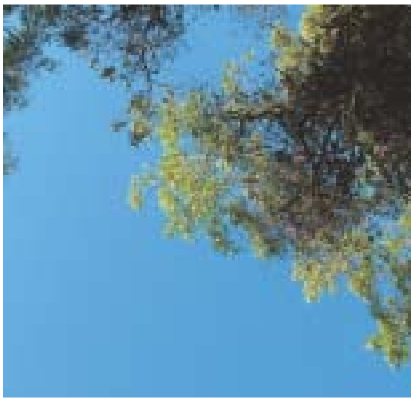
Landholders took these photographs to record their rehabilitation efforts over a period of nine years 1996 (left) and 2005 (right). Photos John and Sue Holt.

Where even adequate BACI monitoring is not possible (this includes most on-ground riparian projects), effort should be made to collect monitoring data from randomly selected locations within the treated zone (helps reduce effects of spatial variability) and data collected periodically over as long a time period as possible (to reduce effects of temporal variability). Rapid assessment tools for monitoring riparian condition have been developed to meet exactly this need.

The next question is "what to monitor?" The two general approaches to this are the condition-pressure-response framework and the ecosystem framework (Whittington 2002). In the first, indicators are chosen to provide information about riparian condition (e.g. extent, structure and floristic diversity of native vegetation), including the pressures affecting that condition (e.g. proportion of area unfenced and open to continuous grazing), and about the responses to those pressures (e.g. uptake of incentive payments for riparian fencing). Pressures to be considered include climate change, changed hydrology, drought flood and fire, pollution and contamination, erosion, dams and water abstraction, vegetation management, grazing, invasion by exotic species, and direct effects of human access.

Under the ecosystem framework, indicators are selected to reflect the crucial characteristics and functions of the riparian zone (e.g. channel size and shape, or shading of the stream surface and water temperatures). These need to be considered in the context of the catchment's geology, topography, climate and land use, as well as position within the landscape, which together set the bounds for riparian characteristics.

Repeated in-stream monitoring is one method of measuring change over time. Photos: (top left) David Kelly, (top right) Guy Roth, (bottom left) Mick Rose, (bottom right) Wayne Tennant.


Indicators of physical condition such as canopy cover may respond faster and be easier to measure than changes in animal populations. Changing canopy cover can be viewed using a 'fish eye' lens to look up from the stream. Photos: (above) Ian Dixon, (below left) Australasia Grebe, Neville Male, (below right) *Litoria caerulea*, Angus Emmott.


Choosing which framework to use should be determined by the purpose of the evaluation being undertaken (e.g. is it important to include policy or management responses), and the availability or ease of collection of the data required. In practice, a mix of indicators from the two frameworks is often selected. It is crucial at this stage of designing your monitoring system to make sure that the data to be collected will support the evaluation intended; not doing so is a frequent cause of failure to evaluate outcomes.

The next question will be "what indicators should be measured?". Some important characteristics of useful indicators are that they: are linked directly to a key aspect of condition, function or pressures (stressors); detect change at the required spatial and temporal scales; can be interpreted without ambiguity; are sensitive to the changes anticipated following riparian treatments; can be measured easily and cheaply with a high degree of accuracy and repeatability; can be measured using existing methods; and, useable data already exists or is being collected. In practice, few if any riparian indicators meet all these requirements, but several meet more than one and are suitable for inclusion in a M&E program.

It is generally preferable to include a mix of indicator types. It can be argued that the terrestrial and aquatic biota associated with riparian zones are the ultimate indicators of change, but it may take time for biotic change to become measurable (e.g. a slow decline in riparian vegetation condition), whereas physical (e.g. area fenced) or chemical (e.g. soil nutrient status) indicators could show likely trends much sooner. As well, because biotic indicators tend to integrate effects across all aspects of the ecosystem, it is often difficult to determine cause and effect relationships with confidence, e.g. there are many potential causes of vegetation decline.

Indicators should also be capable of measurement over the required temporal and spatial scales. Repeated measurement will be required over a timescale sufficient for physical, chemical, and biological changes to occur and be detected, as well as to take account of the affects of natural variables such as floods and fire. Riparian zones are influenced by surrounding land uses and upstream condition, so data for some indicators may need to be collected from these areas as well. Repeated measurement is valuable in confirming or changing the management being used, that is, it supports an adaptive management approach (Walters 1986).

The degree of shading of a stream is a relatively easily measured surrogate indicator for some in-stream processes. Photos Peter Davies.

It is also necessary to determine the degree of accuracy (how close the measured data is to the actual value) and precision (how close are repeated measurements) required of the indicators. Accuracy is important in relation to the effects of detecting a false positive (recording change when in fact there is none) or a false negative (recording no change when in fact there is one). As there is often a power relationship between accuracy and the number of data measurements needed (e.g. four times as many measurements may be needed to halve the sampling error), it is important to pre-determine the level of confidence required in the results to trigger a management or policy decision. Is 100% confidence required, or is 90% or even only 20% sufficient? The answer will depend very much on the questions being asked — this will also determine whether false positives or negatives are the most dangerous. Determining a required level of precision is important when measurements made by different people, or measurements repeated over time, are to be compared. Statistical methods are available to help determine required levels of accuracy and precision.

Although indicators that are linked directly to condition, function or stressor are generally to be preferred, they can be difficult and expensive to measure. As a result, there is often a role for surrogate indicators, that is, something that is indirectly linked to the factor of interest. The frequency of large woody pieces protruding from the water column could be used as a surrogate indicator of complexity in flow velocity, which would be much more difficult to measure directly. Native plant canopy cover and presence of regeneration could be used as a surrogate for vegetation condition. There is often a trade-off between ease of measurement and accuracy in using surrogate indicators, but depending upon the level of confidence required in the data, this may be acceptable.

Combining a range of riparian indicators to give a single score can be useful when you wish to quickly compare different sites. The components may be weighted to determine the composite index, according to their relative importance to the overall assessment required. It is essential to make sure that the different indicators can be combined so that they are all measured at the same scale, otherwise the differences or similarities may be artificial. Some information is inevitably lost in this process of 'averaging' across the individual indicators, and sites that look and behave very differently may end up with the same score. Although a single index is useful for comparative purposes, it should be unbundled back into its components before management or policy decisions are made.

A final point about indicators is that you do not have to measure everything. A small number of well-chosen indicators can be quite sufficient to indicate the direction and size of change over time, and for many purposes this will be all that is required. It is generally far better to focus limited resources on measuring thoroughly a few carefully selected indicators, than to attempt to cover all possible factors but with less replication or limited frequency.

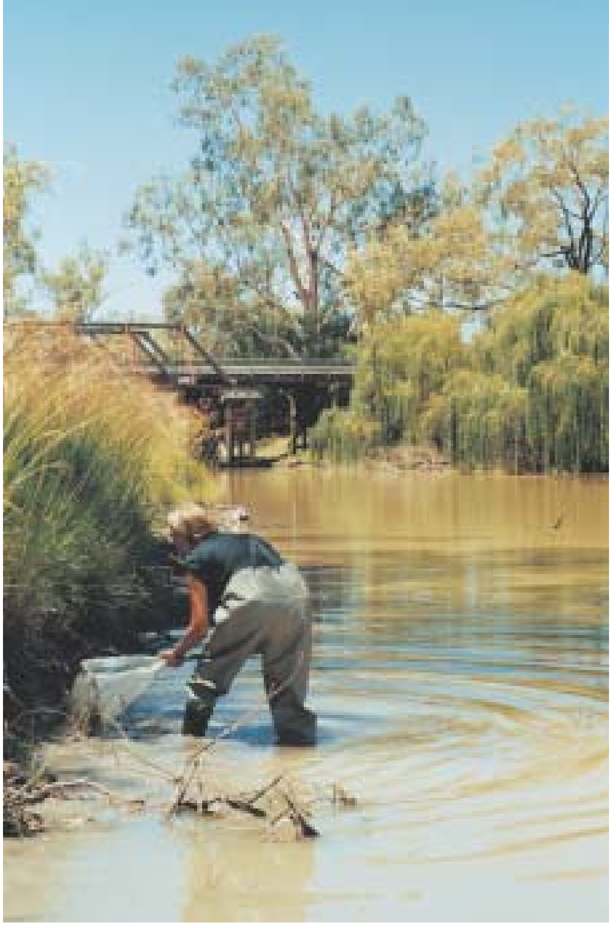


Photo Monika Muschal.

10.4 Monitoring programs

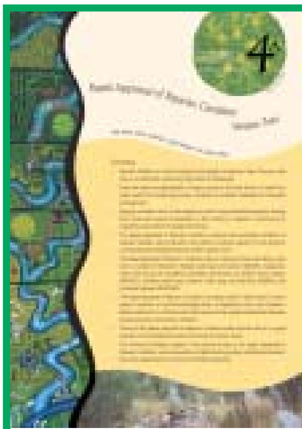
Many national, state and territory, regional, and local programs have been established in recent years for assessment of catchments, rivers, and riparian zones. Several are primarily concerned with monitoring and reporting change in extent, condition or ecological status (e.g. State of the Environment reporting), but some use the collated data for evaluation purposes related to management or policy (e.g. the National Land and Water Resources Audit). These programs use different approaches to assessment, a wide range of indicators, and different measurement methods. A list of programs and of websites with stored data is provided by Whittington (2002).

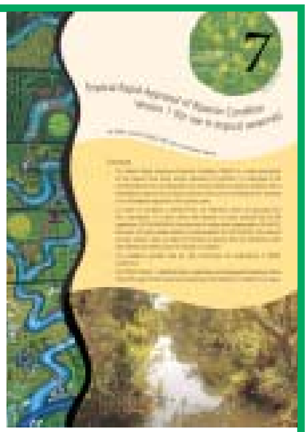
Undertaking the TRARC. Photo Ian Dixon.

10.5 Rapid appraisal methods

In response to the increasing demand for monitoring and evaluation at the outcome level, several methods have been developed for rapid appraisals of environmental condition. These are especially valuable where repeated assessments are required, using non-technical assessors, and over a large number of sites. They often use surrogate indicators for ease and speed, and are suitable for situations where trends over time are more important than absolute measures.

Two such methods have been developed and tested as part of the Land & Water Australia National Riparian Lands Research and Development Program. These are the Rapid Appraisal of Riparian Condition (RARC) method described in Jansen, Robertson, Thompson and Wilson (2003), and the Tropical RARC (or TRARC) reported in Dixon, Douglas, Dowe, Burrows and Townsend (2005). Details of both methods, including their use in practice, are available from the website — www.rivers.gov.au





For further information

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Details about both methods are available on the website www.rivers.gov.au

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GLOSSARY

A

Adventitious roots	With reference to roots emerging from an unusual place on a plant, and which function in a secondary manner to those roots which are produced in the normal places on the plant.
Aerenchyma	A form of plant tissue with large spaces between cells in which gases are stored and diffused.
Aggregate	Cluster of soil particles which adhere to each other and consequently behave as a single mass.
Allochthonous	See autochthonous.
Anabranch	A secondary channel of a river which splits from, and then later joins the main channel.
Anaerobic decomposition	The breakdown of complex organic molecules in the absence of free (gaseous or dissolved) oxygen.
Anoxic	Deficient or absence of free (gaseous or dissolved) oxygen.
Arboreal	Living in trees.
Autochthonous production	Organic matter produced within a stream or river (in contrast with allochthonous matter that is produced outside of it).
Autogenic	Processes operating within the system.

B

Basal (area)	Part of the bed or lower bank that surrounds the toe of the bank.
Basal scour	Erosion of the base of a stream bank by the shear stress of flow.
Benthic	Pertaining to the bottom or bed of aquatic environments.
Biofilm	An organic matrix comprised of microscopic algae, bacteria and other microorganisms that grow on stable surfaces in water bodies (for example, on submerged logs, rocks or large vascular plants).
Buffer strip	A vegetated strip of land that functions to absorb sediment and nutrients.

C

Cantilever failure	Undercutting leaves a block of unsupported material on the bank top which then falls or slides into the stream. A type of mass failure.
Carbon flux	Input and movement of organic carbon.
Channelisation	Topography forcing the runoff flow to converge in the hollows or by large objects such as fallen trees.
Cyanobacteria	Uni-cellar organisms such as blue–green algae. Probably the first oxygen producing mechanisms to evolve.

D

Desiccation	Drying and cracking of bank materials causing the bank to erode more easily.
Detritus	Organic debris from decomposing organisms and their products. A major source of nutrients and energy for some aquatic food webs.
Detritivore	Animal that feeds on dead plant or animal matter, e.g. leaf litter, woody debris, dead grass, dead insects.
Diatoms	The common name for the algae of the division *Bacillariophyta*.
Drip line	The limit of a tree canopy, defined by the pattern of drips from the canopy.

E

Entrained sediment	Sediment that has been incorporated into a flow by rain drop and flow processes.
Eutrophication	An increase in the nutrient status of a body of water. Occurs naturally with increasing age of a waterbody, but much more rapidly as a by-product of human activity.

F

Facultative	Able to adapt from one ecological mode to another, and not strictly bound to one environment.
Fluvial	Pertaining to water flow and rivers.
Filter strip	See buffer strip.
Frost heave	In cold climates bank moisture temperatures fluctuate around freezing, promoting the growth of ice crystals that dislodge bank material.

G

Granivore	Animal that feeds on seeds.

H

Headcut	Sharp step or small waterfall at the head of a stream.
Heterotrophic	Organism or ecosystem dependent on external sources of organic compounds as a means of obtaining energy and/or materials.
Hydrochory	Dissemination of seeds through water.

I

Isotopic signatures	Naturally occurring ratios of stable isotopes in plant or animal tissue. (Isotopes are atoms of the same element with the same chemical properties, but differ in mass.)

J

Julian day	Day based on a calendar year (365 days per year and every fourth year 366 days) introduced by Julius Caesar.

L

Lentic	Standing waterbodies where there is no continuous flow of water, as in ponds and lakes (of freshwaters).
Littoral	The shallow margin at the edge of a lake or wetland. Usually characterised by rooted aquatic plants that are periodically exposed to the air due to fluctuating water levels.

M

Macrophytes	Large vascular plants.
Mass failure	A form of bank erosion caused by blocks of material sliding or toppling into the water.
Mesic	Found in areas with regular availability of water.
Microtopography	Variations in topography of the ground surface at the scale of centimetres to metres.
Monocots	An abbreviation of *monocotyledon* (*mono*, single; *cotyledon*, leaf), which is one of the two major classes of plants, and typified by seedlings with a single leaf; an absence of cambium (i.e. wood); stems with thickened basal portions forming corms, rhizomes, and bulbs; linear leaves with parallel venation; and flowers parts usually in multiples of threes (i.e. commonly six sepals, six petals, etc.).
Morphological	The external structure of a plant (or animal) based on degree of differentiation between species.
Myrtaceous	Belonging to the family Myrtaceae, which includes genera such as *Callistemon*, (bottlebrushes), *Eucalyptus* (gums and bloodwoods) and *Melaleuca* (paperbarks).

O

Obligate	Limited to a particular ecological mode, i.e. confined to a particular habitat.
Organic colloids	Small, low-density particles that can be transported easily by overland flow.

P

Ped	See aggregate.
Periphyton	Algal communities that grow on hard surfaces (such as rocks and logs) or on the surfaces of macrophytes.
Photic zone	Upper portion of a lake, river or sea, sufficiently illuminated for photosynthesis to occur.
Planform	Shape of a river as seen from the air.
Primary production	1. The total organic material synthesised in a given time by autotrophs of an ecosystem. 2. Rate at which light energy is converted to organic compounds via photosynthesis.
Propagules	A dispersive structure, such as a seed, fruit, gemma or spore, released from the parent organism.

R

Rain splash	The dislodgment of sediment by rain which travels down the bank and into the flow.
Rheophytic	A plant adapted to fast flowing water, most often inhabiting stream banks or stream beds, and may have certain morphological or reproductive characteristics.
Rhizome	More or less horizontal underground stem bearing buds in axils of reduced scale like leaves. Serves in vegetative propagation.
Riparian zone	Any land which adjoins, directly influences, or is influenced by a body of water.
Rill erosion	Small, often short-lived channels that form in cropland and unsealed roads after intense rains.
Rotational failure	A form of bank erosion caused by a slip along a curved surface that usually passes above the toe of the bank.

S

Scour	A form of bank erosion caused by sediment being removed from stream banks particle by particle. Scour occurs when the force applied to a bank by flowing water exceeds the resistance of the bank surface to withstand those forces.
Senescent	Old trees with some dead limbs.
Sheet erosion	Erosion on hillslopes by dispersed overland flow.
Slab failure	A type of mass failure caused by a block of soil toppling forward into the channel.
Slaking	Occurs as a result of the rapid immersion of banks. The soil aggregate disintegrates when air trapped in aggregates escapes.
Slumping	The mass failure of part of a stream bank.
Snags	Large woody debris such as logs and branches that fall into rivers.
Stable isotope analysis	A technique to measure naturally occurring stable isotopes (typically of carbon and nitrogen), increasingly used in food web studies.
Stomata	Microscopic perforations consisting of a unique arrangement of cells on a leaf surface through which exchange of gases and transpiration of water vapour occurs between a plant and the environment.
Stratigraphy	The sequence of deposited layers of sediment.
Stream order	Classification of streams according to their position in the channel network, for example, a first order stream has no tributaries. Streams become larger as their order rises and an increasing number of segments contribute to the flow.
Subaerial erosion	Erosion caused by exposure of stream bank to air.
Substrate	1. Substance upon which an enzyme acts. 2. Ground and other solid object on which animals walk, or to which they are attached. 3. Material on which a microorganism is growing, or a solid surface to which cells in tissue culture attach.
Succession	Directional and continuous pattern of colonisation and extinction of a site by populations or plants and/or animals. (Not to be confused with seasonal shifts in species composition.)
Surcharge	The weight imposed on a bank by vegetation.

T

Tensile stress	The force per unit area acting to pull a mass of soil or tree root apart.
Toe	Bottom of the bank.

W

Windthrow	Shallow-rooted, stream-side trees are blown over, delivering bank sediment into the stream.

X

Xeric	Adapted to arid conditions.

RESOURCES

For river and riparian management the most comprehensive range of fact sheets, technical guidelines and manuals can be accessed at www.rivers.gov.au. This website also has a number of interactive catchment diagrams that show well-managed and poorly-managed riparian areas in relation to a particular topic.

www.rivers.gov.au website

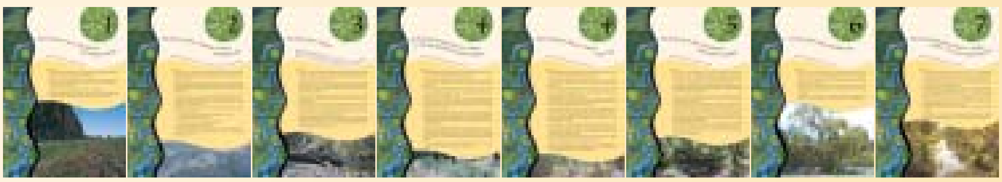
The www.rivers.gov.au website is the best place to visit for up-to-date information and tools designed to assist people working in rivers and riparian lands across Australia. The website has full details of all the products listed here, with most able to be downloaded or ordered in hard copy from CanPrint Communications (freecall 1800 776 616).

Fact sheets

These fact sheets aim to set out the general principles and practices for sound management of rivers and riparian lands. They are grouped according to whether they deal with riparian land, in-stream health, river contaminants or other management issues.

Technical guidelines

These guidelines are aimed at a more technical audience and provide detailed information about the science underpinning recommended best practice in river and riparian management. They have become central reference documents for most catchment management organisations in Australia, as well as providing the most up-to-date river and riparian science for researchers working in the area.



RipRap

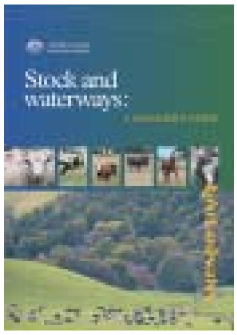
This newsletter provides information about new research, products and case studies. It is the best way of staying up-to-date with what is happening in rivers research across Australia. Editions are based around a particular management theme and written in easily understood language to update policy makers, catchment groups and landholders about the most recent developments in river management.

Industry specific guidelines

These guidelines provide different commodity based industries with river and riparian management information specific to their needs. Two guidelines — 'Managing riparian lands in the sugar industry' and 'Managing riparian lands in the cotton industry' have already been produced. The wool industry now has its own set of guidelines that brings together the latest science and recommended management approaches for riparian areas within the context of a commercial wool growing property. The wool guides are available for high rainfall regions (above 600 mm) and sheep/wheat regions (300–600 mm). In addition there is an accompanying summary document and checklist.

Stock and waterways: a manager's guide

The aim of this book is to help farmers identify their riparian land and understand the role it plays in maintaining a healthy waterway. It offers practical advice on how to manage riparian land both productively and sustainably. It also includes a number of case studies from farmers throughout Australia who have seen the benefits of changing their management practices.



CDs and stories

We have CDs containing all of our publications in the one spot, as well as CDs that tell stories about how people are managing their rivers for future generations. Our "Legacy" CD (released in December 2006) covers scientific findings, PowerPoint presentations and all the products that have been developed by the National Riparian Lands R&D Program over the past 13 years.

All these products are available on the Rivers website at www.rivers.gov.au
They are also available from CanPrint Communications on freecall 1800 776 616.

For information about Land & Water Australia's Rivers Programs.
Telephone: 02 6263 6000 Facsimile: 02 6263 6099
Postal address: GPO Box 2182, Canberra ACT 2601
E-mail: Land&WaterAustralia@lwa.gov.au
Web: www.rivers.gov.au and www.lwa.gov.au

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CHAPTER 2

Diversity and dynamics of riparian vegetation

Samantha J. Capon and John Leslie Dowe

Summary

- ~ Riparian plant habitats are temporally and spatially heterogeneous as a result of fluvial disturbance and comprise numerous different habitat types including; channel, channel bank, floodplain and wetland habitats.
- ~ Plant diversity in Australian habitats comprises a range of taxonomic groups, life forms and functional groups and includes plants only found in riparian areas, as well as those that can move between environments.
- ~ Riparian plant species exhibit a diversity of morphological, physiological and life history adaptations which enable them to persist in these variable and dynamic habitats.
- ~ Vegetation communities in riparian habitats are temporally and spatially dynamic as a result of fluvial disturbance.
- ~ Threats to riparian vegetation in Australia include hydrological change, weeds and inappropriately managed grazing.

2.1 Riparian plant habitats

Riparian zones are amongst the worlds most diverse and dynamic plant habitats (Malanson 1993, Naiman & Décamps 1997). As a result of complex interactions between hydrology and geomorphology, riparian zones are characterised by a high degree of temporal and spatial heterogeneity and can be perceived as mosaics of habitat patches within which soil moisture, sediment and nutrient properties vary (Stromberg 2001). In general, surface water hydrology is considered to be the principal determinant of riparian vegetation diversity, and water dynamics such as flooding exert an overriding influence on riparian habitat characteristics both temporally and spatially (Gregory et al. 1991, Blom et al. 1994, Naiman & Décamps 1997, Stromberg 2001).

Riparian zones typically have higher soil moisture and nutrient content than neighbouring upland systems and this may favour plant biomass production (Megonigal et al. 1997). During inundation, however, soils become anoxic and toxic ions, e.g. of manganese and iron, accumulate in bio-available forms as a result of soil microbial processes (Blom & Voesenek 1996). In addition to changes in temperature and light that occur during submergence, such alterations to the soil can restrict normal plant metabolic processes, including. respiration, photosynthesis and nutrient uptake (Hook 1984). Soil compaction may also result from flooding, increasing resistance to the growth of plant roots (Blom & Voesenek 1996). Additionally, flooding can cause mechanical damage to plants via hydraulic influence on stems (Menges 1986, Young et al. 2001) or through erosion and abrasion of sediments (Naiman & Décamps 1997). Deposition of sediments associated with flooding may bury seedlings or impede germination of propagules (Sluis & Tandarich 2004) but can also create areas of bare substrate suitable for plant colonisation (Stromberg 2001). Furthermore, flooding can provide an additional vector for propagule dispersal called 'hydrochory' as many riparian plant species possess buoyant seeds (Nilsson et al. 1991). Over longer time periods, flooding may influence riparian plant habitats by altering the geomorphic template through changes to channel morphology such as the formation of meanders or abandoned channels (Stromberg 2001).

Hydrochory: dissemination of seeds through water.

Top: Lawn Hill Creek, a stream with permanent flow, and the riparian vegetation dominated by *Melaleuca leucadendra* and *Livistona rigida*. Middle left: Permanent lagoon in the Suttor River system with moderate seasonal rise, in which riparian vegetation, with *Eucalyptus camaldulensis* and *Eucalyptus microtheca*, is seasonally inundated. Middle right: Logan Creek has a riparian zone that is inundated by slow moving floodwaters, here with the base of the dominant trees *Eucalyptus microtheca* and *Acacia cambagei* seasonally submerged. Above left: Barratta Creek, a system with permanent swift flowing water and seasonally inundated, here with *Melaleuca leucadendra*, *Nauclea orientalis* and *Livistona decora*. Above right: A section of the Burdekin River with permanent flow and seasonal dynamic floods, dominated by *Melaleuca leucadendra*. All photos John Dowe.

The effects of flooding on riparian plant habitats depend upon hydrological attributes of flood events such as timing, depth and duration, and frequency. Plant responses to flooding can be influenced by the seasonal timing of flood events, for example if flooding coincides with seed dispersal or germination cues related to temperature (Baskin & Baskin 1998). Flooding depth can control the light environment of submerged plants, and the duration of inundation is significant as many of the stresses to plants associated with flooding, for example, soil anoxia, are cumulative over time (Blom & Voesenek 1996). The rates of floodwater rise and recession may also be influential as, for instance, faster rates of change might be more likely to result in mechanical damage to stems. Finally, flood frequency is an important hydrological attribute as the time elapsed since a prior event will affect which plants are present in a habitat as well as their life history stages and hence, their responses to flooding.

Flood frequency can also determine the influence of other factors in riparian plant habitats as regional characteristics, such as soil properties, rainfall or drought, are more likely to be important when flood frequency is low (Capon 2005). In riparian habitats with a high flood frequency, for example, salinity and fire can have a reduced impact as frequent flooding can wash away salts and fuel, e.g. plant litter and debris (Stromberg 2001). Frequent flooding can also replenish groundwater supplies on which some riparian plants may be partially or totally dependent (Lamontagne et al. 2005). Other characteristics of riparian habitats which are likely to influence vegetation include light, which is often greatest at the edge of riparian habitats and decreases along a gradient perpendicular to the waterbody, intra-specific and inter-specific plant competition and herbivory. Flooding, however, is generally considered to be the primary factor structuring vegetation in riparian habitats (Naiman & Décamps 1997).

Left: The Belyando River in flood, with slow moving flood waters, and submerged riparian vegetation of *Eucalyptus camaldulensis*, *Eucalyptus microtheca* and *Melaleuca bracteata*. Right: Flood debris on the banks of Lolworth Creek, a system that has dynamic seasonal floods. Photos John Dowe.

Left: The Murrumbidgee River in flood with *Eucalyptus camaldulensis*. Photo Lu Hogan. Right: *Eucalyptus coolabah* in the Coongie Lake. Photo Roger Charlton.

Habitat types

Given its broad definition, a diverse array of habitats can be considered 'riparian'. From a vegetation perspective, however, these can be classified into four major groups on the basis of their geomorphologic and hydrological characteristics (Brock et al. in press):

~ channel habitats,
~ channel bank habitats,
~ floodplains, and
~ wetlands.

Factors exerting a significant influence on vegetation, and particularly the frequency and magnitude of flooding, vary with some degree of predictability between these. It is important to note, however, that these habitat types do not necessarily occur all together and their distribution depends on position within the landscape. Riparian habitats in constrained upstream reaches, for example, are likely to be restricted to channel and channel bank habitats, while floodplains and their wetlands occur more commonly in alluvial downstream reaches.

Channel habitats

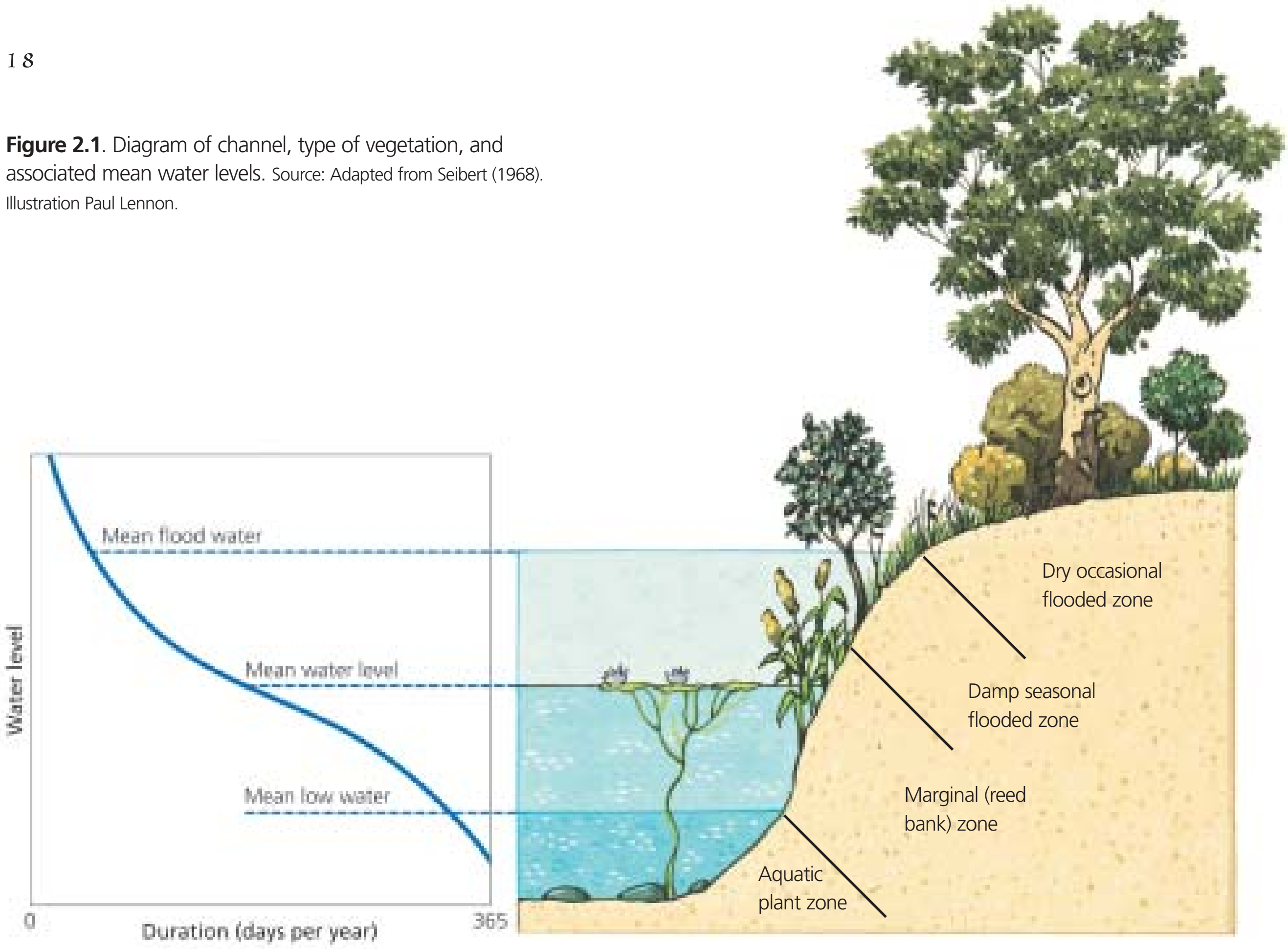
Depending on the permanency of surface water flows, significant areas of active river or stream channels can be exposed for varying periods of time, providing habitat for colonisation by riparian plants. Such habitats experience extreme fluvial disturbance, including high frequency and magnitudes of flooding, as well as erosion and deposition of bed sediments, crucial in determining the composition and structure of within-channel vegetation. When surface water is present, hydraulics can play a significant role, as some macrophyte species may be restricted to areas of slow-flowing water (Mackay et al. 2003). Canopy cover and, therefore, light reaching channel habitats is another important factor (Mackay et al. 2003, Fritz et al. 2004). Channel habitats also include geomorphic features such as depositional bars and islands which are typically composed of coarse substrate materials but are flooded less frequently than channel beds, therefore providing a slightly more stable habitat for riparian plants (Hupp & Osterkamp 1985).

Channel bank habitats

Channel bank habitats comprise those areas immediately adjacent to channels and include levee banks. Flood frequency is lower in channel bank habitats than channel habitats and generally decreases along lateral gradients of elevation or distance away from the channel. The capacity of soils to hold water following inundation is an important determinant of vegetation dynamics in these riparian habitats, and reflects sediment depth and composition as well as height above the stream water level. Levee banks, for example, often flood frequently but may dry out faster than lower lying channel bank areas resulting in differences between vegetation communities (Naiman & Décamps 1997). In channel bank habitats, plants, and particularly deeply rooted trees, are also likely to have access to more permanent surface water within the adjacent channel, as well as to groundwater where this is hydrologically connected to the stream. Other significant physical factors influencing vegetation in channel bank habitats include light, which is likely to be higher at the channel edge, and erosion and deposition of sediments, particularly at the immediate interface with the active channel.

Thick wet season growth in a section of the Burdekin River with sloping banks. Photo John Dowe.

Figure 2.1. Diagram of channel, type of vegetation, and associated mean water levels. Source: Adapted from Seibert (1968). Illustration Paul Lennon.



This photo shows some of the characteristics of an intact riparian zone as illustrated in the above diagram. Photo CSIRO Sustainable Ecosystems.

Narran Lakes in flood. Photo Narran Lakes Ecosystem Project.

Floodplains

Floodplains can be defined as 'areas of low lying land that are subject to inundation by lateral overflow water from rivers with which they are associated' (Junk & Welcomme 1990). Typically, these occur beyond immediate channel bank habitats and may extend for several kilometres away from channels. In the large floodplains of the channel country, however, floodplains can be up to 60 kilometres in width. Vegetation composition and structure in floodplain habitats is determined primarily by flood frequency, depth and duration, which, as in channel bank habitats, usually decline along complex lateral gradients of increasing elevation or distance from channels (Capon 2003, 2005).

Wetlands

A wide variety of wetland habitats can be considered to be riparian based on the definition used here, including freshwater and saline lakes, oxbow lakes, abandoned channels, back swamps, claypans and springs. Within each of these habitat types, further differentiation may also exist between open water or 'bed' habitats and fringing habitats that may be comparable to channel banks. Hydrological properties of wetlands, e.g. permanence of surface water, will have a significant influence on their plant communities and these will depend on a wetland's proximity to the channel as well as local drainage characteristics. Other important factors may include sediment composition, groundwater connectivity and salinity.

One of the Falkiner Memorial Field Station wetlands on the Murray River following flooding to promote growth of black box, nardoo, spikesedge and flowering lignum. Photo NSW Murray Wetlands Working Group.

2.2 Riparian plant diversity

Riparian floristics

Riparian vegetation throughout much of Australia is dominated by a relatively small number of plant species (Cole 1986) and can be characterised as having low species diversity but with locally high individual species abundance (Fielding & Alexander 1996). A wide range of life forms are represented, including trees, shrubs, monocots (i.e. grasses and sedges) and forbs, the latter two groups of which include perennial, annual and ephemeral species. Of the non-vascular plants, many Bryophytes (mosses, liverworts, and hornworts) are restricted to the riparian zone and submerged charophytes (green macro-algae) are also frequently encountered in channel and wetland habitats. Amongst vascular plants, ferns and fern allies have a limited occurrence in riparian zones, e.g. *Marsilea* spp. (nardoo) (Capon 2003), with angiosperms generally comprising the dominant component of riparian flora.

Prominent riparian tree species in semi-arid and monsoonal northern Australia include *Eucalyptus camaldulensis* (river red gum), broad and narrow leaved *Melaleuca* species (*M. argentea*, *M. fluviatilis*, *M. leucadendra*, *M. trichostachya*, *M. viridiflora*), *Casuarina cunninghamiana* (she oak), *Terminalia* spp., and *Lophostemon grandiflorus*, among others. In south-east continental Australia, dominant riparian species include *Callistemon viminalis*, *Casuarina cunninghamiana*, *Eucalyptus camaldulensis*, *Eucalyptus largiflorens*, *Potamophila parviflora*, *Tristania neriifolia* and *Waterhousea floribunda*; in Tasmania *Acacia axillaris*, *Callitris oblonga*, *Micrantheum hexandrum*; and in south-western Australia *Eucalyptus rudis* and *Melaleuca rhaphiophylla* are common. Riparian trees in the arid inland catchments of Australia are often restricted to channel bank habitats and typically include *Eucalyptus camaldulensis*, *Eucalyptus coolabah* and *Acacia stenophylla*. In the very wet rainforest areas of north-east Queensland, it is difficult to identify specifically riparian tree species

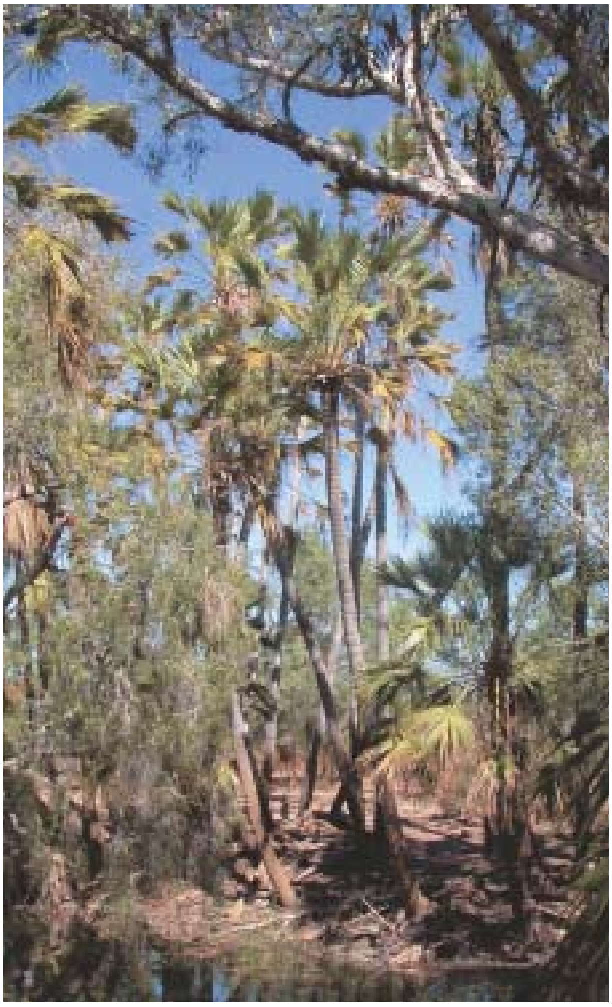
Monocots: an abbreviation of *monocotyledon* (*mono*, single; *cotyledon*, leaf), which is one of the two major classes of plants, and typified by seedlings with a single leaf; an absence of cambium (i.e. wood); stems with thickened basal portions forming corms, rhizomes, and bulbs; linear leaves with parallel venation; and flowers parts usually in multiples of threes (i.e. commonly six sepals, six petals, etc.).

Melaleuca leucadendra, Burdekin River. Photos this page John Dowe.

Melaleuca fluviatilis, *Casuarina cunninghamiana* and *Corymbia tessellaris* on Lolworth Creek.

as most that occur in channel bank habitats are also present in adjacent habitats. Understorey species throughout Australian riparian habitats often include many monocot species with emergent sedges typically dominating fringing vegetation in frequently flooded habitats. Annual and ephemeral forbs can also be frequently encountered in channel bank and floodplain habitats though their appearance in the extant vegetation is often highly dependent on seasonal conditions. Submerged, free-floating and floating-attached aquatic plants are common in channel and wetland habitats but often have patchy distributions.

Plant diversity at the family level in the riparian zone more or less follows the general diversity found across much of Australia. Species in the family Myrtaceae (Australia's most diverse family), in the genera *Eucalyptus*, *Callistemon*, *Leptospermum*, and *Melaleuca*, account for many riparian species. Families well represented in riparian habitats also include Cyperaceae (*Baumea*, *Cyperus*, *Schoenoplectus*), Poaceae (*Brachiaria*, *Chrysopogon*, *Megathrysus*, *Phragmites*), Proteaceae (*Banksia*, *Grevillea*, *Lomatia*), Mimosaceae (*Acacia*, *Carthormion*), Fabaceae (*Aeschynomene*, *Sesbania*), Arecaceae (*Archontophoenix*, *Livistona*), and Euphorbiaceae (*Calycopeplus*, *Cleistanthus*, *Flueggea*). The riparian species in these families can be regarded as evolutionarily specialised members that have been able to adapt to, and successfully exploit, a unique habitat, i.e. the riparian zone. Other families that are represented in riparian vegetation with specialised species, but otherwise have the majority of other genera in non-riparian habitats, include Polygonaceae (*Muehlenbeckia*, *Persicaria*, *Polygonum*) and Onagraceae (*Ludwigia*). Although there are a few grass species that are riparian specialists, most grass species that occur in riparian zones also occur in other habitats, reflecting the ability of grass species to adapt to a diversity of habitats. Additionally, the palm family Arecaceae, has a relatively high proportion of riparian species in northern Australia, particularly in *Archontophoenix* and *Livistona*.



Livistona rigida, Gregory River. Photos this page John Dowe.

Schoenoplectus mucronataus (foreground) and *Pandanus spiralis* (background) Beames Brook.

Melaleuca trichostachya, Douglas River, with typical leaning response to seasonal flooding. Photo John Dowe.

Obligate: limited to a particular ecological mode, i.e. confined to a particular habitat.
Facultative: able to adapt from one ecological mode to another, and not strictly bound to one environment.
Myrtaceous: belonging to the family Myrtaceae, which includes genera such as *Callistemon*, (bottlebrushes), *Eucalyptus* (gums and bloodwoods) and *Melaleuca* (paperbarks).
Aerenchyma: a form of plant tissue with large spaces between cells in which gases are stored and diffused.
Adventitious roots: with reference to roots emerging from an unusual place on a plant, and which function in a secondary manner to those roots which are produced in the normal places on the plant.

In an investigation of riparian species, van Steenis (1981) listed 12 Australian species as obligate rheophytes, which he defined as '*plant species which are in nature confined to the beds of swift-running streams and rivers and grow there up to flood-level, but not beyond the reach of regularly occurring flash floods*'. Additionally, a small number were discussed as facultative rheophytes or riparian trees. These included *E. camaldulensis*, described as a riparian species with seedlings able to develop in swift-flowing water; *Melaleuca argentea* which was described as a rheophyte of sandy and gravelly stream banks and beds; and *Melaleuca bracteata* (to include *M. trichostachya* and *M. linariifolia*) as a riverine species and not a rheophyte.

Evolution of riparian vegetation

Floristic diversity in the riparian zone cannot be separated from processes of evolution and historical biogeography. From the point of view of evolution of riparian vegetation in northern Australia, Bowman and Woinarski (1994) and Bowman (2000) speculated that once diversification of myrtaceous elements commenced following the contraction of rainforest due to continental drying during the Eocene, now extinct diverse gallery forests were eventually replaced by the simpler *Melaleuca/Eucalyptus* associations that are dominant in Australian tropical river systems today. They highlighted the differences between Australian riparian vegetation, being very simple and dominated by only a few species, and that which occurs in South America, which is relatively diverse and not usually dominated by single or small numbers of species. On a reduced time-frame, Fielding and Alexander (2001) provided an examination of river-bed fossils in eastern Australia that indicated that trees structurally similar to present-day *Melaleuca* species were present in past ages, and may be evidence of the previous occurrence of variable discharge and periodically flooded watercourses associated with a strongly seasonal climate.

Plant adaptations

Plants persisting in riparian habitats usually exhibit adaptations that allow them to survive through periodic episodes of fluvial disturbance. These can be either physiological or morphological adaptations, through which plants tolerate flooding as mature individuals, or life history adaptations that enable plants to tolerate the stresses associated with flooding in time or space.

Common morphological adaptations amongst flood tolerant plants include the ability to rapidly elongate stems and petioles upon submergence, allowing plants to emerge from the low light conditions of floodwaters (Blom & Voesenek 1996). The development of aerenchyma in stems and roots, facilitating better gas exchange, is another widespread response to flooding amongst tolerant plants (Blom & Voesenek 1996). Many riparian plant species also develop adventitious roots or initiate increased branching of lateral roots when flooding occurs (Blom et al. 1990). Physiological adaptations may include the ability to switch to alternative metabolic pathways during flooding so respiration can continue under anoxic conditions (Hook 1984).

Melaleuca fluviatilis, Lolworth Creek, with root masses conserving stream bank stability. Photo John Dowe.

Riparian plant species may also display a variety of life history adaptations to flooding, including, for instance, timing significant reproductive events to coincide with regular flood pulses. Some species may delay flowering and seed production until seasonal floodwaters have receded (Blom et al. 1990) while others might flower prior to seasonal floods but have dormant seeds which germinate in response to conditions occurring during floodwater recession (Pautou & Arens 1994). Plants that release seeds before or during a flood may be dispersed widely by floodwaters through hydrochory (Nilsson et al. 1991). Many annual and ephemeral riparian monocots and forbs are likely to maintain large persistent soil seed banks that enable plants to persist within a habitat as dormant propagules until conditions suitable for their germination and establishment occur (Leck & Brock 2000). Germination cues (e.g. temperature, light and oxygen availability) in wetland plant species are often related to flooding (Leck 1989). Furthermore, annual plant species, and some perennial monocots and forbs, frequently exhibit extremely rapid life cycles maximising opportunities for replenishment of the soil seed bank prior to further flooding or the onset of drought (Blom & Voesenek 1996). The ability of riparian trees to regenerate depends on a set of conditions that allows seed dispersal, germination and establishment.

Riparian plants can exhibit adaptations to other stresses and disturbances depending on their occurrence within a particular region. In arid and semi-arid regions, for instance, some riparian plant species are tolerant of both flooding and drought. The widely distributed riparian shrub, *Muehlenbeckia florulenta* (lignum), for example, persists as dormant stems during dry periods, initiating leaf and flower production in response to rainfall or inundation. Investigation of the rheophytic characteristics of *E. camaldulensis*, provided by Sena Gomes and Kozlowski (1980), has also demonstrated that this species is, apart from flood resistant and able to produce active growth whilst water-logged, correspondingly drought-resistent because of a unique arrangement of stomata in the leaves. Some riparian tree species are able to vary their water sources over time in response to climatic conditions (Snyder & Williams 2000, Drake & Franks 2003). Many Australian plants, including members of the Myrtaceae, Proteaceae and Fabaceae families that can occur in riparian habitats,

Rheophytic: a plant adapted to fast flowing water, most often inhabiting stream banks or stream beds, and may have certain morphological or reproductive characteristics.

Stomata: microscopic perforations consisting of a unique arrangement of cells on a leaf surface through which exchange of gases and transpiration of water vapour occurs between a plant and the environment.

Melaleuca fluviatilis, on seasonally flooded Keelbottom Creek. Photo John Dowe.

possess mechanisms that enable regeneration following fire such as the ability to resprout. In naturally saline riparian habitats such as saline wetlands, mudflats or estuarine areas of channels, plants may also display specialised adaptations for salt tolerance, e.g. the ability to excrete salt through leaves. Adaptations to minimise the impact of herbivory and grazing, such as morphological and chemical defences, can also be present in some riparian plant species.

Plant functional groups

A useful approach for considering relationships between plant species and their habitats, and how these contribute to temporal and spatial vegetation dynamics, is to classify plants into functional groups. Naiman and Décamps (1997) describe four broad functional groups of riparian plants based on their adaptations and response to fluvial disturbance:

- ***invaders*** that colonise alluvial sediments via large quantities of wind- and water-dispersed seeds,
- ***endurers*** that can resprout from stems or roots following damage by flooding, fire or grazing,
- ***resisters*** that are tolerant to disturbances such as flooding or fire, and
- ***avoiders*** that lack specific adaptations to disturbance and do not survive in unfavourable habitats.

An alternative approach has been provided by Brock and Casanova (1997) who classify wetland plants into three major groups; 1) submerged, 2) amphibious and 3) terrestrial, on the basis of where and when germination, establishment and reproduction occur in relation to the presence of surface water. Aquatic plants are also often divided into groups on the basis of their form, i.e. submerged, free floating, floating-attached and emergent (Sainty & Jacobs 1994). Other means of classifying riparian plants into functional groups use traits such as life form (i.e. tree, shrub, sub-shrub, monocot or forb) and life span (i.e. annual or perennial) (Capon 2005). Such groups can help to explain temporal and spatial dynamics in riparian vegetation composition and structure with regard to both natural and human disturbances.

2.3 Riparian vegetation dynamics

Temporal patterns

Riparian habitats are temporally dynamic and their characteristics change dramatically over time in relation to flooding. Vegetation tends to reflect these changes with shifts in composition and structure occurring at both short and longer time scales.

Depending on their functional attributes and life history stage, riparian plants can respond to flooding in the short term in a variety of different ways. The hydrological attributes of a flood event, e.g. timing and duration, will also influence vegetation response at this scale. Terrestrial or avoider species may be unable to survive extended periods of inundation and can become locally extinct from the extant vegetation in a riparian

Naturally regenerating river red gums along the Talbragar River. Photo John Powell.

habitat following inundation. In Australian riparian habitats, woody shrubs such as *Acacia* spp. or sub-shrubs including members of the Chenopodiaceae family are often terrestrial species and intolerant of waterlogged soils, dying following long periods of flooding (Pettit et al. 2001, Capon 2003). In contrast, growth may be favoured by flooding amongst many amphibious or submerged plants and invader species can colonise bare sediments following floodwater recession (Hudon 2004). Other species will germinate in response to flooding although very few plant species are capable of germinating in completely anoxic conditions, with the exception of most submerged and some emergent species, e.g. grasses belonging to the *Echinochloa* genus (Baskin & Baskin, 1998).

Most riparian and wetland plant species with persistent soil seed banks tend to germinate during waterlogged conditions following floodwater recession (van der Valk 1981, Baskin & Baskin 1998, Boedeltje et al. 2002, Crossle & Brock 2002). The timing and duration of flood events can be influential in determining germination responses from riparian soil seed banks (Casanova & Brock 2000). In floodplains and temporary wetlands of semi-arid and arid Australia, for example, summer flooding generally promotes the germination of grasses while forbs tend to germinate following winter flooding.

Recruitment of tree and shrub species is also frequently related to patterns of flooding in riparian habitats. Common riparian tree species such as *E. camaldulensis*, *E. largiflorens*, *E. coolabah* and *Casuarina cunninghamiana* often germinate in dense patches following inundation (Dexter 1967, Capon 2002, Woolfrey & Ladd 2001). Longer-term survival of seedlings, however, depends on future climatic conditions and further flooding (Dexter 1967), as well as competition and herbivory. Consequently, seedling and canopy composition in riparian zones can differ substantially indicating that riparian canopy composition can fluctuate over time (Jones et al. 1994).

Large flood events tend to homogenise riparian vegetation composition and particularly that of the understorey. Common monocot and forb species are generally widely distributed within floodplain and wetland soil seed banks and, as a result, germination responses to flooding can be comparable between riparian habitats in close proximity to channels as well as areas at the far edges of floodplains (Capon 2003). With drying, however, vegetation composition exhibits further shifts as species adapted to moist conditions can no longer survive and are replaced by those more tolerant of mesic and xeric conditions.

Mesic: found in areas with regular availability of water.
Xeric: adapted to arid conditions.

Spatial patterns

Due to differences in flooding patterns, riparian zones are extremely heterogeneous spatially, both between and within habitat types. Typically, riparian habitats comprise complex gradients of flood frequency, depth or duration along which vegetation communities can often be found in predictable locations. In frequently flooded areas, vegetation is influenced primarily by abiotic variables and flood tolerant species and evaders, avoiders, submerged and amphibious plants, tend to dominate. Annual and ephemeral species may also be more common in frequently flooded areas as they can quickly complete their life cycles between inundation events (Menges 1986, Trebino et al. 1996, Capon 2003, 2005). In rarely flooded areas, biotic factors such as competition and herbivory are likely to be more important in determining vegetation composition (Blom et al. 1990, Lenssen et al. 1999). Population structures of tree species may also be determined spatially in relation to flood frequency with younger stands commonly occurring in more frequently flooded areas where higher levels of fluvial disturbance can prevent stands from reaching maturity (Gregory et al. 1991, Pettit et al. 2001).

Spatial patterns in riparian vegetation composition and structure also occur along longitudinal gradients within river catchments (Ward et al. 2002). In general, maximum species diversity tends to occur in riparian habitats of the middle reaches or a river catchment. Riparian plant species richness is also often higher along the main channel of a drainage basin than on its tributaries (Nilsson et al. 1994).

2.4 Threats to riparian vegetation

Hydrological change

Changes to natural flooding regimes through flow regulation and water extraction, pose one of the greatest threats to vegetation communities in riparian zones throughout the world (Nilsson & Svedmark 2002, Tockner & Stanford 2002). Riparian vegetation is particularly sensitive to flow alterations and changes in vegetation diversity and dynamics can occur even if mean annual flows are preserved (Auble et al. 1994). In Australia, river regulation commonly involves the reduction of mean annual flows and simultaneous increases in median annual flows (Walker et al. 1995, Puckridge et al. 1998) resulting in reduced frequency and magnitude of flooding. Consequently, riparian habitats are inundated less often and for shorter durations, with reductions in areas wetted also occurring. Additionally, the seasonal timing of annual flood pulses has been reversed through river regulation in some catchments, e.g. the Murray Darling Basin (Thoms & Sheldon 2000).

Hydrological changes affect the character of riparian habitats and have significant implications for the diversity and dynamics of riparian vegetation. Recruitment amongst riparian tree species, for example, is likely to be adversely affected by reductions in overbank flooding (Zamora-Arroyo et al. 2001, Stave et al. 2003). Other species which require flooding to complete important life history stages such as germination, e.g. obligate submerged species, may also decline in riparian habitats if flood volume or frequency are reduced, often to be replaced by more mesic (or xeric) species that are favoured by new habitat conditions (Alvarez-Cobelas et al. 2001). Consequently, spatial patterns in riparian vegetation, such as zonation along flood frequency gradients, might shift in response to altered flooding regimes. In the Macquarie Marshes, for example, reduced frequency of flooding has led to the invasion of grass plains by river red gum (Bren 1992). In general, the overall affect of flow regulation on riparian vegetation is a reduction in vegetation heterogeneity which often results in an eventual loss of biodiversity.

Above: Macquarie Marshes. Photo Bill Johnson. Below: Red gum on a dry creek bed on the Paroo River where it depends on irregular floods for its survival, growth and reproduction. Photo Alison Curtin.

Weeds

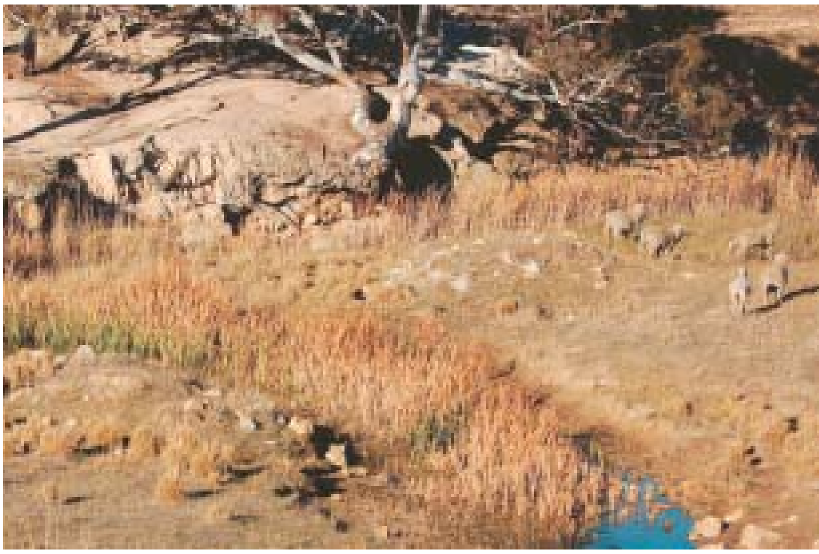
Weeds are also serious threats to the ecological integrity and productivity of many Australian vegetation communities (Grice & Brown 1999) and riparian zones are highly susceptible to weed infestation (Grice 2004). Weed infestations are often the result of disturbance or the build-up of nutrient levels caused by fertilisers or grazing animals. Primary disturbances include vegetation clearance, fire, and stock grazing. Altered flooding regimes may also enable the establishment of weed species in riparian zones (Stromberg 2001). Some weeds are able to infest undisturbed and intact riparian vegetation, in which case the weeds are able to outcompete the native species with regards to light, space, nutrients and moisture. Throughout Australia, many weeds now dominate riparian areas, their dominance perpetuated by grazing activities, associated impacts, and ineffective land management practices. The cost of weed eradication and/or control is high, and if weeds are neglected and become dominant, the productivity and diversity of native riparian vegetation can seriously decline. Although the riparian zone occupies only a small proportion of the landscape, it exerts an influence that affects most of the adjacent landscape, and the presence of weeds limits critical catchment processes and reduces productivity. The study of weed biology is now receiving more attention, and significant funds are being devoted to weed control and eradication.

Top left: Rubber vine, *Cryptostegia grandiflora*, Lolworth Creek. Photo John Dowe. Top right: Willows (probably *Salix babylonica*) growing into the stream of the Lachlan River. Photo Phil Price. Middle right: Castor oil plant, *Ricinus communis*, Keelbottom Creek. Photo John Dowe. Below left: Riparian zone with Para grass, *Brachiaria mutica*, and the aquatic weed Water hyacinth, *Eichhornia crassipes*, Healeys Lagoon. Photo John Dowe. Bottom right: Artichokes are a significant weed problem in the arid parts of South Australia and elsewhere. Photo Phil Price.

Grazing

Grazing is the dominant land-use in Australia (Stewart 1996), and the riparian zone is often severely impacted upon by the activities of domestic stock (Jansen & Robertson 2001), especially when their access to riparian zones is not controlled. Grazing by feral and native animals can also affect the diversity and condition of riparian vegetation. Riparian zones offer a number of attractions for stock, including shelter, relatively higher quality of forage, and access to water. The primary impacts that stock have on riparian vegetation include overgrazing and trampling, both of which may lead to erosion, soil compaction and weed infestation (Clary 1999, Shaw & Kernot 2004), which in turn causes loss of biodiversity, degradation of the natural conditions and loss of water quality (Burrows 2001, 2004). Some secondary effects on riparian vegetation, that are associated with grazing, include the establishment of ponded pastures and burning, both of which significantly affect the structure and composition of vegetation (Douglas & Pouliet 1997).

The presence and grazing of stock have a direct influence on species composition in most habitat types. Low intensity grazed areas have a relatively greater abundance and dominance of native shrubs, twiners and geophytes than high intensity grazed areas in temperate Australia (Clarke 2003). In north eastern Australia, riparian sites that are naturally protected by basalt flows from stock, but with the sites grazed by macropods, had higher species richness, however, there was a higher diversity and abundance of annual grasses in the cattle grazed areas (Fensham & Skull 1999). Following the cessation of grazing, there is evidence suggesting that the natural species composition will be restored, in time, if nearby seed sources are present and able to disperse into the stock exclusion area (Pettit & Froend 2001). With regards to palatable pasture weeds in riparian zones, stock may be used to control some weeds such as para grass (*Brachiaria mutica*) and hymenachne (*Hymenachne acutigluma*) and restore ecological functioning to areas dominated by such weeds (Burrows 2001).



This page. Uncontrolled stock access is the single greatest cause of riparian zone degradation across Australia. Photos: (above) Jenny O'Sullivan, (top right) Roger Charlton, (right) Ian Bell.

Opposite page. Top: This riparian area has been fenced off to exclude stock. Photo Mike Wagg. Below: Fencing used to protect remnant strip of riparian vegetation. Photo John Dowe.

Fencing is the most effective method of controlling access to the riparian zone by stock (Burrows 2001), and is the current recommended management practice in areas where high to moderate intensity grazing occurs (Productivity Commission 2003, Roth et al. 2004). Fencing facilitates the construction of water points away from the source of the water and, as a result, stock can be concentrated away from the riparian zone. However, this may lead to situations where pasture is depleted or reduced to poor quality in the vicinity of water points. Controlled seasonal access to the riparian zone alleviates pressure on riparian vegetation when it is most vulnerable, for example when the seedling establishment phase is active, or during flowering and fruit development phases. A number of methods of rehabilitation of the riparian vegetation following stock exclusion or even when stock are still present have been proposed, including re-establishment of indigenous riparian vegetation with selection of species based on remnant vegetation surveys, historical records, pollen surveys and field trials (Webb & Erskine 2003).

2.5 Management principles

The following are a list management principles for protecting, maintaining and rehabilitating riparian vegetation.

- First, identify and protect areas of existing riparian vegetation assessed to be in good condition. Areas can be compared with local undisturbed or reference sites, and/or assessed for their capacity to provide crucial riparian zone functions and to self-regenerate. Identify threats and act to remove or mitigate them.
- The next priority is to promote natural regeneration or recolonisation where this is possible. This may require checking for availability of seed in the soil or on plants, removal of threats such as grazing animals or weeds, and sometimes deliberate action to promote regeneration (e.g. use of fire).
- Replanting, whether by tubestock or direct seeding, is more expensive and requires careful attention to site preparation, especially for weed management and removal of other threats. Species selection, based on reference to undisturbed sites and local knowledge, is required for different parts of the riparian zone, and for different stages of revegetation succession (e.g. early colonisers versus slow-growing climax spp). If early support (e.g. artificial watering) is needed to ensure success, it may be best to replant small areas sequentially.
- Revegetation activities need to be timed according to season and growth periods, as well as for the likelihood of floods and other disturbances. Plan for follow-up work after the planting, especially to maintain stock exclusion and weed control until the ‘new’ vegetation is fully established. Make use of the detailed guides to revegetation that are now available for most parts of Australia (e.g. through Greening Australia, government agencies, and catchment and community groups).

Conclusion

This chapter has discussed the diversity and dynamics of vegetation in riparian habitats in Australia. In addition to reviewing significant characteristics of riparian plant habitats, this chapter has provided an overview of floristic diversity in Australian riparian zones. It has focused in particular on the importance of flooding and associated fluvial disturbances in maintaining patterns of temporal and spatial heterogeneity and has discussed the major factors currently threatening riparian vegetation in Australia today.

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CHAPTER 3

Temperature and light

Peter M. Davies, Stuart Bunn, Thorsten Mosisch[1],
Barbara Cook and Terry Walshe

Summary

- Riparian vegetation shades streams, decreasing the amount of direct and diffuse sunlight reaching the water surface and reducing daily and seasonal extremes of water temperature.
- Shading controls primary productivity within the stream to a greater extent than nutrient levels, as the growth of most aquatic plants is regulated by light availability. At sites with elevated nutrient levels, shading can therefore control the effect of nutrient enrichment.
- In cleared streams, water temperature can exceed the lethal limits for aquatic fauna, directly influencing local biodiversity and, at lower temperature levels, the growth and development of aquatic plants and animals.
- The temperature tolerance of Australian aquatic macroinvertebrate fauna is similar to that measured elsewhere in the world. In temperate systems, a target of 21°C is recommended, and in northern systems, 29°C for stream water temperatures.
- The degree of shade created by riparian vegetation is influenced by several factors, including canopy height, foliage density, channel width and orientation, valley topography, latitude and season. The effect of shading on the structure and function of stream ecosystems is greatest in small streams.
- Typically, riparian replanting is best conducted in the upland streams of a catchment, particularly those orientated east-west, as this will have a flow-on effect for temperature in the lower reaches. However, for cooler-water refugia in large rivers, replanting tributaries close to the confluence can have considerable benefits for native fish.
- Stream shade has three components — macrotopographic shade (provided by nearby hills), bank shade and vegetation shade. Any restoration activities need to recognise the differential effects of these components.

1 Thorsten Mosisch co-wrote this chapter for the previous edition.

3.1 Water temperature

Riparian vegetation is a major regulator of the ecological health of streams and rivers and consequently a primary focus of river restoration. Despite this important role, it has remained difficult to be prescriptive about the actual amount of vegetation required to achieve ecological goals. A reduction in water temperature is an ecologically-meaningful and easily measured outcome of riparian replanting. In the absence of shade, water temperatures often exceed thermal tolerances of aquatic fauna (Davies et al. 2004a, b). Replanting riparian zones can reduce water temperatures to benefit downstream receiving ecosystems.

Riparian vegetation is very effective in moderating stream temperatures. For example, research in sub-tropical and temperate Western Australia showed that cleared stream sites could heat water at a rate of 10°C.km^{-1} (Rutherford et al. 2004). These high rates only applied over a short stream reach as water temperatures quickly reached a dynamic equilibrium. Due to the typical patchy nature of the shade found along the streams studied, it was difficult to determine how long water takes to reach equilibrium, however, it has been estimated that this occurs after ~1200 metres (about 4 hours travel time) (Rutherford et al. 2004).

Temperature has both direct and indirect effects on the ecological health of streams. Colder waters contain higher dissolved oxygen concentrations compared to warmer waters (Horne & Goldman 1994). For example, a 10°C increase in temperature (a change commonly-recorded in streams following riparian clearing) can reduce oxygen concentration by over 2.5 mg/L^{-1}, which may represent a quarter of the total oxygen present.

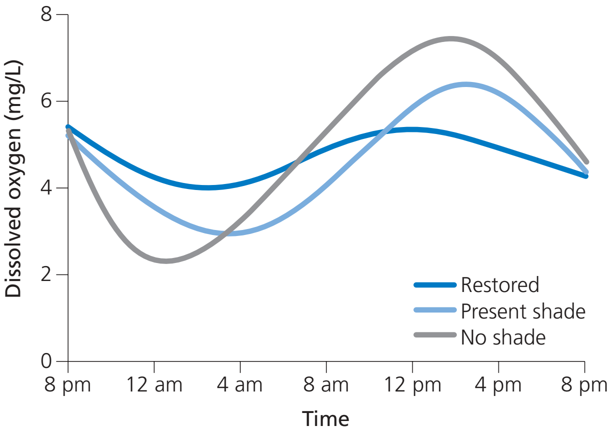


Figure 3.1. The effect of riparian clearing on the amplitude of 24 hour dissolved oxygen concentrations.

Elevated water temperatures generally raise ecosystem respiration and consequently oxygen consumption. Following riparian clearing, the combined effects of a lowering in oxygen saturation and increased respiration can drive systems anoxic, particularly at night (Bunn & Davies 1992, Davies et al. 2004a).

Figure 3.1 shows a series of 24 hour dissolved oxygen (DO) curves for three systems differing in the level of riparian shade. The curve for "no shade" shows DO values close to zero prior to sunrise, largely a consequence of elevated respiration. The amplitude of the DO curve for "no shade" is more extreme than the sites with increased riparian protection. The photos below show Tranter Creek (far north Queensland) at three stages of restoration: no shade, present shade and restored).

Sub-lethal impacts of elevated water temperatures

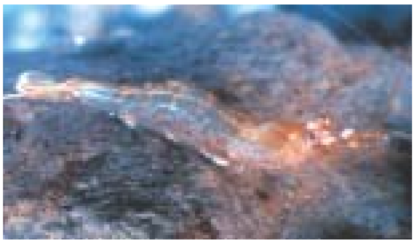
Water temperature, including elevated temperatures, can have the following direct effects on aquatic fauna.

- Effects on growth and development of most aquatic organisms (such as algae, invertebrates, fish, reptiles and amphibians) (see the photos on following page).
- Control of larval development (Vannote & Sweeney 1980).
- Influencing egg development, timing of hatching, and emergence of adults (Hynes 1970).
- Premature emergence of adults, possibly at times when climatic conditions in the terrestrial environment are unsuitable for adult survival or when few mates from adjacent forested sites are present.
- Overall reduction in fecundity because larvae mature at smaller sizes in warmer water and smaller insects produce fewer eggs (Vannote & Sweeney 1980).
- Modifying the trigger for migration, spawning, egg development and hatching of many fish species (Sloane 1984, Cadwallader & Lawrence 1990, Gehrke 1994).

The effect of temperature on the life-cycles of many aquatic invertebrates is substantial. For example, the onset of egg development and hatching of the common glass shrimp *Paratya australiensis* in subtropical rainforest streams are both strongly influenced by temperature (Hancock & Bunn 1997).

Three stages of restoration: opposite page, no shade; below left, present shade and below right, restored. Photos Peter Davies.

Examples of aquatic fauna and algae.


Glass shrimp


Ephemeroptera (mayfly) larvae


Odonata (dragonfly) larvae


Mary River cod


Algal bloom


Filamentous green algae

Photos this page Peter Davies.

The rate at which many fish grow also increases with temperature, although it probably declines in most species as they reach their upper thermal limit. Fish have higher rates of feeding and digestion at warmer temperatures, however, the amount of energy used up in finding and digesting more food at these temperatures means that growth is not commensurate with the higher rates of feeding and digesting (Allan 1995).

Temperature influences the broad taxonomic composition of aquatic algal assemblages, although each species may have its own optimum and range. Diatoms (for example, the benthic forms in Australian arid streams) tend to dominate at approximately 5–20°C, green and yellow–green algae at 15–30°C, and blue–green algae at greater than 30°C (DeNicola 1996). Many species of stream animals, particularly invertebrates but also some fish, are adapted to cool stream water with high oxygen concentrations and are susceptible to elevated temperatures. Some data on temperature preferences and tolerances for aquatic invertebrates and fish in New Zealand are available (Collier et al. 1995). However, little similar information is available for Australia. One Australian example is that larval lampreys (ammocoetes) will die at or above 28.3°C; this accounts for their distribution being restricted to Australia's southernmost streams.

Determining upper lethal temperatures in aquatic insects

Exceedance of thermal limits of aquatic biota has a major influence on local biodiversity. Early studies of the temperature tolerances of aquatic invertebrates have mainly been in the USA, and showed that some groups, such as mayflies (Ephemeroptera) and stoneflies (Plecoptera) were sensitive to elevated temperature. In New Zealand, the upper thermal tolerances of 12 stream aquatic invertebrates collected from the Waihou River has been assessed (Quinn et al. 1994), and a wide range of upper thermal tolerances were observed. Again, mayflies and stoneflies were shown to be temperature sensitive.

Setting target temperatures for Australian systems

To ensure the survival of mayflies in Australian systems, the most sensitive group to elevated temperatures, 'target' temperatures of 21°C ('cold' water species) and 29°C (northern water species) have been recommended (Davies et al. 2004a) (Table 3.1). These are similar to values derived by Rutherford et al. (1997) who adopted a 'conservative' upper limit target stream temperature of 20°C for New Zealand streams.

Table 3.1. Upper lethal temperatures for a variety of aquatic invertebrates occurring in streams worldwide. Highlighted in blue are values for Australian species.

Group	Species	Lethal temperature (°C)	Acclimation (hours)	Author(s)
Planaria	*Dugesia tigrina*	31.9	5.0	Claussen & Walters (1982)
	Dugesia dorotocephala	32.4	5.0	Claussen & Walters (1982)
	AVERAGE	**32.2**		
Amphipoda	*Paramelita nigroculus*	34.1	13.5	Buchanan et al. (1988)
	Paracalliope fluviatilis	24.1	15.0	Quinn et al. (1994)
	Gammarus limnaeus	14.6	6.4	Gaufin & Hern (1971)
	AVERAGE	**24.3**		
Decapoda	*Paratya curvirostris*	25.7	15.0	Quinn et al. (1994)
	Cambaroides japonicus	27.0	16.0	Nakata Kazuyoshi et al. (2002)
	Pacificastacus leniusculus	31.1	16.0	Nakata Kazuyoshi et al. (2002)
	Orconectes rusticus	34.4	5.0	Claussen (1980)
	Orconectes rusticus	35.6	15.0	Claussen (1980)
	AVERAGE	**30.8**		
Diptera	*Atherix variegata*	32.0	10.0	Nebeker & Lemke (1968)
	Atherix variegata	32.4	6.4	Gaufin & Hern (1971)
	Simulium sp.	25.1	6.4	Gaufin & Hern (1971)
	AVERAGE	**29.8**		
Coleoptera	*Hydora* sp.	32.6	15.0	Quinn et al. (1994)
Ephemeroptera	***Nyungara* sp.**	**21.9**	**15.0**	**Davies et al. (2004a)**
	***Centroptilum* sp.**	**20.5**	**15.0**	**Davies et al. (2004a)**
	Ephemerella subvaria	21.5	10.0	Nebeker & Lemke (1968)
	Deleatidium sp.	22.6	15.0	Quinn et al. (1994)
	Zephlebia dentata	23.6	15.0	Quinn et al. (1994)
	Stenonema ithaca	31.8	10.0	DeKozlowski & Bunting (1981)
	Stenonema tripunctatum	25.5	10.0	Nebeker & Lemke (1968)
	Ephemerella invaria	22.9	10.0	DeKozlowski & Bunting (1981)
	Cinygmula sp.	11.7	6.4	Gaufin & Hern (1971)
	Ephemerella doddsi	15.5	6.4	Gaufin & Hern (1971)
	Ephemerella grandis	21.5	6.4	Gaufin & Hern (1971)
	Hexagenia limbata	26.6	6.4	Gaufin & Hern (1971)
	AVERAGE	**22.1**		
Plecoptera	*Zelandobius furcillatus*	25.5	15.0	Quinn et al. (1994)
	Taeniopteryx maura	21.0	10.0	Nebeker & Lemke (1968)
	Isogenus frontalis	22.5	10.0	Nebeker & Lemke (1968)
	Allocapnia granulata	23.0	10.0	Nebeker & Lemke (1968)
	Pteronarcys dorsata	29.5	10.0	Nebeker & Lemke (1968)
	Acroneuria lycorias	30.0	10.0	Nebeker & Lemke (1968)
	Paragnetina media	30.5	10.0	Nebeker & Lemke (1968)
	Paragnetina media	33.0	10.0	Heiman & Knight (1972)
	Isogenus aestivalis	16.5	6.4	Gaufin & Hern (1971)
	Pteronarcella badia	24.4	6.4	Gaufin & Hern (1971)
	Pteronarcys californica	27.0	6.4	Gaufin & Hern (1971)
	AVERAGE	**25.7**		

Table 3.1. continued

Group	Species	Lethal temperature (°C)	Acclimation (hrs)	Author(s)
Odonata	***Austroaeschna anacantha***	**33.8**	**15.0**	**Davies et al. (2004)**
	Boyeria vinosa	32.5	10.0	Nebeker & Lemke (1968)
	Ophiogomphus rupinsulensis	33.0	10.0	Nebeker & Lemke (1968)
	Libellula sp.	42.8	15.0	Martin & Gentry (1974)
	Macromia illinoiensis	43.1	12.0 to 32.0	Garten & Gentry (1974)
	Neurocordulia alabamensis	42.6	12.0 to 32.0	Garten & Gentry (1976)
	AVERAGE	**38.0**		
Trichoptera	***Cheumatopsyche* sp. AV2**	**30.7**	**14.0**	**Davies et al. (2004)**
	Parapsyche elsis	21.7	6.5	Gaufin & Hern (1971)
	Limnephilus ornatus	24.8	6.4	Gaufin & Hern (1971)
	Neothrema alicia	25.9	6.4	Gaufin & Hern (1971)
	Drusinus sp.	27.3	6.4	Gaufin & Hern (1971)
	Brachycentrus occidentalis	29.7	6.4	Gaufin & Hern (1971)
	Brachycentrus americanus	29.0	10.0	Nebeker & Lemke (1968)
	Aoteapsyche colonica	25.9	15.0	Quinn et al. (1994)
	Pycnocentrodes aureola	32.4	15.0	Quinn et al. (1994)
	Pyconocentria evecta	25.0	15.0	Quinn et al. (1994)
	Symphitopsyche morosa	30.4	10.0	DeKozlowski & Bunting (1981)
	Brachycentrus lateralis	32.8	10.0	DeKozlowski & Bunting (1981)
	Hydropsyche spp.	30.3	6.4	Gaufin & Hern (1971)
	Chimarra obscura	36.5	19.0	Moulton et al. (1993)
	Chimarra obscura	31.4	12.0	Moulton et al. (1993)
	Chimarra aterrima	33.6	19.0	Moulton et al. (1993)
	Hydropsyche simulans	35.6	19.0	Moulton et al. (1993)
	Hydropsyche simulans	34.4	12.0	Moulton et al. (1993)
	Ceratopsyche morosa	34.2	19.0	Moulton et al. (1993)
	AVERAGE	**30.1**		
Mollusca	*Potamopyrgus antipodarum*	32.0	10.0, 16.0 and 24.0	Winterbourn (1969)
	Potamopyrgus antipodarum	32.4	15.0	Quinn et al. (1994)
	Sphaerium novaezelandiae	30.5	15.0	Quinn et al. (1994)
	AVERAGE	**31.6**		
Oligochaeta	*Lumbriculus variegatus*	26.7	15.0	Quinn et al. (1994)

Hemicordulia tau. Photo Angus Emmott.

Modelled temperatures for Australian systems

Modelled water temperatures for Australian streams without riparian vegetation are shown in Figure 3.2. For most bioregions, the absence of riparian cover results in water temperatures which exceed the tolerance levels for aquatic biota.

Targets and priorities for riparian restoration

The temperature and light inputs of an individual stream reach will depend on a number of factors, including:

~ meteorological conditions at the reach,
~ channel morphology of the reach,
~ flow within the reach,
~ the amount of vegetative and topographic shade at the reach, and
~ upstream meteorological, channel morphology, flow and shade conditions.

Contrasts between Australian bioregions and catchments depend largely on seasonal effects of air temperature and rainfall. Summer stress will be relatively more exaggerated where high air temperatures co-occur with times of low flow, as is the case in regions with a Mediterranean climate. In the tropics, where high flows occur in summer, in-stream temperatures will exhibit less diurnal variation. An illustration of this biogeographic contrast is provided in Figure 3.3, where

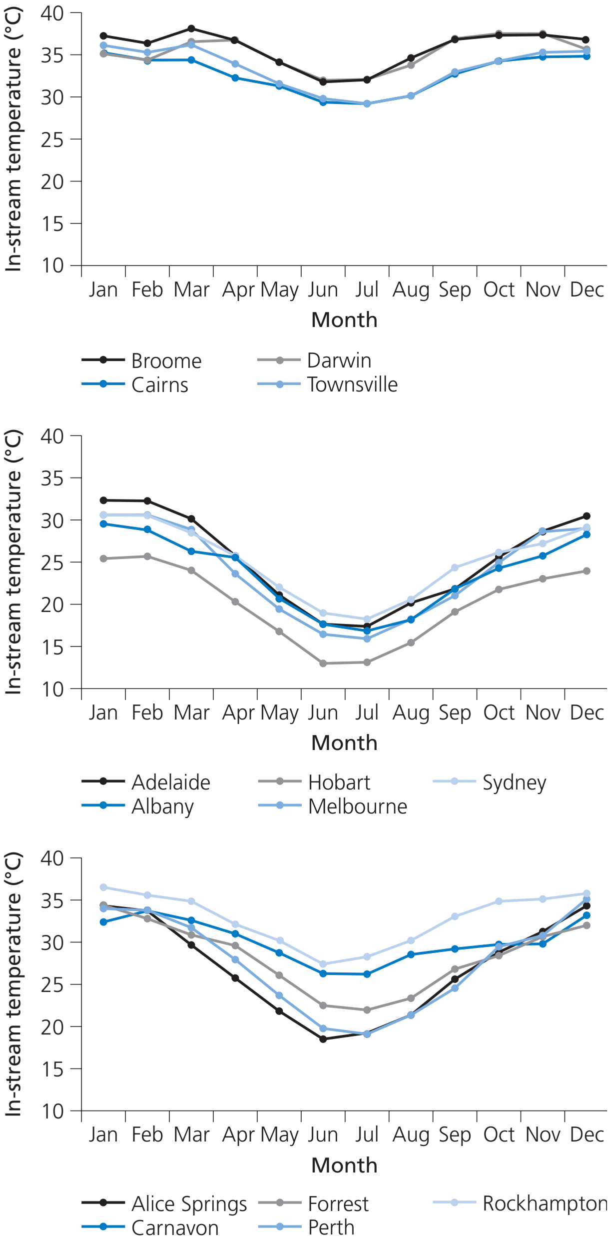


Figure 3.2. Average maximum daily in-stream temperatures at 14 locations for a hypothetical first-order stream having zero shade.

Different types of first-order streams in varying riparian environments.
Photos: (top) Canegrowers, (middle and bottom) Peter Davies.

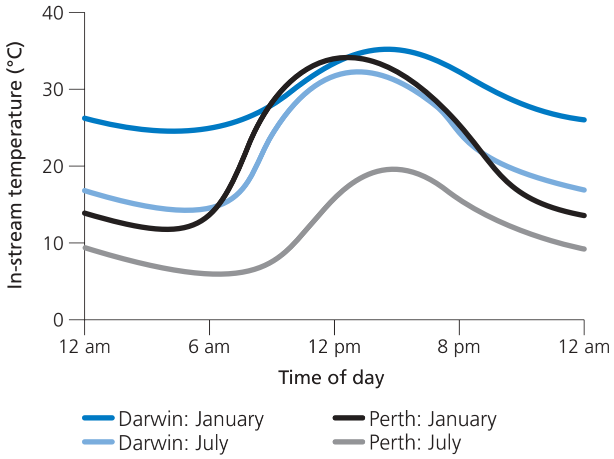


Figure 3.3. Biogeographic and seasonal contrasts in diurnal in-stream temperature. The curves are model simulations representing first order streams having zero shade under flow and weather conditions typical of summer and winter in Darwin and Perth. Note that Darwin's summer curve is considerably flatter than Perth's summer curve because of the higher summer flow in the tropics relative to Mediterranean climates.

average weather and flow conditions for summer and winter are used to simulate the daily change in in-stream temperature for a first order stream located in south-west Western Australia and in the tropics.

Because *average* monthly weather and flow conditions are used, the curves in Figure 3.3 under-represent the magnitude of day to day variation in in-stream temperature. Individual rainfall events and extreme weather conditions within any one month can have a strong influence on in-stream temperature, even within higher-order streams.

Prior to European settlement and broad scale land clearing, it is reasonable to assume that during the warmest times of the year and during times of low flow, most bioregions and catchments in Australia still experienced periods of temperature stress that equated to lethal or sub-lethal effects for resident biota. At large spatial scales, in times of elevated thermal stress higher order streams would effectively act as seasonal refugia for sensitive components of the biota. At a more local scale, deeper pools in lower order streams may also provide refugia. Under natural conditions, the interplay of climate and flow would sometimes result in the transient loss of habitat and the imposition of thermal barriers to effective dispersal. With the widespread removal or degradation of riparian vegetation, the problem today is that what was once a localised and transient loss of habitat, has become a common feature in space and time throughout many catchments. Shade provided by intact native vegetation is dependent on structural form and plant height (Table 3.2).

3.2 Light

All aquatic plants need sunlight (diffuse or direct) in order to photosynthesise. During photosynthesis, inorganic carbon (CO_2) is transformed into carbohydrates in a reaction described by the 'photosynthetic equation', which (in highly simplified form) can be summarised by $CO_2 + H_2O = CH_2O + O_2$.

$$\underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O} \underset{\text{Primary production}}{\overset{\text{Light}}{\rightleftharpoons}} \underset{\text{sugars}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2}$$

Primary production $\longrightarrow$

Respiration $\longleftarrow$

Primary production is determined by the rate of photosynthesis (or the rate at which light energy is converted to organic carbon). Respiration is the opposite process. In respiration, carbon dioxide is a by-product of the consumption of organic carbon by animals and microbes and also of the processes of cellular maintenance in aquatic plants. Consequently, light plays an essential role in the process and rate of photosynthesis, the products of which in turn support the respiration and growth of other aquatic organisms.

The distribution and production of aquatic plants in stream systems can be affected by a number of factors, but light availability is clearly the most important (Hill 1996). An increase in solar irradiation can result in increased production and enhanced biomass values in communities consisting of benthic algae (Lowe et al. 1986, Hill & Knight 1988, Hill et al. 1995) and macrophytes (Canfield Jr & Hoyer 1988).

Optimum light requirements differ for various plant groups and there is evidence that light intensity is a major factor determining the composition of stream algal assemblages (Hill 1996, Mosisch et al. 1999, 2001). For example, chlorophytes (green alga) require higher light intensities than diatoms (Langdon 1988). In a review of published minimum and maximum growth irradiances of phytoplankton groups, cyanobacteria and diatoms were found to be able to tolerate lower light intensities than were chlorophytes (Richardson et al. 1983). The filamentous chlorophyte *Spirogyra* required high irradiance levels to grow and is unable to survive under low light conditions (Graham et al. 1995). Filamentous chlorophytes (particularly members of the Zygnematales, including *Spirogyra*, *Zygnema* and *Mougeotia*) are common in clear-cut, forest streams (Lyford & Gregory 1975, Shortreed & Stockner 1983).

Table 3.2. Structural formations of Australian vegetation (adapted from Specht et al. 1995).

Life form and height of tallest stratum	Foliage cover of tallest stratum (%)			
	100–70	70–30	30–10	<10
Trees >30 m	Tall closed-forest	Tall open-forest	Tall woodland	
Trees 10–30 m	Closed-forest	Open-forest	Woodland	Open-woodland
Trees 5–10 m	Low closed-forest	Low open-forest	Low woodland	Low open-woodland
Trees <5 m	Very low closed-forest	Very low open-forest	Very low woodland	Very low open-woodland
Shrubs >2 m	Closed-scrub	Open-scrub	Tall shrubland	Tall open-shrubland
Shrubs 0.25–2 m	Low closed-scrub	Low open-scrub	Low shrubland	Low open-shrubland
Shrubs <0.25 m			Dwarf open-shrubland	Dwarf sparse-shrubland
Hummock grasses			Hummock grassland	Open hummock grassland
Herbaceous layer	Closed-grassland	Grassland	Open-grassland	Sparse-grassland
Sedges	Closed-sedgeland	Sedgeland	Open-sedgeland	Sparse-sedgeland
Herbs	Closed-herbland	Herbland	Open-herbland	Sparse-herbland
Ferns	Closed-fernland	Fernland		
Reeds/rushes	Closed-reedland	Reedland		

Examples of diverse riparian vegetation. Above: Closed forest. Photo Ian Rutherfurd. Below: Low open forest. Photo Ian Dixon.

Top: Open heathland. Above: Low open woodland. Below: Open grassfield. Photos this column Peter Davies.

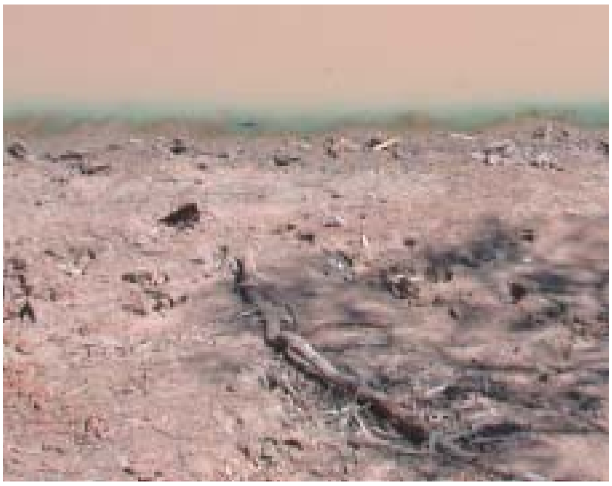
Shaded streams have lower water temperatures that favour in-stream health and productivity. Photos: (left) Roger Charlton, (right) Natalie Blood.

Assessment of aquatic food webs has shown that micro-algae such as diatoms are more readily consumed by organisms higher up the food chain than are larger plants such as filamentous algae and macrophytes (Bunn et al. 1998). Lower light inputs to streams (caused by shade and/or turbidity) and lower water temperatures enhance the production of palatable food material (Bunn et al. 1998, Bunn & Davies 2000). Furthermore, excessive growths of macrophytes and filamentous green algae in stream channels, when stimulated by high light intensity and high nutrient levels, cause major changes in aquatic habitat and can reduce oxygen levels through plant respiration and the decomposition of accumulated organic matter. At high light levels, there is a shift in plant growth to macrophytes (Bunn et al. 1998) which do not readily enter aquatic food webs (Bunn et al. 1997). In this case, macrophytes encroach the channels, increasing the incidence of localised flooding. Shading alone, independent of nutrient status, was found to control invasive macrophytes that had choked the channels of open streams in the tropical canelands of far north Queensland (Bunn et al. 1998) and streams in the sub-tropics (Mosisch et al. 2001).

It is worth noting here that riparian shading may not be the only factor limiting light availability within the water column in some streams and rivers. In many of the inland-draining river systems in central Queensland (such as the Paroo, Warrego, Cooper and Diamantina) sustained high turbidities, which limit light availability, are a natural characteristic. A study of ecosystem processes in the permanent pools of Cooper Creek, near Windorah in Queensland, has revealed a highly productive littoral band of benthic filamentous cyanobacteria (*Schizothrix*) as a "bath-tub ring" (see photo below) (Bunn & Davies 1998, Bunn et al. 2003). The vertical distribution of this productive band is clearly light-limited in these highly turbid systems.

The previous discussion demonstrates that variations in productivity and composition of aquatic plant groups, which often reflect changed light availability (e.g. following clearing of riparian vegetation), can lead to dramatic changes in the structure and function of stream ecosystems. At one extreme, productive diatom communities in cool, shaded streams can represent a high-quality source of food for primary consumers. At the other extreme, prolific growth of filamentous green algae and invasive macrophytes in open stream channels can lead to loss of aquatic habitat and severe water quality problems.

With turbid water, in-stream production is possible only near the surface and along the shallow margins. Photo Peter Davies.



3.3 Factors influencing the degree of shading by riparian vegetation

The effectiveness of riparian vegetation in shading a stream channel depends on factors such as canopy height, foliage density, channel width and orientation, valley topography, bank height, latitude and season (see Figure 3.4). Up to 95% of the incident solar radiation can be blocked by a full riparian tree canopy covering a narrow stream channel (Hill et al. 1995, Hill 1996). Nuisance stream algae and macrophytes can be significantly restricted by a dense canopy of overhanging riparian vegetation (Mosisch et al. 1999, 2001).

Probably the most visual factor determining the effectiveness of riparian shading is stream channel width. Moving down the stream network, the shading effect of riparian vegetation decreases as the stream channel widens. The total quantity of light available for algae and other aquatic plants in streams is also dependent on latitude and on seasonal differences in day length and sun angle. An important factor determining the impact of this is the orientation of the stream channel in relation to the trajectory of the sun. In addition to seasonal (or long-term) variations in incident sunlight, benthic stream communities can also be subjected to short-term variations in irradiance; for example, through the sun-fleck effect in a stream channel shaded by dense riparian vegetation (Hill 1996).

Factors such as orientation can have a local effect; canopy cover alone in south-east Queensland explains most of the variation in below-canopy light regime (Bunn et al. 1999, Mosisch et al. 1999). In this study, 75% canopy cover was required to reduce light intensities below the thresholds required for growth of filamentous algae. However, although 75% shading may be needed to reduce the light threshold for aquatic plants, more moderate levels of shading (for example, 50%) may be sufficient to reduce water temperatures — vegetation has

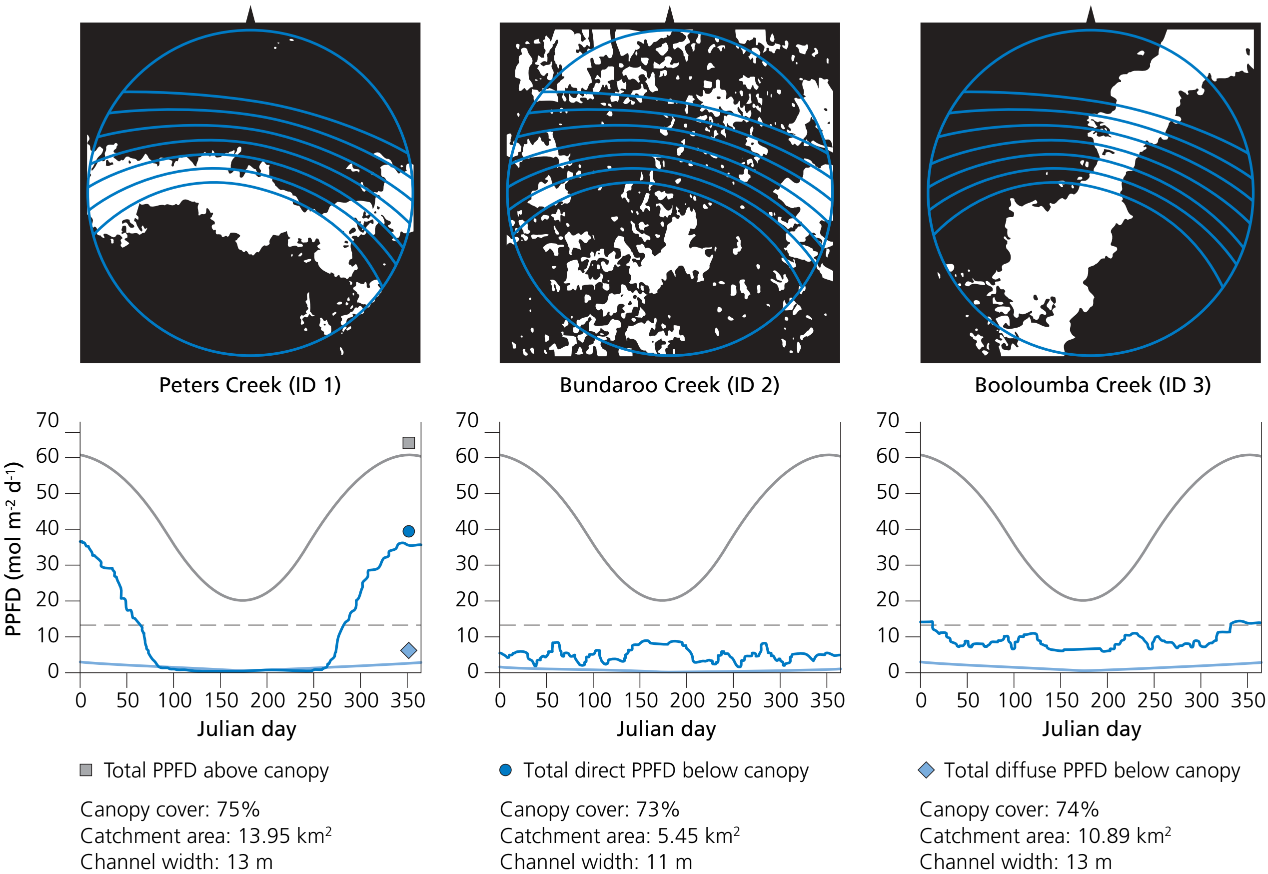


Figure 3.4. Canopy photos and light intensities of forest streams showing effect of orientation in south-east Queensland (Mary River). The dashed line indicates the threshold level of radiation required for growth of filamentous algae (PPFD of 12.8 mol m^{-2} d^{-1}). The east–west aligned channel (Peters Creek) is subjected to greatly reduced irradiance levels during the middle of the year as a result of shading by riparian vegetation along the northern stream bank. During summer, stream communities are subjected to highly elevated light intensities as a result of the solar tracks passing along the long axis of the canopy gap. This results in light conditions favourable for the growth of filamentous chlorophytes. In contrast, the north–south oriented channel of the Booloumba Creek site is subjected to much less extreme variation in irradiance because all solar trajectories pass over only a short distance of the canopy gap. Irradiance levels in this case stay at, or below the threshold level required for increased growth of filamentous chlorophytes. Source: Bunn (1997).

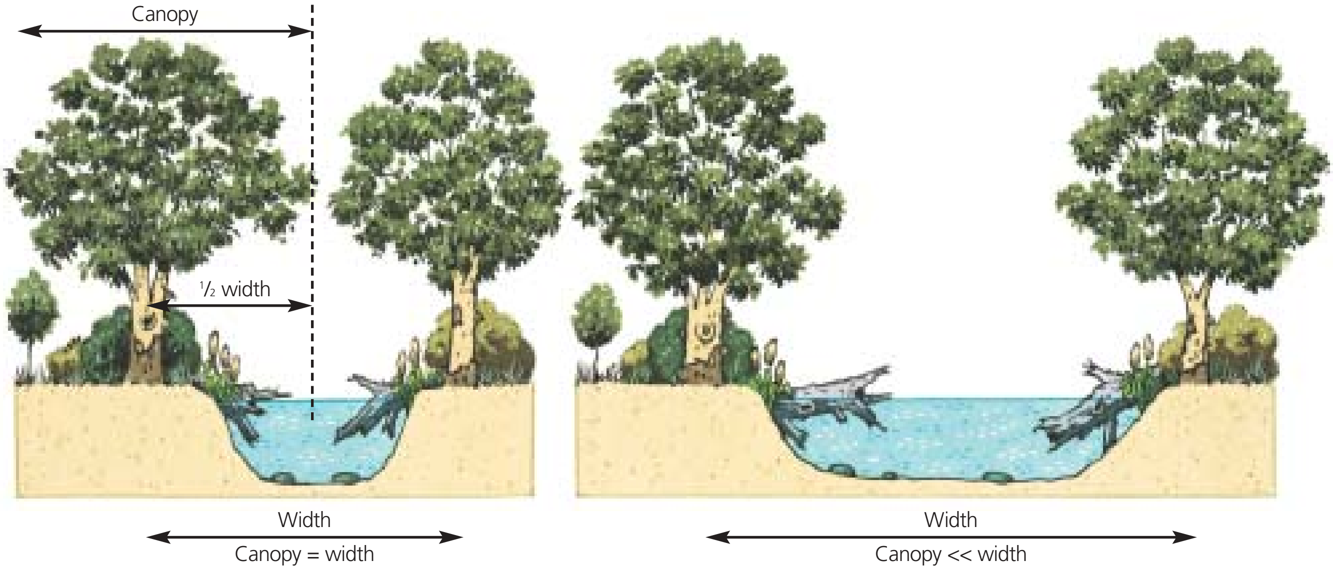


Figure 3.5. Influence of channel width on cover. A small stream could be completely shaded if the active channel width (w) was equal to or less than the width of the tree canopy (c). As channel dimensions increase, and vegetation height and width remain relatively uniform, riparian shading of the channel becomes less effective. Note that the shallow littoral zone may still be effectively shaded even in these larger streams. Source: Unpublished data, T. Mosisch (1997). Illustration Paul Lennon.

a greater filtering effect in the infra-red/red region of the solar spectrum, that is responsible for most of the heating of surface water. Stream orientation may be more important in influencing water temperature in temperate systems.

Even in situations where the main part of a wide stream channel does not receive any shade, algae and aquatic macrophytes located along the edges of the channel can still be subjected to the shading influences of trees and large shrubs for some period of the day (Hill 1996). Consequently, riparian vegetation may exert a major control on the distribution and productivity of semi-aquatic and aquatic plants in the shallow littoral zone of larger rivers.

In rainforest streams, 75% cover can be achieved by mature vegetation on channels about 8–10 metres wide or less; which translates to sub-catchments of ~8–10 km^2 or less. Note that these relationships will vary with latitude. At higher latitudes (for example, southern Victoria and Tasmania) the canopy cover required to prevent excessive growths of filamentous algae is less than this due to the lower intensity of incoming solar radiation. In more-open forest types, effective shading (75% cover) may be achieved along only smaller streams. Nevertheless, this shade is important as most of the total catchment area is made up of such streams.

This chapter demonstrates that riparian vegetation, which influences the amount of light reaching streams and also water temperatures, has the ability to affect the growth of aquatic plants and animals, water quality, aquatic habitat and ecosystem function. Controlling the light and temperature environment by maintaining or replanting riparian vegetation is, therefore, an important consideration in the management of riparian areas.

The following guiding principles are important for setting priorities for riparian restoration to meet temperature and light targets (see Davies et al. 2004b):

~ Restore upland (lower order) streams before higher order streams (however, for thermal refugia for fish in major rivers, revegetation of tributaries is recommended near the confluence).
~ Restore reaches with negligible riparian vegetation before trying to improve low density vegetation.
~ Restore streams on north-west aspects before those on south-east aspects.
~ Preferentially restore reaches where soil properties favour the establishment of replanted vegetation.

To assist stream managers in setting priorities based on in-stream temperature Land & Water Australia's *River and Riparian Management Technical Guideline*, number 5 'Managing high in-stream temperatures using riparian vegetation' provides a step-by-step process that can be used to determine where restoration efforts need to be focussed. The guideline is available from www.rivers.gov.au or in hard copy from CanPrint Communications on 1800 776 616.

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CHAPTER 4

Aquatic food webs

Stuart Bunn and Peter M. Davies

Summary

- Organic matter from aquatic and terrestrial sources provides the carbon energy that 'drives' aquatic food webs. Most streams and rivers are heterotrophic — that is, more carbon is consumed (e.g. by animals and bacteria) than is produced within the system by aquatic plants. However, despite the presence of vast amounts of carbon in streams and rivers, only a small proportion of the total is truly available for consumption by aquatic animals.
- A large proportion of the total carbon pool in many streams and rivers is in the form of wood, which provides an important substrate for algal colonisation, especially in lowland rivers.
- In temperate forest streams, coarse-particulate organic matter, fine-particulate organic matter and dissolved organic matter derived largely from the riparian zone are important sources of carbon for aquatic food webs.
- Food webs in tropical, subtropical and arid zone streams show a greater dependence on algal carbon, as do those in most lowland rivers. Macrophytes in larger rivers and wetlands appear to contribute very little directly to aquatic food webs, though they are clearly an important food source for some species of water-birds.
- Riparian fruits and arthropods may also be an important food source for fish and other vertebrates in forest streams.
- Riparian vegetation regulates in-stream primary production in small streams and supplies energy and nutrients; consequently, its removal can radically change the quality and quantity of carbon in food webs and the function of aquatic ecosystems.

4.1 Sources of organic carbon for aquatic food webs

Carbon is the principal building block of all living tissue and the fundamental element that drives ecosystems. In aquatic systems carbon sustains populations of fish, water-birds and other aquatic or semi-aquatic vertebrates. Understanding the fluxes of organic carbon and the nature of interactions among producers and consumers is not only a fundamental theme in the ecology of streams and rivers (Robertson et al. 1999, Douglas et al. 2005), it is also essential knowledge for the sustainable management of riverine environments as healthy ecosystems. This is because many human activities affect food web structure and important ecosystem processes (e.g. though excessive nutrient loading or disruption of essential nutrient cycles — Vitousek et al. 1997).

Terrestrial sources

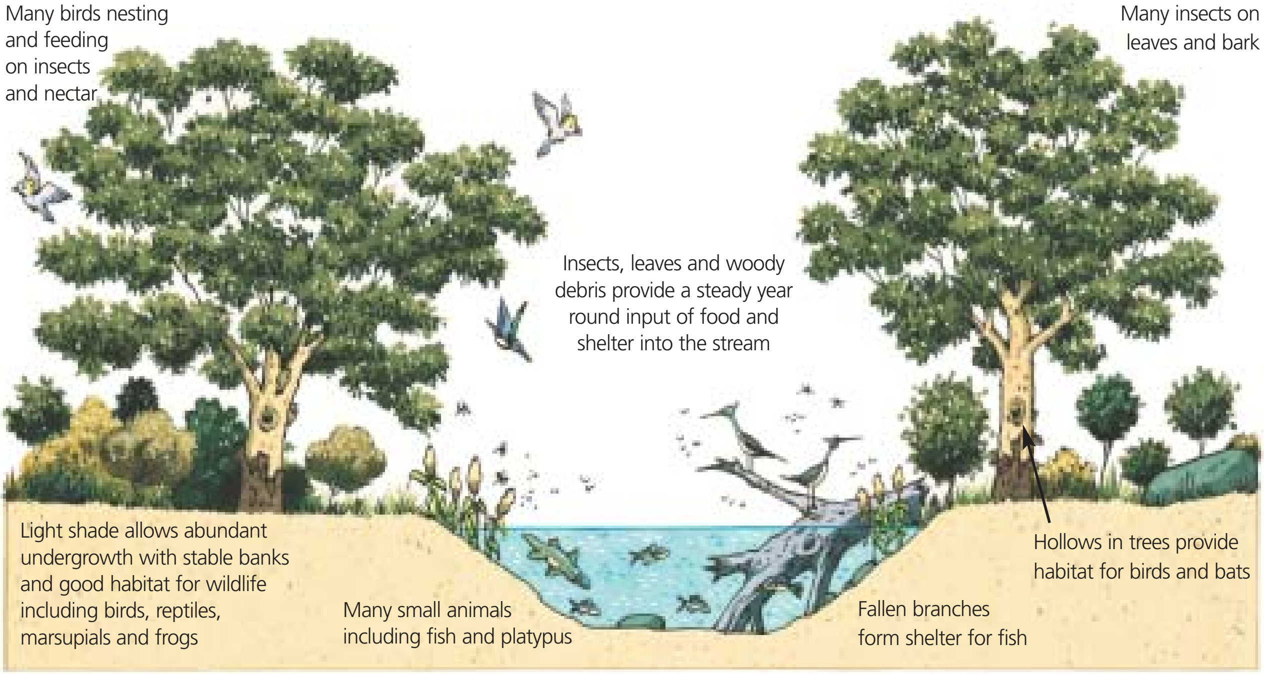
Forested streams receive large quantities of terrestrial organic carbon in the form of:

~ logs and branches,
~ leaf litter, bark and other coarse-particulate organic matter (CPOM),
~ fine-particulate organic matter (FPOM),
~ dissolved organic matter (DOM).

These enter directly from the riparian zone or are washed or blown in from elsewhere in the catchment. Leaves usually make up the greatest proportion of direct inputs of litter, although bark, branches and fruits may contribute significantly in some forest types (Briggs & Maher 1983, Bunn 1986, Campbell et al. 1992, Lake 1995). Other riparian inputs, such as insects and fruits, can also be important sources of carbon for in-stream consumers (Gregory et al. 1991, Pusey & Arthington 1993).

Much of the variation in litter fall in stream and river ecosystems can be explained by the amount of rainfall, with arid lands having the lowest values (Benfield 1997, Bunn et al. 2005). Litter fall in the dry eucalypt forests is less than that in the wetter forests (Pressland 1982, Lake 1995, Benfield 1997). Contrary to what might be expected, the quantities of litter fall in Australian forests are comparable with those of the deciduous and coniferous forests of North America and Europe.

A large proportion of the total carbon pool in many streams and rivers is in the form of large wood (Robertson et al. 1999). Natural wood loadings in Australian streams and rivers appear to be largely dependent on the density of fringing riparian trees (Marsh et al. 2001). Once in the stream, wood usually moves and decomposes slowly compared with other



Leaf litter and fine organic material from the riparian zone are a major source of carbon entering streams. The total amount of terrestrial carbon entering depends on the climate and vegetation (see diagram and photos). Illustration Paul Lennon.

Left: Moist forest provides significant carbon inputs to streams. Photo Peter Davies. Above: Dry eucalypt forests have lower inputs. Photo CSIRO Sustainable Ecosystems. Below: Arid rivers have relatively low inputs of terrestrial carbon from the riparian zone. Photo Ian Dixon.

Logs and branches form a major proportion of the total carbon pool in forest streams. Photo Martin Read.

carbon sources and so remains in situ for longer. Decomposition of woody material can contribute significantly to the supplies of DOM (Cummins et al. 1983) and FPOM (Ward & Aumen 1986). These are readily transported in the water column and may provide food for aquatic organisms.

FPOM in streams is derived from a number of sources, including the processing of CPOM and wood, riparian soil particles, flocculated DOM, and algal production (Ward 1986). The relative contributions of these sources to the FPOM pool are not well known. This is unfortunate, because the source of FPOM dictates its quality as food for invertebrate consumers.

DOM can be a major component of the total organic carbon budget of streams and rivers (Meyer 1986, Lake 1995, Robertson et al. 1999). Some carbon from this source is derived directly from the leaching of soluble carbon compounds from litter in streams. However, much makes it way to the stream via groundwater (e.g. Trotter 1990).

Aquatic sources

Primary production in small forest streams is limited by the degree of riparian shading (Feminella et al., 1989; Boston & Hill 1991, Chapter 3). Benthic (bottom) microalage are the most important primary producers in these small streams, whereas phytoplankton plays a relatively minor role, especially in turbulently flowing systems. Macrophytes are typically rare in shaded forest streams and also contribute little to the overall production. There are significant latitudinal differences with higher rates of production in tropical streams compared with those in more temperate regions (e.g. Lamberti & Steinman 1997, Bunn et al. 1999). Similarly, rates of primary production in arid and semi-arid streams are also typically much higher than their temperate counterparts, in response to lower riparian cover and latitude (Bunn et al. 2005). In many Australian lowland rivers, naturally high turbidity has a far greater influence on the distribution of aquatic plants and rates of primary production than does riparian shade (Bunn et al. 2003, Bunn et al. 2005). The effect of control on aquatic primary production by riparian vegetation in forest streams is most striking in systems where the canopy has been removed (e.g. Bunn et al. 1998, 1999). The loss of riparian shade and inputs of nutrients (e.g. from agriculture) can lead to explosive growths of nuisance algae and macrophytes (see Chapter 3).

Autotrophy and heterotrophy

In many stream and river systems, the inputs of organic matter from riparian and catchment sources (i.e. allochthonous carbon) far exceed the amount produced from aquatic plants within the stream channel (autochthonous carbon). This is especially true for small forest systems but is also the case for many large rivers. When more organic carbon is consumed and respired (e.g. by animals and bacteria) than is produced by aquatic plants, stream ecosystems are described as heterotrophic — that is, they are dependent on external sources of carbon. In simple terms, this occurs when respiration (R) exceeds gross primary production (P)

Forest streams are typically well shaded and this has a major control on the composition and production of aquatic plants. Photo Stuart Bunn.

In some arid zone streams, high levels of suspended sediment in the water control aquatic primary production. Photo Stuart Bunn.

Loss of riparian cover can result in prolific growths of nuisance aquatic plants and lead to a decline in stream health. Photo Nick Schofield.

In some cases, weeds can invade the channel and destroy aquatic habitat, here shade cloth is being used to kill weeds. Photo Stuart Bunn.

and P:R ratios are less than one. In this regard, most streams function in a very different way from many other aquatic ecosystems such as lakes and oceans, which are often autotrophic (that is, where P:R ratios are greater than one).

As expected, small forest streams studied in Australia appear to be heterotrophic (Robertson et al. 1999). For example, a patch-weighted annual P:R of approximately 0.72 was estimated for upland streams in dry sclerophyll forest in south-western Australia (Davies 1994). An annual P:R value of 0.83 was recorded for Keppel Creek, a mixed eucalypt forest in the Victorian highlands (Treadwell et al. 1997). Similar values have been recorded for small, undisturbed forest streams (catchments less than 10 km^2) in the wet tropics of northern Australia (mean P:R = 0.57) and in similar-sized sub-tropical streams in south-east Queensland (mean P:R = 0.87) (Bunn et al. 1999). To a large extent, this heterotrophic nature is a reflection of the high degree of canopy cover and low light levels in these small streams, which limit algal production. However, the rates of gross primary production recorded for these forest streams are at the low end of the world scale (Lamberti & Steinman 1997) and it is likely that the poor nutrient status of soils across much of the Australian continent is a key contributing factor (Bunn & Davies 1990).

Terrestrial inputs can also be an important contributor to the carbon pool of streams in semi-arid or sparsely wooded catchments (Boulton 1988). However, the open riparian canopy in these systems diminishes the controlling influence on in-stream primary production (shade) and the relative contributions of in-stream sources of carbon are often greater than in similar-sized streams in forested catchments (Lake 1995). In one of the few early studies of stream ecosystem function in Australia, it was found that a woodland stream site near Armidale, NSW, was autotrophic (P:R = 1.22) (Pidgeon 1978). Desert streams typically have much higher values of gross primary production and higher P:R ratios than their forest stream counterparts (Lamberti & Steinman 1997). This is even the case in highly turbid systems, such as those in the Lake Eyre Basin of Australia (Bunn et al. 2003, 2005).

Models of large river ecosystems

The sources of carbon, and their overall quality and quantity, change according to the position in the stream hierarchy. This is partly because the direct (lateral) contributions of carbon from riparian vegetation decrease relative to inputs from upstream processes as you travel downstream, and partly because the increased channel dimensions downstream reduce the extent to which vegetation regulates in-stream primary production.

Undoubtedly, the strongest links between the catchment and the stream, in terms of energy and nutrients, exist in the smaller tributaries. However, the importance of riparian influences on larger rivers is less well understood. Three major conceptual models have been proposed to describe ecosystem processes in large rivers and differ considerably in their predictions of the relative importance of terrestrial and aquatic sources of production (Figure 4.1).

The River Continuum Concept (RCC) (Vannote et al. 1980) emphasises the importance of carbon and nutrients 'leaking' from upstream processes to the lower river reaches. In this model, middle order reaches (where the direct effects of riparian shading are diminished) are seen to be more dependent on in-stream primary production (P>R). FPOM is argued to be the principal carbon source in downstream reaches and much of this is derived from upstream processing. Direct inputs of CPOM from adjacent riparian vegetation are thought to be insignificant in lowland river reaches, where in-stream primary production may also be limited by turbidity and depth.

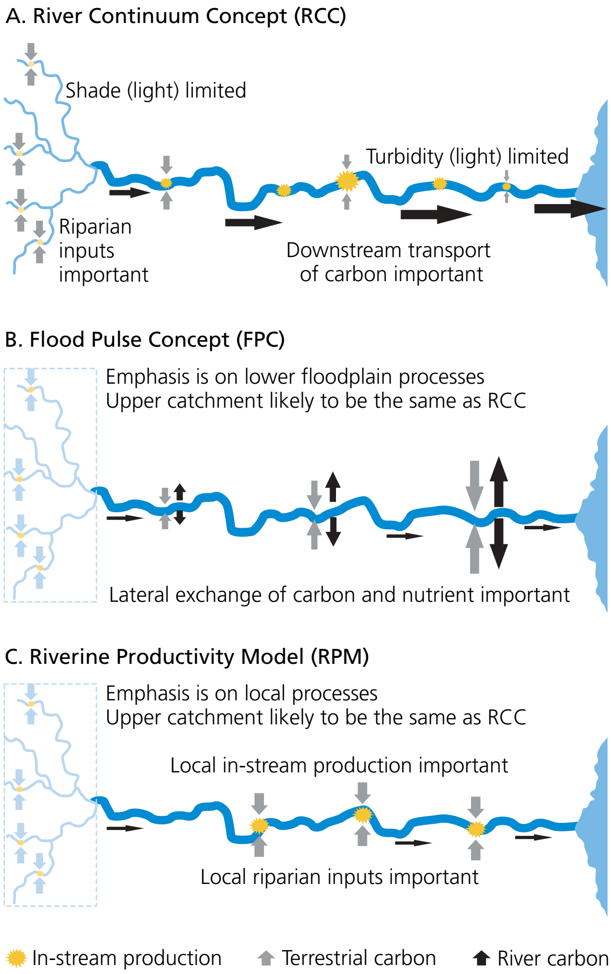


Figure 4.1. Three conceptual models of large river ecosystem function (redrawn from Bunn 1998). (a) River Continuum Concept (Vannote et al. 1980); (b) Flood-Pulse Concept (Junk et al. 1989); (c) Riverine Productivity Model (Thorp and Delong 1994).

The Flood Pulse Concept (FPC), derived for large (floodplain) river systems, emphasises important river–floodplain interactions and suggests that riverine food webs are driven by production within the floodplain rather than by organic matter transported downstream (Junk et al. 1989). Inundation of floodplains also promotes microbial activity and decomposition of litter on the forest floor and increases nutrient availability (Malanson 1993, Molles et al. 1995).

The Riverine Productivity Model (Thorp & Delong 1994) emphasises the importance of local autochthonous production (phytoplankton, benthic algae and other aquatic plants) and of direct carbon inputs from adjacent riparian land. The RCC and FPC models are considered to have underestimated the role of local sources and have overemphasised the transport of organic matter from headwater streams (RCC) or floodplains (FPC). Although the RPM was originally

In larger rivers, the degree of riparian control on in-stream processes is diminished. Food webs in these systems are likely to be strongly dependent on aquatic production, rather than on terrestrial carbon from upstream. Photo Stuart Bunn.

Flood pulses in large floodplain rivers provide an opportunity of lateral exchange of terrestrial carbon and nutrients. However, it is unclear as to whether this is an important contributor to river food webs. Photo Angus Emmott.

The boom of aquatic production that is associated with these infrequent events sustains dryland rivers during dry spells. Photo Narran Lakes Ecosystem Project.

proposed for highly regulated river systems that have been effectively isolated from their floodplains, Thorp and Delong (2002) have since proposed that this model may also be more broadly applicable to unregulated, floodplain rivers.

These three models of ecosystem processes in large rivers differ considerably in their emphasis of the strength of direct riparian linkages and the relative importance of terrestrial and aquatic sources to food webs (see Walker et al. 1995, Bunn 1998, Robertson et al. 1999). Recent work on waterholes in turbid, arid rivers highlights the importance of local sources of primary production during dry spells, supporting the RPM (Bunn et al. 2003). Flood pulses also clearly play a significant role in these systems, although in contrast to the FPC, much of the production during floodplain inundation appears to be driven by aquatic sources (Bunn et al. 2005, in press). While the lower River Murray may well have functioned according to the predictions of the FPC prior to European settlement, the extensive reduction in duration and frequency of flood pulses has undoubtedly changed this. Research on ecosystem processes in a regulated 100 kilometre stretch of the Murrumbidgee River showed a shift from strongly heterotrophic upstream to almost balanced downstream, with much of the primary production dominated by phytoplankton (Vink et al. 2005). Further research is currently underway to improve our understanding of ecosystem processes in the Murray and other Australian lowland rivers.

4.2 Food webs

Changes to the structure and composition of riparian vegetation, particularly those influencing the degree of shading (see Chapter 3), can obviously have a considerable effect on the quantity and quality of primary carbon sources for aquatic consumers. However, as in most aquatic systems, only a small fraction of the total carbon present is actually consumed by larger animals, enabling it to enter the food web. Much of it is mineralised by bacteria or simply transported to the sea. Not all carbon is of sufficiently high quality for 'larger' (that is, multi-cellular or metazoan) consumers in the food chain, and not all is truly 'available' because other factors prevent consumers from reaching some sources (for example, the availability of stable substrate may limit the numbers of filter-feeding invertebrates). As a consequence, large variations in the quantity and composition of organic carbon may not have any direct flow-on effects to primary and higher order consumers, especially if it is highly refractile and of low food quality.

Carbon from aquatic and terrestrial sources is directly consumed by invertebrates and some fish and decomposed by aquatic fungi and bacteria. Aquatic insects represent much of the biodiversity, abundance and biomass of animals in streams and rivers and are major consumers of organic matter (Bunn 1992). In turn, these smaller primary consumers are essential elements of the food web, which supports predatory invertebrates, fish, other aquatic vertebrates, terrestrial and semi-aquatic consumers in the riparian zone.

Understanding stream and river food webs requires identification of the sources of organic carbon that are consumed and assimilated by metazoan consumers. This difficult task has been made simpler with the advent of stable-isotope tracing techniques (Peterson & Fry 1987, see box on opposite page). Multiple stable isotope analysis offers a powerful alternative approach to the traditional methods of assessing food resources used by consumers.

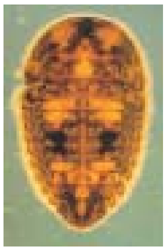
Food webs in small streams

There is considerable evidence that food webs in small, temperate forested streams are dependent on riparian inputs of carbon (Hynes 1975, Vannote et al. 1980, Rounick et al. 1982, Rounick & Winterbourn 1982, Winterbourn et al. 1986, Rosenfeld & Roff 1992). Riparian inputs of organic matter (CPOM, FPOM and DOM) also appear to be important in the food webs of some small forest streams in Australia (Bunn 1986, Davies, 1994, Lake 1995, Bunn et al. 1999). However, it is often not clear which of the major components of terrestrial carbon (CPOM, FPOM or DOM) is most important.

Logs and branches form a hard substrate and carbon source for aquatic bacteria, fungi and some specialised invertebrates, all of which contribute to the decomposition of wood in streams. Although fungal biomass on wood can be high (Sinsabaugh et al. 1991), bacteria and actinomycetes (slime moulds) are probably the major decomposers in aquatic environments (Aumen et al. 1983, Harmon et al. 1986, Boulton & Boon 1991). The complex biofilm of fungi, bacteria and algae that colonises submerged wood may in turn provide a valuable food source for grazing invertebrates (Scholz & Boon 1993).

Processing of CPOM by benthic invertebrate 'shredders' (organisms which eat leaves) is considered to be the most significant means of terrestrial carbon

Right: *Anisocentropus kirramus* — this caddis larva is a conspicuous shredder in east coast rainforest streams. Photo J. Hawking.
Far right: Water pennies (Psephenidae) are common grazers in many forest streams. Photo J. Hawking.
Below left: The glass shrimp (*Paratya australiensis*) is a fine particle feeder (collector-gatherer). Photo J. Marshall.
Below right: The stonefly nymph (*Stenoperla*) is an active insect predator in cool forest streams. Photo J. Marshall.



entering stream food webs in the northern hemisphere (Cummins 1974). However, shredders seem to be poorly represented in many Australian upland streams (Lake 1995), suggesting that their role in converting CPOM to FPOM is less important. Although invertebrates are clearly involved in the processing of leaf litter (Bunn 1986, Lake 1995), only a small proportion of the litter input is actually consumed (Towns 1991, Davies 1994). In many forested streams, fine-particle feeders (collector–gatherers in particular — Cummins & Klug 1979) appear to be the dominant group in terms of abundance and richness (Lake 1995), and FPOM is likely to be an important carbon source.

Stable–carbon isotope analysis has been used to estimate that at least 70% of the biomass of aquatic invertebrates in small jarrah forest streams was of terrestrial origin (Davies 1994). Similar work in small rainforest streams in south-east Queensland has also shown that many invertebrate taxa, including abundant glass shrimps, have stable carbon isotope values similar to those of terrestrial vegetation. However, grazing invertebrates (mostly psephenid beetle larvae and the cased larvae of caddis flies) are a conspicuous component of these streams and have isotope signatures reflecting an important contribution of benthic microalgae (Bunn et al. 1999). Similarly, Schmitt (2005) found that most of the spatial variation in carbon and nitrogen isotope signatures of primary consumers from subtropical streams in the Brisbane River catchment was explained by spatial variation in isotope signatures of algae (and not macrophytes or terrestrial organic matter). Data on tropical rainforest streams in far north Queensland also suggest that benthic microalgae (mostly diatoms) play an important role in stream food webs. For example, data from Opossum Creek (an upper rainforest tributary of the Johnstone River in northern Queensland) suggest that at least 70% of the biomass carbon of consumers in this stream was of algal origin (Douglas et al. 2005). Despite a dense riparian canopy, these streams appear to have sufficient light to sustain relatively high rates of primary production and, despite the presence of a considerable pool of terrestrial organic matter, algal carbon plays an important role in the food web.

Few comparable data are available for food webs in small semi-arid or woodland streams, where the riparian canopy is naturally open. However, recent stable isotope data from a range of streams in the Granite Creeks region in south-eastern Australia suggest a significant contribution of algal carbon to the diets of many invertebrates (except crayfish) and fish (Bunn unpublished data).

Stable isotope analysis

The term 'isotope' is often equated with short-lived radioactive isotopes. However, most elements of biological importance have at least two stable isotopes, although one form is often far more abundant in natural materials than the other(s). Slight variations in the ratio of these isotopes can occur because of fractionation during chemical and biochemical reactions (for example, carbon isotope fractionation during photosynthesis). The technique of stable-isotope tracing relies on the precise measurement of these variations in naturally occurring stable isotopes.

While stable-isotope analysis has been used for many years by geochemists to understand global elemental cycles, until recently its application to studies of biological and ecological processes had developed slowly. Stable-isotope tracing has now become one of the most innovative and powerful methods in the study of the flux of energy and nutrients in ecological systems (Peterson & Fry 1987, Lajtha & Michener 1994). Some major advances in our understanding of ecosystem processes have been made in recent years using this approach. Stable-isotope analysis of carbon has proved particularly effective in the study of aquatic food webs, where there are often marked differences in the isotope signatures of the major primary sources (see, for example, Peterson & Fry 1987, Boon & Bunn 1994, Bunn et al. 2003).

Although considerable fractionation of carbon isotopes can occur when plants fix carbon dioxide during photosynthesis, very little change occurs when organisms eat and assimilate the plant material. The carbon isotope signature of a consumer is determined by diet alone and reflects the signatures of the plant (or plants) consumed: in essence, 'You are what you eat'. Stable-isotope analysis has several advantages over traditional methods for determining the diet of consumers. In particular, the isotope signature of a consumer reflects material assimilated rather than merely ingested, and provides an integration over time based on the tissue turnover rates (that is, weeks to months), rather than a snapshot of food recently ingested (Peterson & Fry 1987). Mixing models have now been developed to enable the estimation of the relative importance of multiple sources to consumer biomass (e.g. Phillips & Gregg 2001, Phillips & Koch 2002).

Food webs in large arid rivers appear to be dependent on algal sources of carbon. Photo J. Marshall.

Food webs in large rivers

The importance of organic carbon derived from upstream riparian inputs to large river food webs, compared with that derived from lateral exchange (either from direct riparian inputs or pulsed inputs from the floodplain) is unknown. However, there is growing evidence, especially for tropical river systems, that little of this terrestrial organic matter contributes to the aquatic food web, and much is instead decomposed via a microbial pathway that is essentially decoupled from higher order consumers (Lewis et al. 2001). Furthermore, the fact that there is very little evidence of assimilation of terrestrial carbon in coastal food webs (Haines & Montague 1979, Peterson et al. 1985, Loneragan et al. 1997) suggests that much of the particulate organic matter carried by larger rivers is of poor quality for aquatic consumers. Primary consumers in these large rivers appear to derive much of their biomass carbon from inconspicuous sources (such as benthic or plankton microalgae), which are more palatable than the riparian particles carried many kilometres from their headwater source or available on inundated floodplains.

This also appears to be the case for large arid river systems in Australia. Stable isotope analysis of the food web in permanent waterholes on the Cooper Creek system in western Queensland indicates that many of the larger consumers, including freshwater prawns (*Macrobrachium*), crayfish (*Cherax*) and fish (for example, *Macquaria*) are ultimately dependent on a narrow littoral band of highly productive benthic algae and phytoplankton (Bunn et al. 2003). This is a surprising result as the algae are clearly limited by high water turbidity and the highly anastamosing channel system and extensive floodplain offer considerable potential for riparian inputs of organic matter.

In lowland rivers, where the depth of the water means that primary production is confined by light limitation to a narrow littoral zone, the presence of large woody pieces within the photic zone greatly increases the availability of 'hard' substrate for algal colonisation. Primary production by these algal communities may contribute a significant amount of the carbon entering these rivers. The presence of logs and branches also indirectly promotes primary production by stabilising fine gravel and sand substrates, which are in turn colonised by primary producers (Trotter 1990, O'Connor 1991).

Increases in light and, as is often the case, nutrients, may lead to considerable autotrophic production in larger rivers but, as noted, this does not necessarily imply that such sources are assimilated by aquatic consumers. Under low-flow conditions, the more lentic (slow-flowing) character of larger rivers can lead to the development of a rich planktonic community. More palatable groups of algae (such as diatoms) may contribute significantly to food webs, as they are known to do in many lakes (Wetzel 1990). However, this does not appear to be the case for many cyanobacteria, particularly those known to be responsible for toxic algal blooms (Boon et al. 1994). Stable isotope studies have confirmed that little carbon from blue–green algae is incorporated in planktonic food webs in lentic systems, although they may be a major contributor to the nitrogen pool (Estep & Vigg 1985, Bunn & Boon 1993).

Contribution of conspicuous aquatic plants to stream food webs

Recent studies of stream food webs in Australia and overseas suggest that benthic microalgae, particularly diatoms, can play an important role in the aquatic food webs of forest streams, despite the low levels of primary productivity and the enormous inputs of riparian carbon. Benthic algae (diatoms and filamentous cyanobacteria) also appear to be the major source of carbon supporting the aquatic food web of the turbid waterholes in the arid channel country. Aquatic invertebrates and other primary consumers (for example, tadpoles) will selectively feed on available high-quality sources of organic carbon in preference to the low-nutrient detrital sources derived from riparian litter inputs.

It is important to note here, however, that other groups of aquatic plants, particularly filamentous green algae, macrophytes and toxic blue–greens, do not appear to contribute to aquatic food webs (Bunn & Boon 1993, Boon et al. 1994, France 1996). Macrophytes can be conspicuous components of larger river systems (particularly the floodplain wetlands) and are often assumed to be important sources of carbon for aquatic consumers. Until recently, most of this organic production was considered to enter aquatic food webs as detritus rather than by being eaten as living tissue (Fenchel & Jørgensen 1977, Webster & Benfield 1986, Mann 1988). However, others have argued that direct consumption is more common, and more important to ecosystem function, than previously thought (Lodge 1991, Newman 1991). Certainly, macrophytes are known to be an important food source for waterfowl (Brinson et al. 1981, Lodge 1991). They also provide the structural matrix for productive epiphytes, which may then form the basis of grazing food webs (Wetzel 1990).

Notwithstanding, recent studies using stable isotope techniques provide little evidence of a significant contribution from macrophyte carbon, either through direct herbivory or via a detrital pathway (Hamilton et al. 1992, Bunn & Boon 1993, France 1996, Lewis et al. 2001). The presence of highly conspicuous and productive primary sources does not necessarily imply that these are readily available to consumers.

Stable isotope analysis has also provided strong evidence that C_4 plants (that is, those which fix carbon from carbon dioxide via the Hatch-Slack photosynthetic pathway, such as *Urochloa* — Para grass) contribute very little to aquatic food webs. Aquatic invertebrates collected beneath floating mats of Paspalum in the Orinoco wetlands (Venezuela) had carbon isotope signatures similar to those of microalgae, even though terrestrial insects from the mats showed direct assimilation of this C_4 source (Hamilton et al. 1992). C_4 plants contributed only a small proportion of the carbon-supporting aquatic food webs in the central Amazon, even though they accounted for over half of the annual primary production (Forsberg et al. 1993). Similar work in a tropical lowland stream in the sugarcane fields of far north Queensland also shows a minor contribution of C_4 carbon from cane and Para grass (an invasive pasture species) to aquatic food webs (Bunn et al. 1997). Feeding experiments have shown that shredders avoid consumption of C_4 plants and may have a limited ability to process and assimilate this material (Clapcott & Bunn 2003).

Aquatic macrophytes, *Triglochin procerum* and *Ranunculus* sp. Photo Kay Morris.

Photo Angus Emmott.

Contribution of riparian fruits and arthropods

Although riparian inputs of leaves and detritus may be an important food source for forest stream invertebrates, they are rarely eaten directly by aquatic vertebrates (Garman 1991). In contrast, terrestrial invertebrates and fruits falling from riparian land are important to the diets of many freshwater fish and other freshwater vertebrates. These terrestrial sources are easily accessed by fish in small streams, where there is overhanging vegetation and numerous bank eddies. Similar conditions can be found at the margins of larger streams where overhanging vegetation and large woody pieces cause eddies (Cloe & Garman 1996).

Riparian fruits make up the bulk of the diets of several Australian species of freshwater tortoise (Kennett & Tory 1996, Kennett & Russell-Smith 1993). The amount of fruit entering streams has been quantified in investigations of litter inputs (Benson & Pearson 1993), but few comprehensive studies have been undertaken.

Terrestrial insects have been found to form approximately one-third of the diet of the freshwater crocodile (*Crocodylus johnstoni*) (Webb et al. 1982) and a large proportion of the diets of many freshwater fish — 50% in the case of archerfish (Toxotidae) (Allen 1978); 20–50% for rainbow fish (Melanotaeniidae) (Pusey et al. 1995); 20–50% for native minnow (Galaxiidae) (McDowall & Frankenberg 1981, Cadwallader et al. 1980, Closs 1994); 60–95% for pygmy perch (Nannopercidae) (Morgan et al. 1995); and 30% for jungle perch (Kuhliidae) (Hortle 1989).

Despite the acknowledged importance of terrestrial arthropods in fish diets, studies quantifying the gross input, rate of input and availability of this food resource are non-existent in Australia and are few worldwide (Garman 1991). Factors which may affect the input include weather patterns (Angermeier & Karr 1983, Garman 1991), seasonality in arthropod numbers (Mason & MacDonald 1982, Garman 1991, Cloe & Garman 1996) and riparian vegetation type (Cadwallader et al. 1980, Mason & MacDonald 1982).

Freshwater sawfish. Photo David Morgan.

4.3 Consequences of riparian clearing for stream ecosystem function

Riparian vegetation clearly plays an important dual role in stream ecosystems, regulating in-stream primary production (through shading) and supplying energy and nutrients. The importance of these functions becomes most apparent when riparian vegetation is removed (e.g. Bunn et al. 1999, England & Rosemond 2004). To a limited extent, slight increases in light and nutrients associated with land clearing could have a positive effect on productivity in rivers, in that they stimulate high-quality algal sources. It is important to distinguish between algal sources (such as diatoms and some benthic cyanobacteria) that are preferentially eaten and other aquatic plants that are not. The former groups appear to require the low light conditions of shaded, forested streams or warm, turbid river pools, while the latter require much higher light conditions (see Table 4.1) and are most likely to proliferate in the absence of riparian shade.

Table 4.1. Irradiance levels for different algal groups and taxa

Group/taxon	Irradiance (µmol m–2 s–1)	
Diatoms (a)	< 50	Irradiance level at which these algae are likely to dominate a benthic community
Diatoms and cyanobacteria (a)	50–100	
Chlorophytes (a)	> 100	
Filamentous chlorophytes (b) (*Stigeoclonium*, *Ulothrix*)	≥ 150	
Cladophora glomerata (c)	300	Optimal irradiance levels for the filamentous green algae listed
Pithophora oedogonia (c)	970	
Ulothrix zonata (c)	1100	
Spirogyra (c)	1500	
Mougeotia (c)	330–2330	

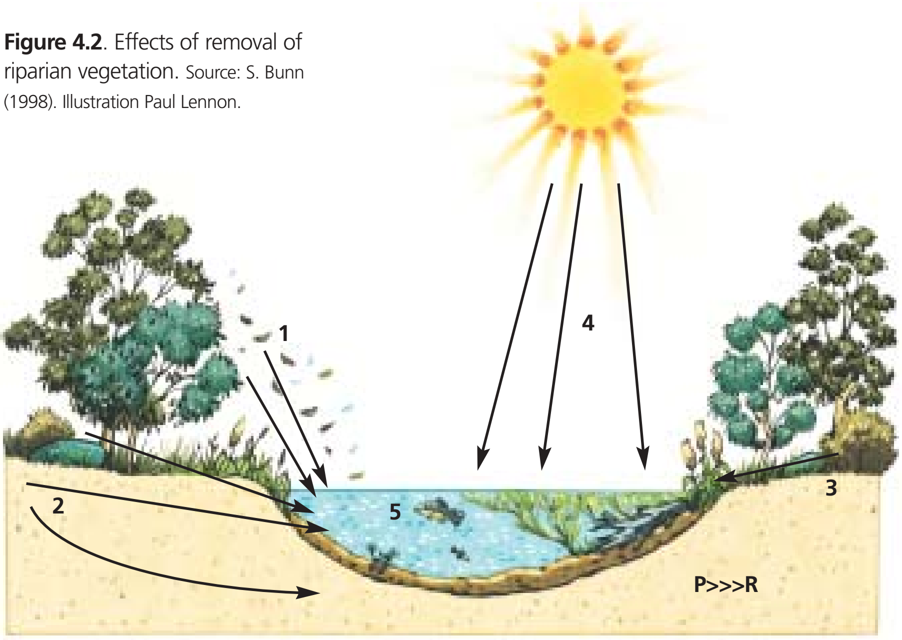
a. Steinman et al. 1989, b. Steinman & McIntire 1987, c. Graham et al. 1995.

The large vascular plants and filamentous algae that often proliferate in the absence of shade restrict flow, trap sediment, and ultimately result in marked changes in habitat and lowered water quality. A spectacular example of this is the excessive growth of para grass in stream channels in the canelands of northern Queensland (Bunn et al. 1997, Bunn et al. 1998). Clear relationships have been established between the extent of riparian cover and plant biomass (Canfield Jr & Hoyer 1988) or production (Gregory et al. 1991, Bunn et al. 1999).

Removal of riparian vegetation can also directly reduce the inputs of litter and, perhaps more importantly to fish and other higher order consumers, of fruits and insects. In addition to reducing inputs, riparian clearing can reduce primary and secondary production and has other aquatic habitat-related impacts (see Figure 4.2).

The direct changes to the carbon dynamics of streams and rivers associated with the removal of riparian vegetation have a tremendous impact on ecosystem function, particularly if coupled with increased nutrient inputs. Although eutrophication is a consequence of high nutrient levels, it is the accumulation of 'unconsumed' plant biomass (carbon) that ultimately leads to water quality problems, loss of habitat, and major declines in stream ecosystem health and biodiversity. Protecting and maintaining riparian vegetation is, therefore, vital for in-stream health.

Figure 4.2. Effects of removal of riparian vegetation. Source: S. Bunn (1998). Illustration Paul Lennon.



1. Reduced inputs of leaf litter (CPOM) and terrestrial invertebrates.
2. Changes in the quantity and quality of FPOM and DOM from surrounding catchment.
3. Reduced inputs of logs and branches.
4. Prolific growth of filamentous algae and aquatic macrophytes stimulated by high sunlight and nutrient run-off. These sources are not readily consumed by aquatic invertebrates and cause major changes in habitat.
5. High respiration from plant growth and decomposing organic matter leads to reduced oxygen and lowered water quality. This together with loss of habitat results in loss of biodiversity and major impacts to ecosystem function.

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CHAPTER 5

Managing the effects of riparian vegetation on flooding

Ian Rutherfurd, Brett Anderson and Anthony Ladson

Summary

- The major effect of removing riparian vegetation and wood from streams has been the changes in channel form (widening, deepening and straightening) that have occurred. It is important to consider that we are returning vegetation to a channel system that now has a much larger flow capacity.
- The major hydrological effect of returning vegetation to streams is via its influence on roughness and flow resistance.
- Revegetating riparian zones, or adding large wood to stream channels, increases the stage of floods at a cross-section and reach scale, although in many cases the effects are likely to be small. The effect will be greatest where the vegetation is planted across the full width of a floodplain.
- Adding or removing large wood (snags) in streams has little effect on the height and duration of large floods.
- At catchment scale, the cumulative effect of riparian revegetation is to increase flood stage and duration in headwater streams (where flooding is usually not a problem anyway), but decrease flood stage in larger streams, further downstream, where flooding may in the past have been a problem (local-scale versus network-scale effects).
- Although the effect of riparian vegetation on flooding is modest in comparison to the effects of dams and river regulation, it should be considered in planning major revegetation works. The effect is largely positive for downstream catchments, where riparian vegetation will reduce the depth of flooding. The decreased flow depth comes at the cost of slightly longer flood durations.
- Riparian revegetation should be seen as a catchment scale tool that can have a beneficial effect on flooding in lowland areas. Whilst flow regulation and landuse change affect the amount of water available in floods (magnitude and frequency), riparian vegetation affects the velocity of the flood wave delivered to the stream. All of these interacting aspects need to be considered together.

5.1 Flooding issues

Large pieces of wood (snags), and riparian vegetation growing within a watercourse, have been considered to block channels, and slow down flood flow, thereby increasing flood height. As a result, for the last 150 years people have been removing vegetation from stream bed and banks in order to reduce flood risk for adjoining landuses. At present, however, replanting native riparian vegetation is the single most common stream rehabilitation activity in Australia. Nearly 80% of all stream restoration projects involve riparian revegetation, and many involve returning wood to the stream bed.

This turnaround in management approach has meant that, in the life-time of many landholders, they have seen publicly-sponsored efforts to drain swamps, to remove wood from streams, and to clear riparian vegetation. Now they see publicly-sponsored efforts to reverse this work: to replant riparian vegetation and return snags to rivers (Erskine & Webb 2003). Since much of the rationale for removing vegetation was related to flooding and drainage, it should not come as a surprise when landholders ask whether returning riparian vegetation will also lead to a return of historical flood levels. In fact, many landholders resist efforts at riparian revegetation on the grounds that it will increase flooding problems. Are they right to do so? This chapter

A well vegetated upland riparian zone. Photo Ian Rutherfurd.

reviews recent scientific assessments of the hydraulic and hydrological consequences of revegetating riparian zones, and of returning snags to streams. These consequences in turn have effects on flood magnitude (i.e. height or stage), and flood duration. For waterway managers, this chapter addresses the following types of issues that they might encounter:

1. A farmer will not give us permission to revegetate his stream because he is concerned that his property will be flooded. What can I say to the farmer, is this a risk?
2. If we replant a 5 metre strip of vegetation along the banks of all 1st and 2nd order streams in this 1000 km^2 catchment, what will be the effect on flood levels in the catchment as a whole?
3. If we revegetate 3 kilometres of the banks of this riparian zone, what will be the effect on flood level?

5.2 What is flooding?

Before we can discuss the effect of vegetation on flooding, we need to define what flooding is. A flood occurs when water goes over the top of a stream bank and out of the channel. The flood can also be described as a hydrograph (Figure 5.1), with a rising discharge limb, a peak, and a falling limb.

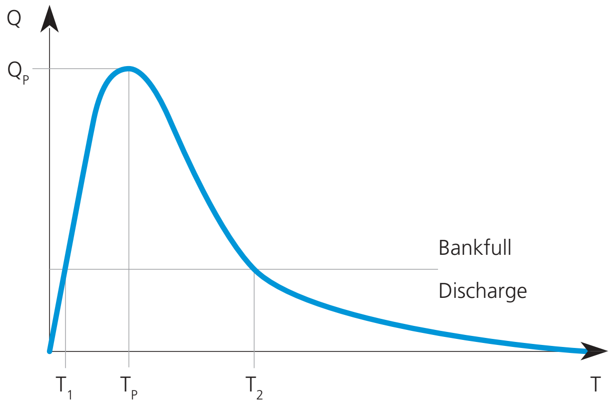


Figure 5.1. A typical hydrograph showing the change in discharge (Q) with time (T).

Catchment flood characteristics may be quantified using a variety of metrics. For this chapter interest lies in the properties of the flood hydrograph defined by the following variables shown on Figure 5.1:

~ Peak (Q_P),
~ Time to peak (T_P),
~ Duration ($T_2 - T_1$).

Other simple metrics include:

~ Flow velocity (main channel, floodplain),
~ Over-bank location,
~ Flood frequency.

A degraded lowland riparian zone. Photo Roger Charlton.

The peak of a flood. This shows that the flow out onto the floodplain can be a very slow moving pool. Photo Ian Rutherfurd.

The 'size' (or magnitude) of a flood can be measured by three related properties of the flow; the stage (or height) of the water surface[1] the duration of the flood (defined as the period of time that it is overbank), and the frequency of the flood (being how often a particular flood can be expected in a period of time). Thus, a natural floodplain could be expected to be flooded every year or two. The frequency of this flood would be 'annual' or 1–2 years recurrence interval. The stage would be defined as, for example, a "5 metre stage on the Jonesville gauge". The duration of the annual flood could vary from a few days over bank, to perhaps a week, before the water falls back within the channel. In small tributaries the hydrograph can rise and fall in hours, in large, low-land rivers, the floodplains, under natural conditions, could have stayed flooded for weeks or months.

The amount of water in a flood (the discharge) is a product of the cross-sectional area of the flow, multiplied by the velocity of the flow. The faster the velocity, the smaller the cross-sectional area, and so the lower the stage of the flood. If the flow is blocked, the velocity falls and the stage rises. A flood should be thought of as a wave of water passing down a channel, getting larger as it goes because new tributaries contribute water to the wave. Standing at one point, an observer sees the river rise and fall. This wave tends to slow down as it moves downstream, this means that the wave spreads out, or 'attenuates'. The wave contains the same amount of water, but as it slows down, the elevation of the peak of the wave (amplitude) rises, and the duration (or length) of the wave increases.

Another important influence on the size of the wave is the presence of floodplains. Floodplains reduce the size of the wave by siphoning off some of the water from the main flow and storing it for a time, effectively slowing down a part of the flow. The size of the wave (peak discharge) at a given location, therefore depends on how fast waves from the various tributaries come together, and how much water has been detained along the way.

Engineers and land holders have worked to clear, straighten and de-snag channels in order to reduce the flow resistance that would slow the flood flow and attenuate the peak. The aim of all of these 'channelisation' works has been to increase the velocity of the flood wave, decrease its height, and encourage it to pass through as quickly as possible (Brookes 1988, Mason et al. 1990, Shankman & Pugh 1992). Our research question is: does **revegetation** influence the size of the flood wave?

What makes up riparian vegetation in the context of flooding?

Riparian vegetation affects flow by coming into contact with the flowing water. Thus, vegetation growing in different parts of the cross-section interact with different flows. In the bed of the channel are the submerged macrophytes (such as reeds), and the woody pieces, that interact with all flows. As we move up the stream banks the plants are accustomed to less and less inundation. Hydrophytes give way to grass, bushes and trees up the face of the stream bank. Above the top of the bank, vegetation only interacts with annual floods.

1 Note that 'stage' refers to the height of the water relative to some reference point, usually 'gauge zero'.

A flood wave moving down Snapes Creek in Gippsland. This photo is taken near the peak of the flood, which will return within the banks within about 12 hours. Photo Ian Rutherfurd.

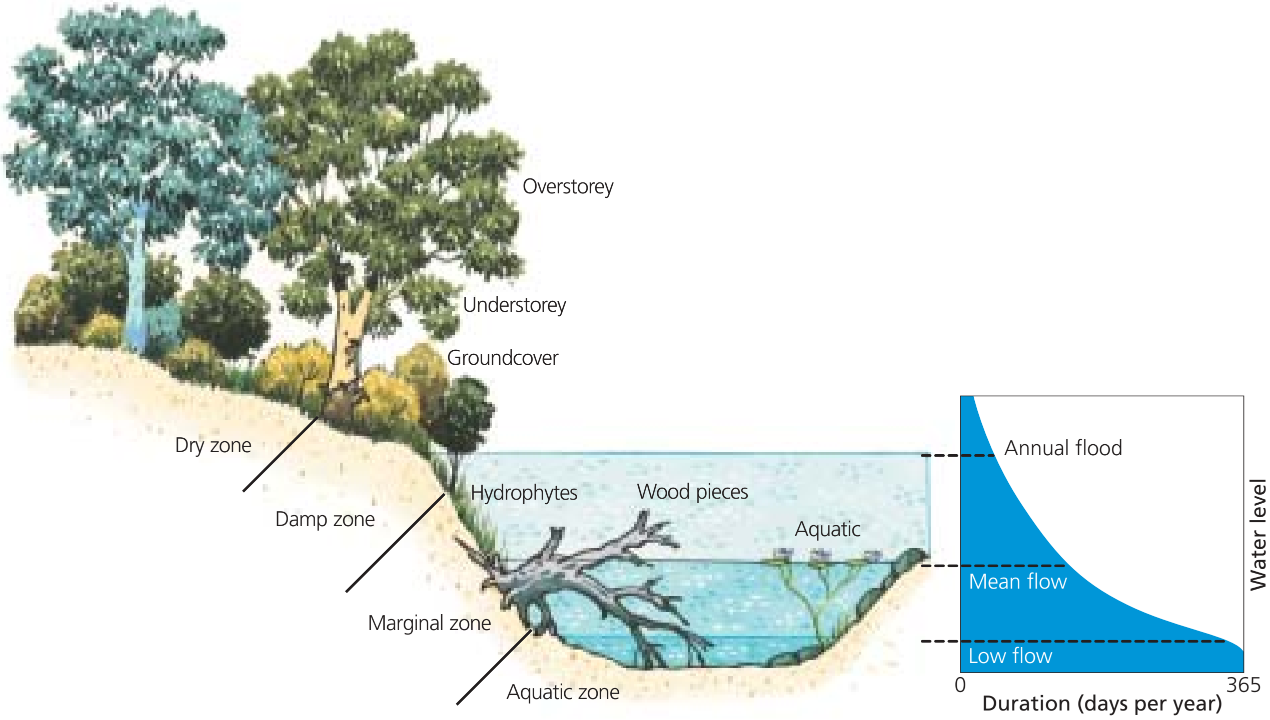


Figure 5.2. Schematic example of riparian vegetation and its interaction with flow. Illustration Paul Lennon.

5.3 What effects can vegetation have on flooding?

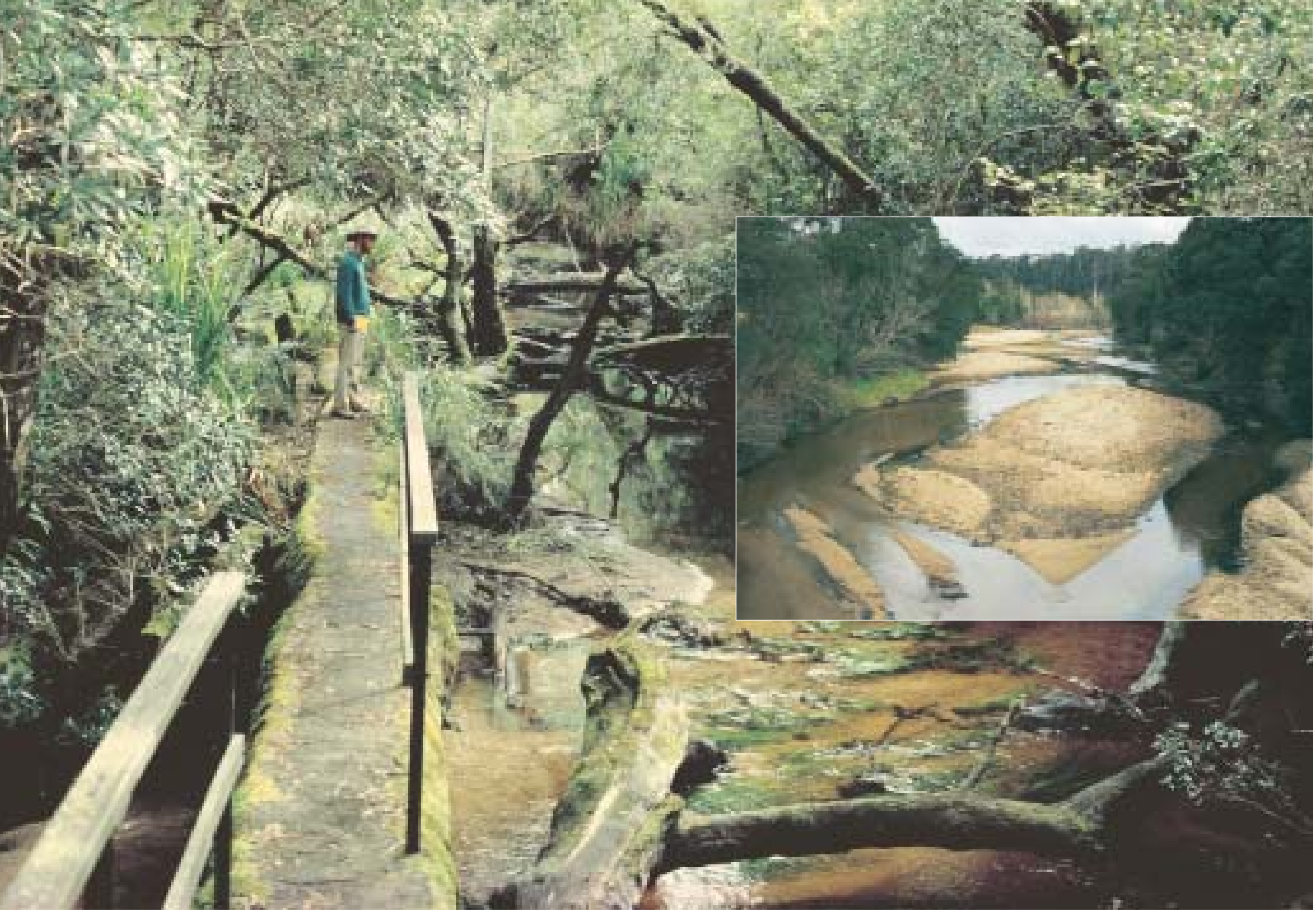
Vegetation can affect flooding in three ways: by affecting the shape and size of the stream channel (geomorphology), by altering the amount of water reaching the stream channel (hydrology), and by altering the resistance to flow (hydraulics).

Geomorphic effects of removing vegetation

When vegetation (including large woody pieces) has been removed from Australian stream channels, there are numerous reports of major changes in channel form. Such changes have included gullying, bed-deepening, and widening. There is no question that the consequences of removing vegetation on channel morphology are at least as important for flooding as are the direct effects on flow. Morphological changes to the cross-section of channels, and extension of the drainage network by gullies, alter the hydraulics and hydrology producing changes in flow and in floods.

A good example of this effect in Australia, is a comparative study by Brooks et al. (1999a, 1999b, 2003) comparing the Thurra and Cann Rivers in eastern Victoria. The contemporary condition of the Cann River differs profoundly from that which has prevailed for thousands of years, while the adjacent and undisturbed, well-vegetated Thurra system has remained relatively stable. The researchers traced a channel metamorphosis that has resulted in a 700% increase in channel capacity and 150-fold rise in the rate of lateral channel migration, changes that are attributed to clearing riparian vegetation and removing large woody pieces from the channel.

Left: Removing vegetation from the bank and catchment has led to widening and deepening. Right: Gullying triggered by catchment and riparian clearing. Both photos Roger Charlton.



Research by Andrew Brooks has demonstrated that the Cann River (inset) originally had the same form as the adjacent Thurra River, but widened and deepened in response to channelisation and riparian clearing. Photos Andrew Brooks.

Wood in streams has the potential to significantly and sometimes systematically shape channel processes across a wide range of scales (Montgomery & Piegay 2003). For example, as well as providing a direct physical barrier to flow, it affects channel form by:

~ creating steps in the longitudinal profile (Harmon et al. 1987, Keller & Swanson 1979, Marston 1982, Webb & Erskine 2003);
~ moderating sediment storage and scour within channels:
  – underpinning the forming of bars and benches (Malanson & Butler 1990, Webb & Erskine 2001),
  – regulating bedload transport (Beschta 1979, Fetherston et al. 1995), and
  – causing localised scour (Abbe & Montgomery 1996, Marsh et al. 2001).
~ contributing to the formation of pools (Buffington et al. 2002, Marsh et al. 1999, Robison & Beschta 1990, Webb & Erskine 2003) which improves habitat through the provision of cover (Hortle & Lake 1983, Richmond & Fausch 1995);
~ enhancing overbank deposition of fines, reported as the dominant deposition process on floodplains by Gurnell and Gregory (1981).

In recent years, research and experience have shown the beneficial effects of riparian vegetation on the stability of stream banks and the role of in-channel vegetation and wood in controlling bed grade and erosion. The important contribution of both to maintaining habitat complexity and biodiversity have also been accepted. This new knowledge underpins the current emphasis on reversing past clearing to improve the condition of many streams and rivers.

In this chapter we are not concerned with the effects of removing vegetation, but with the consequences of returning it. In most cases, riparian vegetation and wood is being returned to streams that have already altered the form of their channel. It is important to emphasise that revegetating streams will not simply reverse the effect of clearing the streams, returning them to their 'pre-European' form. Instead, we are considering the effects of returning vegetation to already altered channels.

Hydrological effects of riparian vegetation

Vegetation can have numerous impacts on the amount of rainfall that becomes runoff, and enters streams (Table 5.1). Although riparian zones make up only a small percentage of the total area of a catchment, they can make up a large percentage of the land adjoining first-order streams which is the main source of runoff. Overall, the main effect of riparian vegetation on hydrology (i.e. the amount of water entering streams) is on base flow rather than on flooding. Thus, the remainder of this chapter deals with the hydraulic effect of vegetation on flow resistance.

Table 5.1. Hydrological impacts of vegetation.

Role of vegetation	Mechanism
Physical impacts	
1. Interaction with overbank flow by stems, branches and leaves generating turbulence and limiting rilling and rain splash	*Quick flow* *
2. Flow diversion by log jams	*Quick flow* *
3. Change due to litter in the infiltration rate of flood waters and rainfall	*Infiltration*
4. Increase in turbulence as a consequence of root exposure	*Quick flow* *
5. Increase of substrate macroporosity by roots which prevents slaking	*Infiltration*
6. Increase of the capillary fringe by fine roots	*Infiltration*
7. Stemflow — the concentration of rainfall by leaves, branches and stems	*Interception*
8. Condensation of atmospheric water and interception of dew by leaves	*Interception*
Physiologic processes	
1. Hydraulic lift, uptake of water from deep soil layers	*Soil moisture*
2. Hydraulic redistribution, lateral water flow to support root growth in dry soil zones which also limits soil moisture fluctuations, reducing desiccation	*Soil moisture and infiltration*
3. Water storage in large roots	*(Storage)*
4. Water storage in the stem	*(Storage)*
5. Water storage in branches and leaves	*(Storage)*
6. Evapotranspiration	*Soil moisture*

* These processes also have significant hydraulic implications.

Resistance effects of riparian vegetation at a cross-section and a reach

The scientific literature contains a number of excellent reviews on the topic of fluvial resistance; most recently works by Bathurst (1993) and Yen (1991). However, most of the work on the resistance effects of vegetation are based on studies of small vegetation elements. What is missing is a way of representing the effects of all plants, small and large. Dawson and Charlton (1987) list some of the factors that influence the magnitude of resistance offered by a plant or stand of plants:

~ the height of vegetation relative to the depth of flow,

~ plant characteristics such as stem diameter, leaf size, surface texture and specific gravity which vary with the age of the plant and often the season,

~ flexibility of the stems or the whole plant stand (e.g. in the case of a reed bank),

~ orientation of stems within the plant and their areal density,

~ degree of stem compaction with increasing flow velocity and the associated change in stand permeability,

~ distribution of individual plants within a stand, their frequency and dispersion pattern,

~ orientation of the plant with respect to the local flow direction.

Vegetation affects flood velocity, and so flood stage, in three ways:

1. by directly occupying space in the channel cross-section, and so reducing capacity,
2. by using energy in the flow (such as by vibrating), and
3. (the most important effect) is to block flow and reduce velocity.

Stream with flow close to bankfull. Note the flow in the canopy of the trees on the right side of the photo. Photo Ian Prosser.

The way to think about the effect of vegetation is in terms of 'backwater' curves. Behind each piece of vegetation that blocks the flow, the water level rises slightly as the velocity slows. This raised water level then slows the water immediately upstream, which also rises, which raises the water level upstream, and so on. The result is a curve of slower, higher, water extending upstream from the blockage. The larger the blockage by the vegetation, the higher and longer is the backwater curve. The lower the slope of the channel, the further upstream the backwater effect will extend (Figure 5.3).

A backwater curve is essentially a form of water storage. If velocity is slowed at one point, then the water will not be delivered downstream so quickly. The water that is already downstream will drain away, and so the water level will drop. Thus, slowing a flood wave will increase the depth and duration of that flood wave upstream, and the storage will produce a fall in the downstream hydrograph. The effect of vegetation is essentially a balance between slowing of the floodwave by local roughness (leading to a local rise in flood stage and increased storage) versus slowing of the flood wave as it propagates through the network (leading to a lower peak downstream, but longer duration).

The way to think about the hydraulic effect of vegetation is to consider four scales of effect:

1. the local backwater effect of a single plant and a small group of plants, then
2. to combine all of the effects of the backwaters from many plant communities at a given cross-section, then
3. combine the effect over a series of cross-sections, at a reach, and
4. finally consider the attenuation of a flood wave as it passes through the whole catchment (see Figure 5.4).

Reeds (macrophytes) provide high resistance to flow until they lie down, when they can actually reduce resistance. Photo Guy Roth.

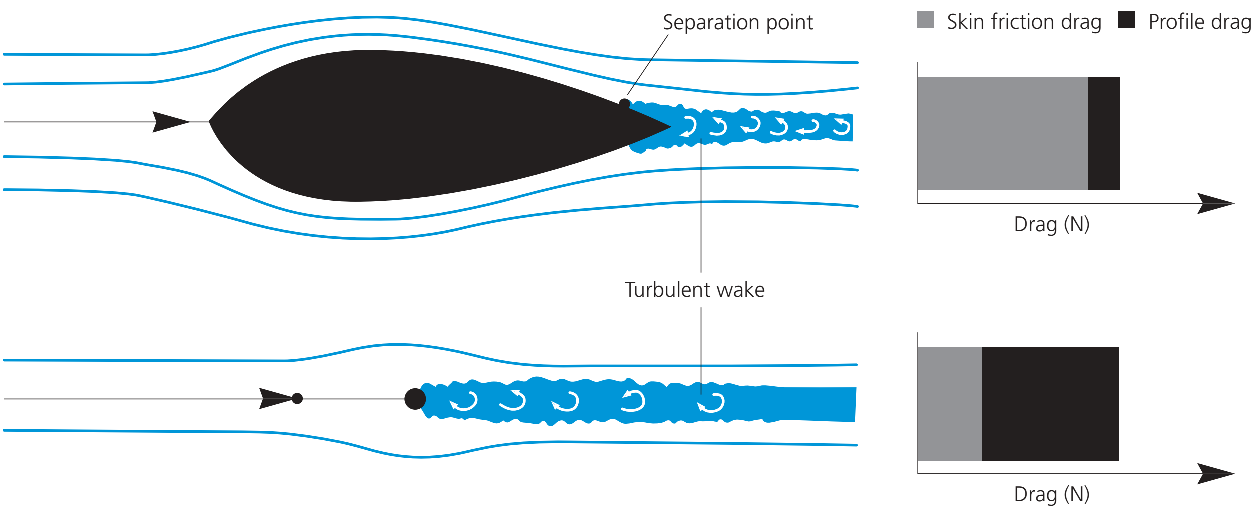
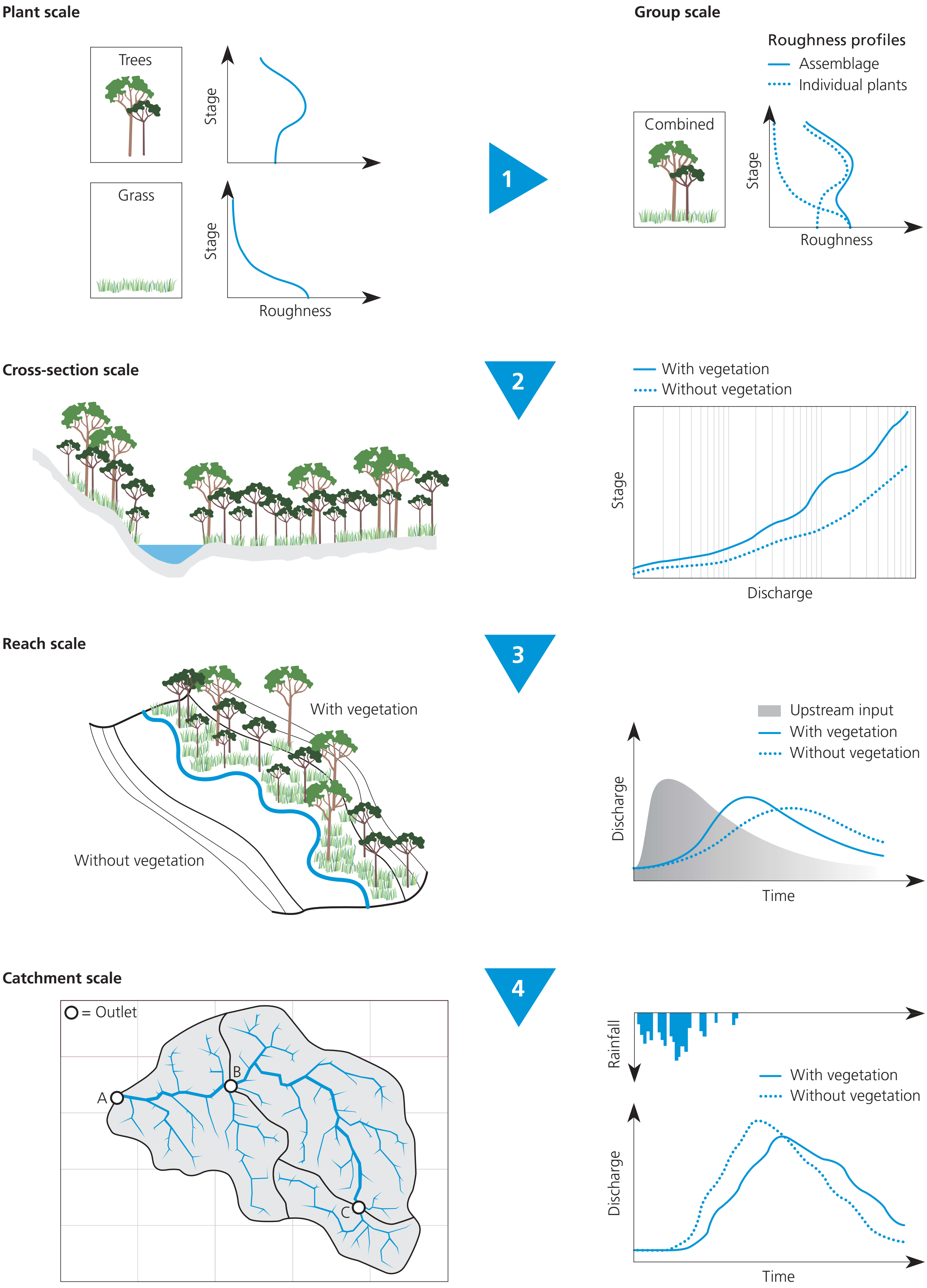


Figure 5.3. Comparison of the drag of streamlined and cylindrical obstructions (adapted from Vennard & Street 1982, p. 97). Vegetation produces 'drag' on the flow. Two very different sized objects can produce the same amount of drag due to its two components skin friction (i.e. the length of contact with the water) and profile drag (which is a description of how 'streamlined' the object is).

Figure 5.4. Conceptual diagram of the effect of riparian vegetation on discharge at the scale of a plant, a cross-section, a reach, and a catchment. Figure redrawn from diagram provided by Brett Anderson.



A comment on compound channels

Before we discuss the effect of vegetation on hydraulic resistance, it is important to mention compound channels. Riparian vegetation occurs at the interface between the channel and the floodplain. Even without vegetation, this is a complicated hydraulic environment, with the high velocity flows in the channel interacting with the low velocity flows on the floodplain. One of the key effects of riparian vegetation is to alter the hydraulic relationship between the floodplain and the channel.

There are excellent reviews of compound channel hydraulics by Knight and Shiono (1996), and Helmio (2002). As the floodplains of a compound channel are inundated, the conveyance of the floodplains is initially small by comparison with that of the main channel. Consequently, the flow velocity on the floodplains is much lower than in the main channel. The velocity difference results in a zone of turbulence at the interface between the two flows, often described as a vertical shear layer. Extensive three dimensional mixing of main-channel and flood plain flows produces a momentum transfer across the interface leading to velocity reduction in the main channel. The penetration is reduced as riparian vegetation density increases, which in turn, further reduces the velocity in the main-channel (Naot et al. 1996).

The relative effect of riparian vegetation on momentum transfer depends a great deal on whether the stream is straight or sinuous. For example, Burkham (1976) shows that flow resistance is low where the channel is straight and parallel to the floodplain, but high where the channel meanders across the floodplain. In his analysis of three floods down the Gila River in Arizona, Burkham (1976) observed that roughness (Manning's *n*) (definition in box below) decreased by an average of 30% where floodplain trees were cleared. Thus, in relative terms, revegetating the riparian zone of a straight stream will have more effect on flooding than it will on a meandering stream.

The effect of individual plants on roughness

The effect of vegetation on roughness varies dramatically with flow depth. For example, when we consider grasses, at low flows the water flows through and around the grass, and the grass will provide maximum resistance to flow. As the depth of flow increases, the grass will be submerged, then it will probably be pushed down by the flow, which will reduce the resistance. This is because:

~ the volume density of stems/foliage (collectively called biomass) is the primary determinant of the magnitude of flow roughness for plants,

~ plant flexibility causes streamlining of stems/leaves under flow pressure that may reduce flow resistance by over 50% (where flow pressure is either energy or velocity driven by channel slope),

~ vegetation roughness profiles exhibit distinct characteristics over two different depth ranges. The ranges are defined by whether the plant is emergent or submerged.

What is 'roughness'?

If you have ever tried to work out discharge, flow depth or channel dimensions to carry a particular flow, you have probably needed to estimate a roughness coefficient, the most common being Manning's *n*. Simply put, the amount of water that can pass a particular cross-section depends on the slope of the reach, the area of the channel, and the resistance to flow in the channel. These variables are embodied in Manning's equation (see below) in which, Q is discharge, A is the cross-sectional area, S is slope, R is hydraulic radius (area divided by wetted perimeter) and the resistance is lumped into a single coefficient, Manning's *n*.

$$Q = \frac{AR^{2/3}S^{1/2}}{n}$$

Although this formula has been criticised, it remains the standard method for estimating flow velocity and discharge in ungauged sites. Thus, Manning's *n* is a key parameter in water resources work, including floodplain management, stream restoration, and the design of hydraulic structures.

Manning's *n* typically ranges from 0.01 in smooth concrete channels with no obstructions to 0.10 in streams with large amounts of large woody pieces and vegetation that impedes flow. Rarely, values as high as 0.2 have been used. We will use *n* as a surrogate measure for resistance in streams associated with vegetation.

Stream roughness coefficient tables have been developed for vegetation in Australian rivers and can be found under tools and techniques on the rivers website — www.rivers.gov.au

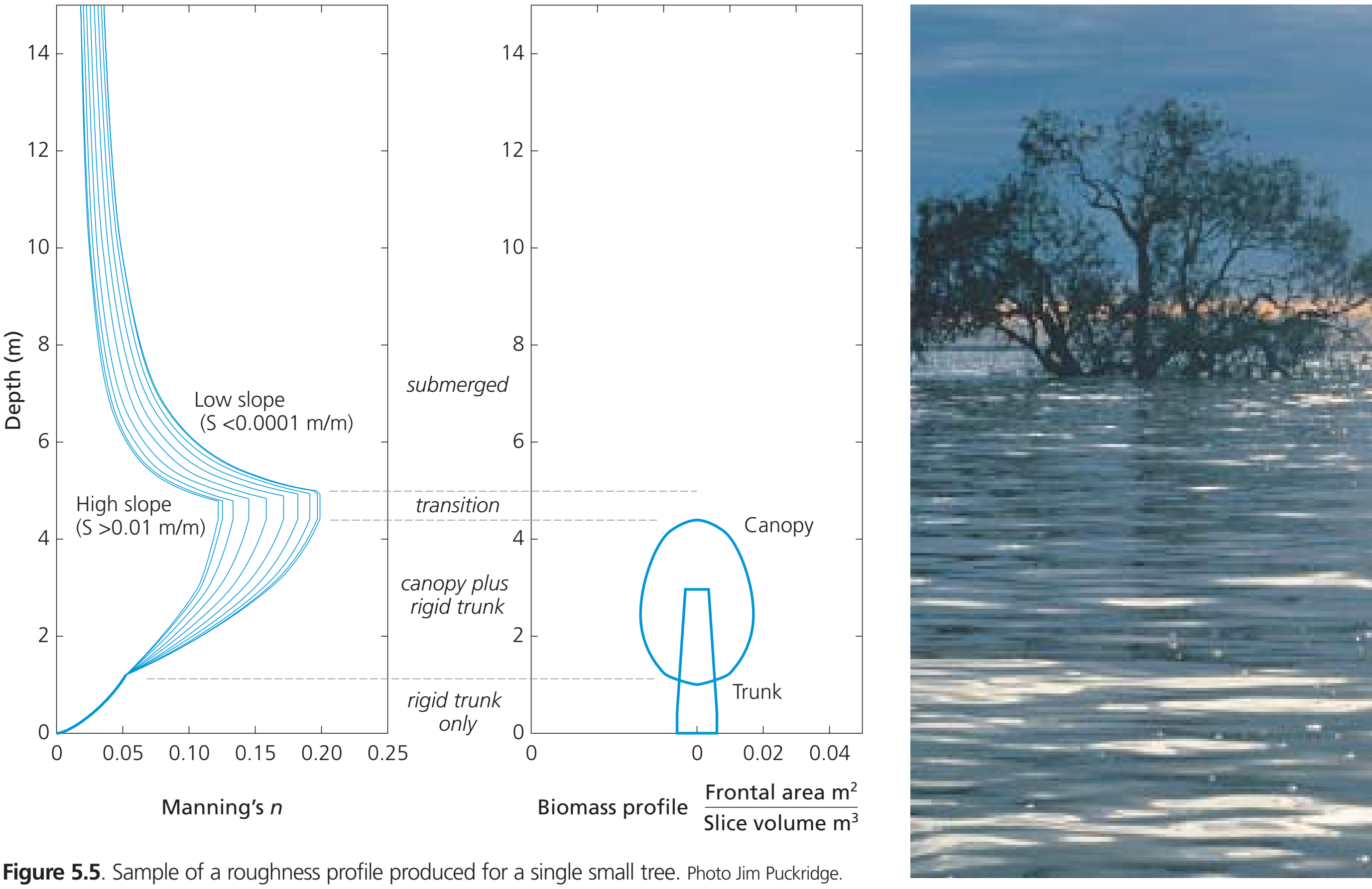


Figure 5.5. Sample of a roughness profile produced for a single small tree. Photo Jim Puckridge.

Roughness effects of vegetation communities

Vegetated channels have consistently higher roughness than equivalent channels (i.e. channels of the same size and shape) without vegetation. Although we can use a roughness of 0.05 as a general estimate for vegetated channels, the roughness effect varies with stream slope, stage and discharge. The usual effect is for the roughness to decline as the bed of the stream is drowned out, then the roughness reaches a maximum as the grass, and the canopies of bushes intersect the flow. The general rule of thumb is that the **lower** the slope of the stream, the greater the roughness effect of the vegetation.

Roughness effects of large wood in streams

A comprehensive review of the literature regarding the physical significance of wood in streams was completed by Gippel et al. (1992). With regard to the hydraulic significance of wood, this review, and the associated and subsequent experimental and field results (Gippel 1995, Gippel et al. 1996a, Gippel et al. 1992, Gippel et al. 1996b, Shields & Gippel 1995), represents the seminal work in the area. In the next sections we summarise this work. Table 5.2, for example, illustrates that clearing timber out of streams always reduces roughness, but the amount varies greatly. In large channels, such as the Murray River below the Hume Dam, removing the snags produced only a small decrease in roughness (0.037 to 0.033), whereas in the Deep Fork River in Oklahoma clearing reduced roughness from 0.15 to 0.04. This means that removing snags may have only a limited effect on flooding but, as described earlier, have a major effect on channel depth, width, and on loss of aquatic habitat.

The hydraulic effect of adding large wood in streams

Millions of logs have been removed from Australian streams to reduce flooding (Erskine & Webb 2003). We are interested now in the flood consequences of putting logs back into streams. In this section large wood will be referred to as snags. Snags have a small, to insignificant, effect on the frequency or duration of large floods (i.e. perhaps greater than the 20 year flood). However, snags can increase the duration of smaller floods (i.e. the length of time that floods are on the floodplain). By 'smaller' floods we mean the 1 to 2 year events. Clearly, the larger the snag in relation to the size of the stream, the greater the effect, so a given snag will have a relatively greater effect on a smaller channel. In general, snags will **not** affect even small floods when:

Table 5.2. Field measurements of the roughness due to wood in streams (expanded after Gippel et al. 1992). Australian rivers in blue.

Source	Site and treatment	Roughness (Mannings n)	
		obstructed	cleared
*Kikkawa et al. (1975)	Channelised reach of Gono River, Hiroshima (*n* estimated)	0.040	0.035
*Shields and Nunnally (1984)	De-snagged U.S. rivers and streams	0.050–0.045	0.045–0.035
*Gregory et al. (1985)	Clearance of debris dams in Highland Water, Hampshire (low flow measures)	0.516	0.292
*Taylor and Barclay (1985)	De-snagged reach of the Deep Fork River, Oklahoma (*n* estimated)	0.150	0.040
Shields et al. (2001)	Cleared and snag-obstructed reaches of the South Fork Obion River, Tennessee	0.053	0.043
*S.R.W.S.C. (1981)[1]	Clear and snag-obstructed reaches of the Wannon River, Victoria	0.079	0.036
*Binnie and Partners (1981)	Channel clearing, Ovens River, Victoria	0.045	0.035
*M.D.B.C. (unpublished)[2]	De-snagging of River Murray, Hume to Yarrawonga (*n* computed by model)	0.037	0.033
Gippel (1999)	Clear and snag-obstructed reaches of the Edward River, Victoria	0.130–0.056	0.060–0.050

* Sourced from Gippel et al. (1992). (1) S.R.W.S.C. State Rivers and Water Supply Commission. (2) M.D.B.C. Murray-Darling Basin Commission.

~ The projected area of the snag is less than 10% of the area of the cross-section. The 'projected' area is the area of the snag in a two-dimensional cross-section across the stream. A log needs to be very large to occupy 10% of the cross-section of a third order or higher stream.

~ The snag is angled at 40° to the flow (i.e. with the upstream end of the log against the bank).

~ The snag is submerged in a backwater at higher flows. That is, the level of the flood could be hydraulically controlled by some feature downstream. For example, a bridge crossing downstream may constrict the flood

Left: Large wood in the bed of the Campaspe River. Replacing wood at these densities would probably not lead to an increase in bankfull flood stage. Photo Ian Rutherfurd. Right: Typical natural loads of timber in a stream. Photo Simon Treadwell.

flow. This constriction will then produce a backwater upstream. If a log falls within that backwater, then it will have no hydraulic effect on flow at all during that flood. As the flood level falls, however, the log will eventually produce its own shorter backwater. The same principle applies to a backwater produced by a log: if another log falls within that backwater, it will have no hydraulic effect on flow. A rule of thumb for this effect is that a log that is five to six log diameters upstream of another log of similar (or larger) size, will not affect flood level, because it will be within the backwater of the existing log.

~ Several snags in line will not produce any more afflux than a single snag, so long as each piece is located within two times the diameter of the next piece up or downstream. Thus, up to six pieces can be placed parallel to each other in a line. In general, any piece of wood will add little extra afflux (i.e. rise in water level) if it is placed within four log diameters of the next piece.

Chris Gippel has measured the effect of removing logs in several situations. The following three examples illustrate that removing even dense piles of logs in a large stream does not produce dramatic change in water level at bankfull flow.

~ In a 30 metre wide channel, 2 metres deep, a log 20 metres long and 1 metre in diameter (i.e. blocking one third of the channel area), in a flow of 1.5 m s^{-1}, causes a 5% increase in water surface elevation (100 millimetres).

~ Seven LWD accumulations were removed from the Tumut River (40 metres wide, 2.5 metres deep) and the effects on flow conveyance measured (Shields & Gippel 1995). Removing the snags reduced upstream water surface level by about 0.2 metres, and increased conveyance by about 20% at bankfull flow. The afflux (i.e. the backwater effect) extended for about 3 kilometres upstream. The effect on major floods would be negligible.

~ Removing 96 items of woody debris from the channel of the Lower Thomson River did not produce a measurable effect on the height of bankfull flow.

This new understanding explains why removing one or even several pieces of wood from a stream in most situations has a negligible effect on local flooding, either in height or duration. However, there is plenty of evidence of the negative effects of removing wood, including channel deepening and widening, loss of aquatic habitat, and infilling of pools that are essential refugia over summer low flows. Unless a hydraulic survey shows that removing wood will result in significant reduction in flood effects, it is best to 'let sleeping logs lie'.

5.4 Quantifying the effects of vegetation and wood on reach scale hydraulics

Our research has also examined the hydraulic (flood) effect of revegetating a reach of river. Fread (1991) conducted numerical tests using a one-dimensional flow routing simulation on a lowland river where a segment of the reach was assigned either an elevated or depressed roughness coefficient (±20%). The results of his trials are shown in Figure 5.6 for elevated roughness, which demonstrates substantial changes in stage (maximum deviation of 0.6 metres over a base of 6 metres, a change of around 10%). These model results are also supported by the work of Romanowicz et al. (1996), who showed that reach flow characteristics are most changed by conditions at a flow constriction, and least affected by average roughness over, for instance, the floodplain. Thus, local regions of high roughness extending continuously in a direction at right angles to flow can act as substantial flow controls.

Representing the reach scale effect of revegetating streams of different size

The following examples show the hydraulic effect of revegetating the riparian zones of typical small, medium and large rural streams. The variables that control the effect of the vegetation are described in Table 5.3.

Developing a model of vegetation resistance

After reviewing over 200 vegetation resistance studies it became clear that, despite the myriad of forms, plants behave in very similar ways. Four key properties determine vegetation resistance: 1) stem density, which increases resistance; and then three factors that moderate the impact of vegetation: 2) free space; 3) flexibility and 4) flow depth. We developed a numerical model

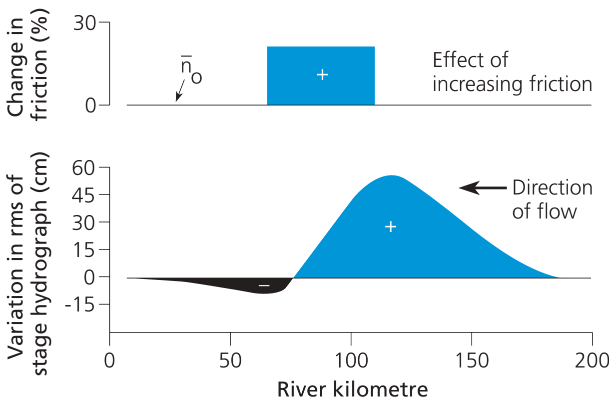


Figure 5.6. Sensitivity of stage to a discrete zone of increased roughness (after Fread 1991, p. 430).

Table 5.3. Variables that control the effect of vegetation on stream roughness and stage. The second column shows the effect of the variable on vegetation roughness.

Variable	Effect on hydraulics	Direction of change
Cross-sectional area of the channel	The bigger the channel, the smaller the relative effect of the vegetation	Bigger cross section = smaller blockage
Position of vegetation on the boundary	The lower in the cross section, the greater the effect	The lower the vegetation on the bank = higher the stage
Density of vegetation across the channel	Greater density of vegetation provides greater resistance	Greater the density = higher stage
Density of vegetation along the stream	Generally, the greater the density of the vegetation along the banks the greater the flow resistance	Greater planting density along the banks = higher stage
Length of bank vegetated	The backwater will extend from the upstream end of a clump of vegetation	Longer vegetated zone = longer flood effect
Slope of the channel	Everything else being equal, the lower the slope, the greater the relative effect of vegetation on roughness	Greater slope = less roughness effect

(ROVER — **R**esistance **o**f **V**egetation in **R**ivers) that represents these vegetation characteristics in a hydraulic model. This model allows us to estimate the effect of vegetation on flood stage. Table 5.4 provides some more detail on each mechanism, and gives an indication of the size of the impact.

A feature of the resistance of plants is the wide fluctuation with flow depth. Therefore, in ROVER, plant resistance is described by a curve showing the variation of Manning's n with flow depth. The specific shape of the curve depends on the four plant properties (via a set of numerical relationships). The model is able to accurately reproduce the resistance of the following plant types: mature trees; grasses; aquatic plants; flexible saplings (cedar, spruce and willow); and fallen timber (snags).

How will planting riparian vegetation affect flood height in a long reach?

A local rise in flood stage at one point will lead to a decrease in flood stage downstream due to storage. The first part of the trade-off — the increase in flow depth — is readily calculated at a particular site by applying ROVER. The problem, therefore, became how to quantify the sensitivity of flood wave size to the amount of vegetation in the channel network upstream of the site. While similar sensitivity tests have been run in the past by other investigators, resistance was specified in these tests as a single constant value, and the effect of vegetation was added as a second constant increment. This work breaks new ground by considering vegetation resistance as a property that varies with flow depth, and changing the resistance increment according to channel

Table 5.4. Key plant properties used in ROVER; the resistance mechanism and indicative impact.

Plant property	Mechanism	Resistance impact
Stem density	Stems and leaves create drag by causing turbulence. Resistance usually increases in proportion to density; so twice the density causes twice the resistance	High stem density may increase resistance by a factor of 2 to 4
Free space	Rivers are rarely choked by vegetation and the free space between plants reduces the overall resistance as water preferentially flows along unobstructed pathways	Negligible until plants occupy more than 10% of the flow area
Flexibility	The force of flowing water can cause flexible stems to bend, become more streamlined, and hence produce lower drag	Resistance may decline by 50% or more
Flow depth	As plants become submerged, a layer of water is able to pass freely over the plant, decreasing total resistance rapidly	Resistance declines exponentially with the depth of the free layer

Rules of thumb for the effect of vegetation on floods levels

Flood levels at a cross-section

1. If vegetation does not block more than 10% of the cross-sectional area, it will probably have little effect on stage. This is why vegetation has more effect on small streams than large ones.
2. If the stream has a width/depth ratio greater than 17, vegetation is unlikely to have any affect on flooding because the cross-section is too wide and shallow (Masterman & Thorne 1992).
3. Vegetation in the bed has more influence on flow than does vegetation on the top of the bank.
4. If the vegetation lies down during a flood, then it probably has little effect on the flood stage.

Flood levels at catchment scale

5. In what sort of catchment types will flood stage be most affected by riparian revegetation? The answer is where the catchment:
   a. is long and thin in shape,
   b. has a high drainage density, and
   c. has a short, steep headwaters section, and then a long low-gradient section.

Photo John Dowe.

size and slope. To explore this variability required not only high resolution flood routing (to handle the variation of resistance with flow depth) but also a large number of trials.

Numerical simulations were run for flood waves traversing a 50 kilometre river reach with ROVER used to generate appropriate resistance functions for densely vegetated channels and floodplains. A series of channels of different shapes, sizes and slopes were tested, and in total the passage of several thousand floods was simulated. Figure 5.7 shows the results for four typical simulations. Floods of two different sizes were injected at the top of the reach; a large flood (light blue shading) and a moderate flood (dark blue shading). The two events were routed down an identical 50 kilometre reach, once with dense vegetation flanking the channel (dotted lines) and then with no vegetation present (solid lines).

Figure 5.8 (overleaf) shows flood hydrographs for three different cross-section shapes. The input hydrograph is the solid line, and the dotted line is the same hydrograph when it has travelled 10 kilometres further downstream. Note that in this simulation, vegetation delays the peak by between 5 and 10 hours, depending on the shape of the cross-section. The wider and shallower the cross-section, the greater the attenuation due to vegetation. Note too, that the effect of the vegetation is much less with a large input discharge.

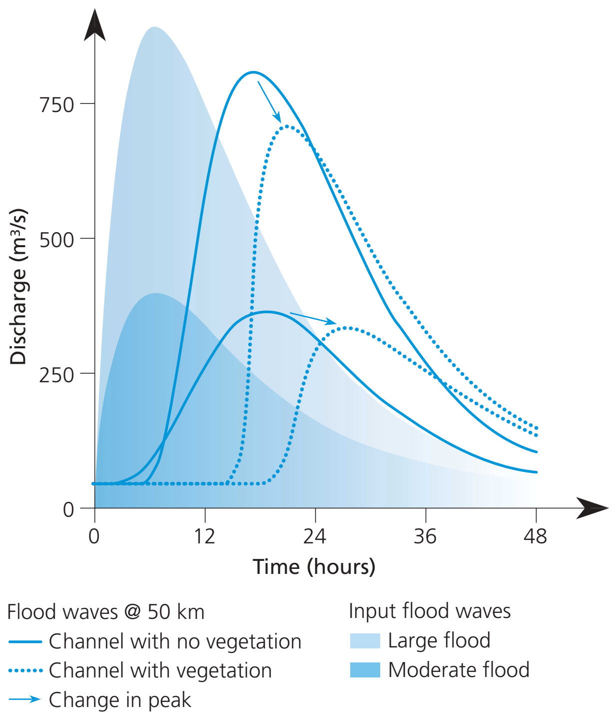


Figure 5.7. Numerical routing of two flood waves down a 50 kilometre reach, with and without vegetation. Source: Brett Anderson (unpublished thesis).

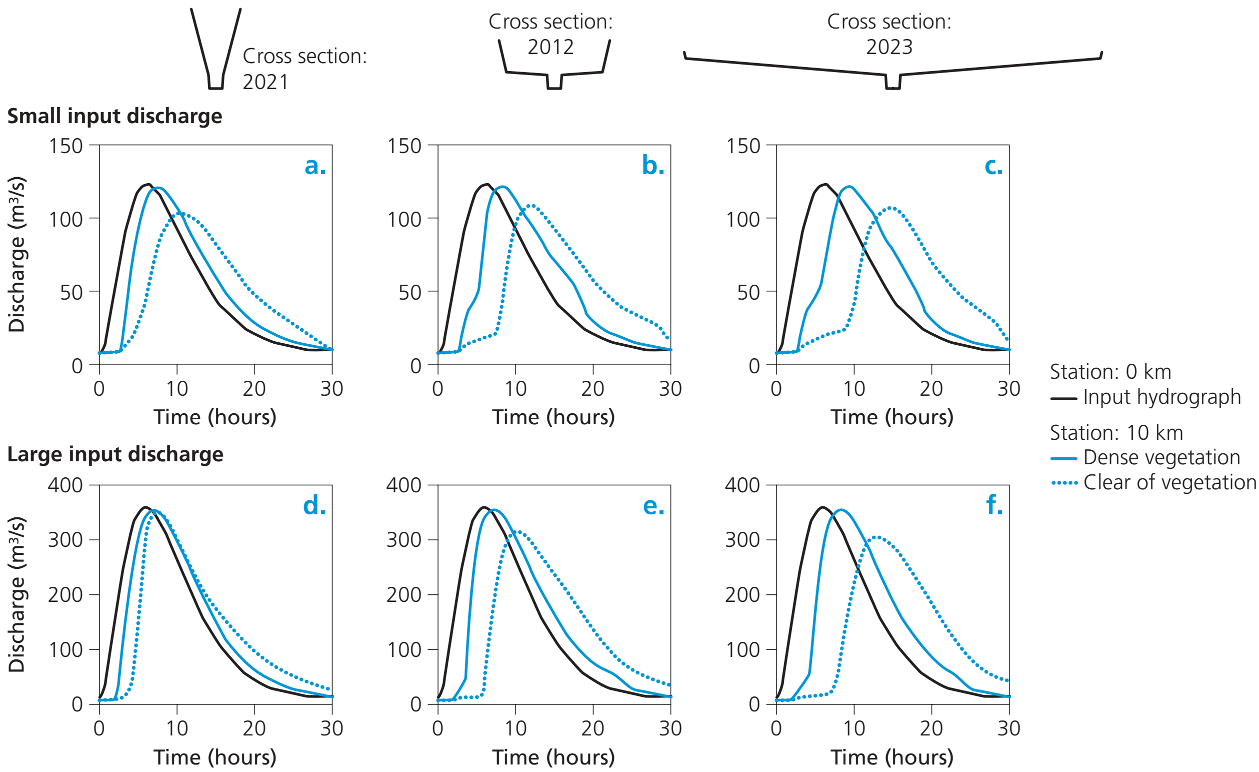


Figure 5.8. Sample of simulated waves computed for different channel shapes, showing the input hydrograph and hydrographs at the 10 kilometre station for channels with vegetation, and clear of vegetation. Source: Brett Anderson (unpublished thesis).

These results confirm that, in channels of higher roughness, the flood arrives later and that the peak flow is attenuated when compared to channels cleared of vegetation. Furthermore, the response to large floods differed from small floods with smaller attenuation of the peak observed in the case of the small flood. The effect of vegetation on a travelling flood wave can be profound. Dense vegetation can slow the wave speed in some cases from running pace, 8 kilometres/hour, to closer to a walk, 3 kilometres/hour. These slow-moving flood waves also disperse more than their fast moving counterparts.

Figure 5.8 demonstrates the effect of channel dimensions and discharge size on the reach scale attenuation effect. These results show:

1. small discharges are relatively more attenuated than are large discharges (compare a and d),
2. for large discharges, the flood wave is slowed more in channels with wide floodplains (compare d and f).

So far, we have developed a new model to calculate the local resistance effect on flood stage at a cross-section, then we have quantified how it attenuates floods along a single reach of river. Next, we need to evaluate the gross impact of the change in these flood routing parameters on the hydrograph generated by an entire stream network. To do this, a second, large-scale numerical model is required. This is the Murrumbidgee model that we describe next.

Photo Ian Rutherfurd.

5.5 What will be the effect of revegetation on flooding at the scale of a whole catchment

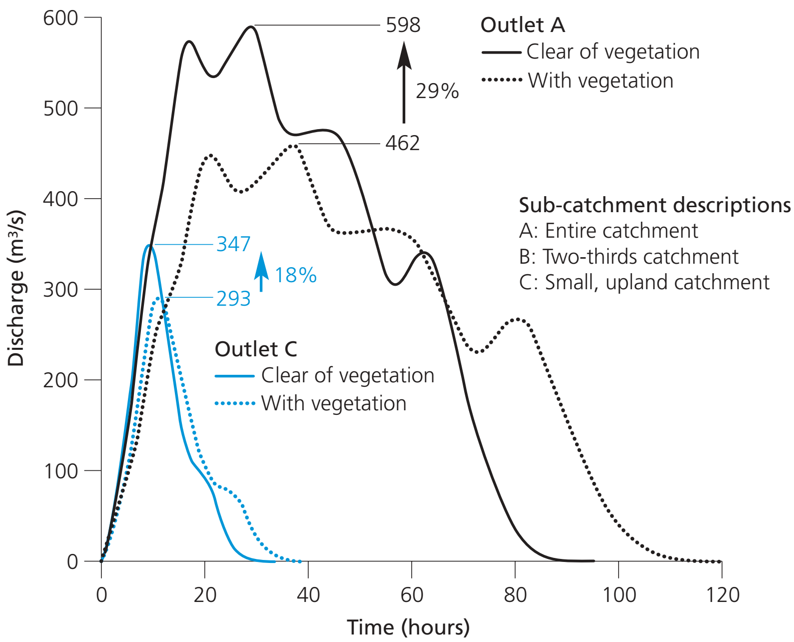
The detailed simulations along the 50 kilometre reaches (previous) showed that the effect of vegetation on flood routing primarily causes variations in wave speed and in the dispersion coefficient. Thus, by varying only the wave speed and the dispersion coefficient we can predict the difference between the size of a flood wave generated by channel networks with and without riparian vegetation. The model is generic, in that it can be applied to any network of channels. To demonstrate the potential impact of a whole-of-catchment revegetation project, we have chosen a set of simulations using the channel network of the upper Murrumbidgee River above Wagga Wagga.

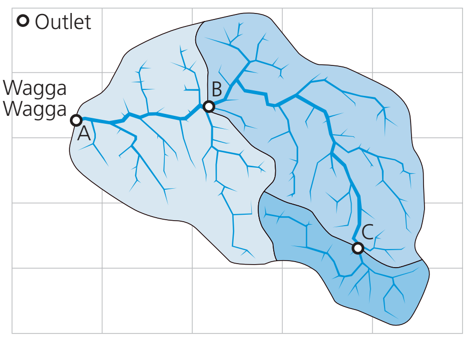
Revegetating the entire riparian zone of the Murrumbidgee River has a considerable effect on the size and timing of the flood peak reaching different outlets (Figure 5.9). At outlet C (the upstream site) the peak is attenuated by 18%, at the larger outlet A, the peak is attenuated by 29%.

Two models of the upper Murrumbidgee catchment were generated, one with vegetation and one without. Rainfall events ranging in intensity (millimetres/hour) and duration (hours) were routed through each channel network, giving two different flood hydrographs at Wagga Wagga; we will refer to these as the inflow hydrographs. Figure 5.10 (overleaf) shows the inflow hydrographs as solid lines, with the lower curve delayed and more highly attenuated as a result of dense vegetation in the upstream network (see 'upstream decrease'). In fact, the additional resistance in the upstream network reduces the peak flow depth at Wagga Wagga from 8.0 metres down to just 6.1 metres.

However, this reduction assumes that the channel at Wagga Wagga is clear of vegetation. But if this reach also has dense vegetation, then the local stage will be higher. The dashed lines in Figure 5.10b show the increase in stage that results when the stage-discharge relationship is adjusted to account for the presence of dense vegetation (see 'local increase'). For this location on the Murrumbidgee, the additional resistance causes the peak flow depth to rise by about 1.0 metre. Hence, or this particular flood event at Wagga Wagga, the reintroduction of vegetation both locally, and to all of the upstream channel network, produces a flood with a reduced peak flow depth (down from 8.0 metres to 6.9 metres). For this case, the peak of the flood is actually reduced by the presence of dense vegetation through the network despite there being vegetation at Wagga Wagga. In terms of the trade-off, the effect of vegetation on the flood wave produced by the upstream network is larger than the local impact on flow depth.

Perhaps more important than the effect on discharge, is the effect on stage shown in Figure 5.10d. This illustrates the combined effect of cross-section roughness, and network attenuation. At the upstream





Sub-catchment dimensions

		A	B	C
Order		5	5	4
Area (x 1000 km²)		26.4	16.5	3.6
Relief (m)		1240	1090	600
Slope (m / 100 m)		0.87	0.86	0.80
% channel length	1st	44	45	50
of stream order:	2nd	30	25	26
	3rd	12	14	21
	>3rd	14	16	3
	Total (km)	2340	1480	340

Figure 5.9. Effect of revegetation on discharge at two stations (upstream and downstream) of the Murrumbidgee, for two recurrence interval flows. The lumpy character of the hydrograph is a product of different tributary inputs (modelled for 20 millimetres rainfall for 1 hour duration).

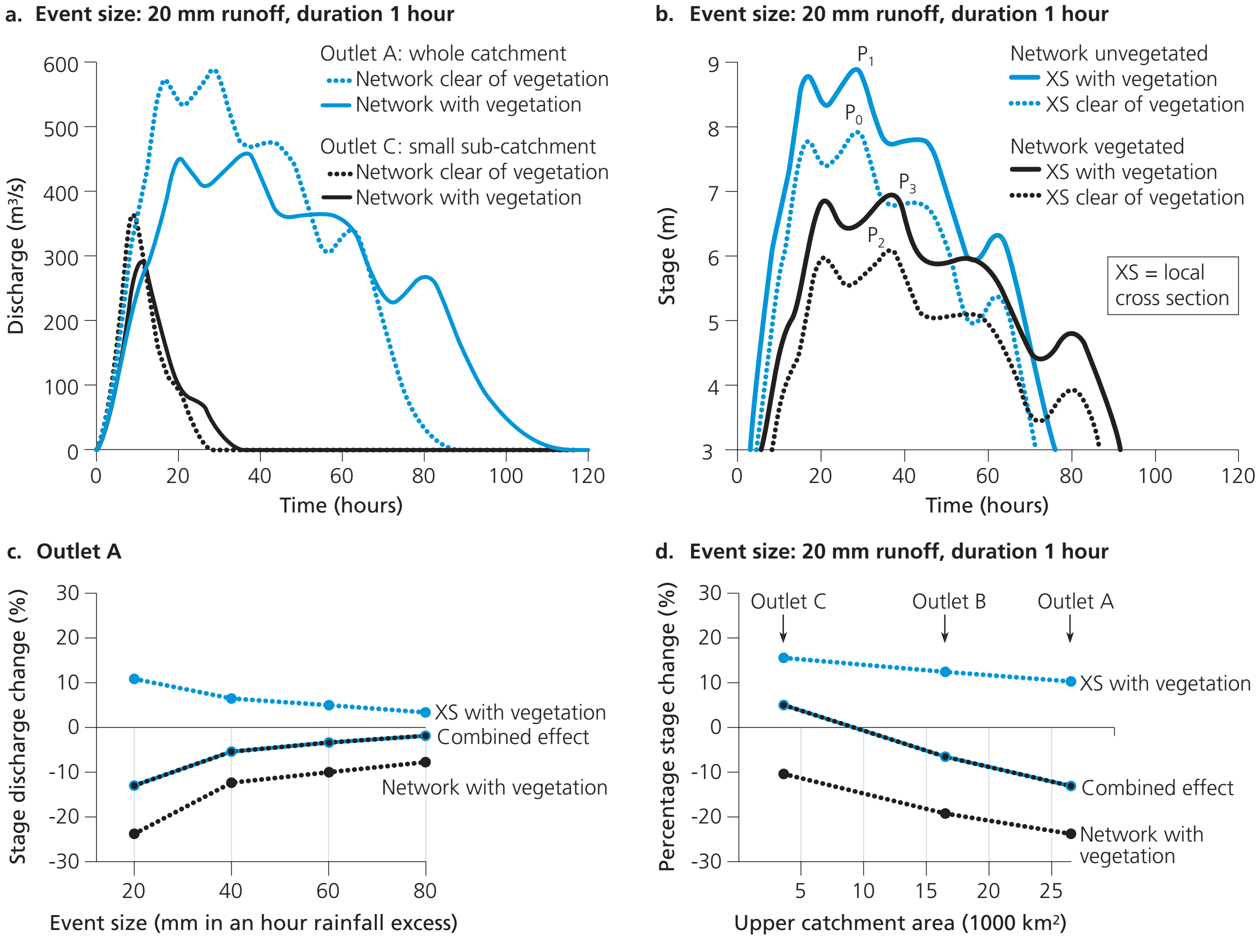


Figure 5.10. a) and b) Stage hydrographs at Wagga Wagga comparing the relative importance of local and upstream vegetation condition. c) Percentage stage change at Wagga Wagga (Outlet A) for a given event size. d) Percentage stage change down the catchment (from outlet C to A) with the addition of riparian vegetation.

outlet, the combined effect of cross-section resistance and network attenuation is to increase the stage of a given flood when vegetation is added. By contrast, attenuation of the flood wave downstream means that outlets B and C both show a decreased stage for the same recurrence interval flood. That is, the effect of riparian vegetation is to decrease flood depth at downstream sites. In this model example, the stage falls by about 10% at the downstream outlet C. Thus, the effect of the riparian vegetation is to slightly increase the depth of flooding in catchments less than a few thousand square kilometres, and decrease the depth of flooding in larger catchments. The other consequence of decreasing flood depth is that flood duration must increase to compensate.

You will also note, from Figure 5.10c that the size of this effect decreases with the size of the flood or storm event. Stage is 20% higher at the upstream catchment outlet for a 20 millimetres per hour storm, but this effect disappears with an 80 millimetres per hour storm. Thus, the effect will be most marked at small and moderate sized floods.

5.6 Implications for riparian revegetation

The effect of revegetating the riparian zone on flooding can be seen in the differences between the local effect, which is to increase flood height, versus the whole of catchment effect, which is to hold back the flood, and so reduce downstream flood height. When the whole catchment is considered the latter effect can be dominant, demonstrating the counter-intuitive conclusion that the introduction of resistance can provide flood protection. The more comprehensive set of results from which this example is drawn, Anderson (2005), shows that the balance of the impact of replanting may fall either way. The relative impact varies depending on where the 'local' cross-section is located in the catchment, the size of the flood event considered, and of course how much of the channel network is replanted and at what density.

The question that sparked this study was whether the reinstatement of riparian vegetation was in fact going to catastrophically increase flood hazard at the scale of large catchments, by undoing over a century of vegetation removal. This research provides a clear answer to this question. Even in a large catchment, the impact of total riparian revegetation could be changes in peak depth and overbank duration in the order of 10% to 20%.

What are the impacts of riparian vegetation on flooding relative to other impacts?

It is important to put this result into perspective. The effect of riparian revegetation on flooding in the streams of south-east Australia will always be dwarfed by the effect of large dams, flood levees, and other major structural changes. These structures and measures provide protection far greater than any changes that might be wrought by riparian restoration at catchment-scale. The fact that in places the restoration actions may result in additional protection can be considered a bonus. Figure 5.11 shows that large dams in Victoria have reduced the frequency of the natural 1 year Average Return Interval (ARI) flood to 2 to 15 years, and the natural five year ARI flood to 6 to 100 years. By contrast, the effect of returning riparian vegetation would be to alter the duration and timing of the flood rather than in dramatic changes in its recurrence interval.

Research by the former Cooperative Research Centre for Catchment Hydrology has demonstrated the effect of landuse change on hydrology. The main focus of this work has been on catchment water yield, rather than on flood magnitude, frequency and duration. Reforestation and pine plantations are able to halve water yield from a catchment. Similarly, revegetating the pasture Glendu catchment in New Zealand with pines, led to a halving in peak monthly runoff per hectare, suggesting a major impact on the size of floods (Fahey & Jackson 1997) (Figure 5.12). At catchment scale the effect of landuse change (e.g. reforestation) would have a more substantial effect on the depth and duration of flooding (i.e. the amount of water in a flood), whereas the effect of riparian vegetation is to alter the timing of the delivery of that flood.

Over coming decades, it is likely that catchment reforestation will be combined with riparian revegetation. The effect will be to reduce discharge (due to landuse effects) and to slow the downstream passage of flood peaks. The total effect could be substantially reduced flood levels in the long, lowland sections of streams. Having said this, the effect will almost certainly be mediated by the continuing effect of dams along the path of large, regulated streams.

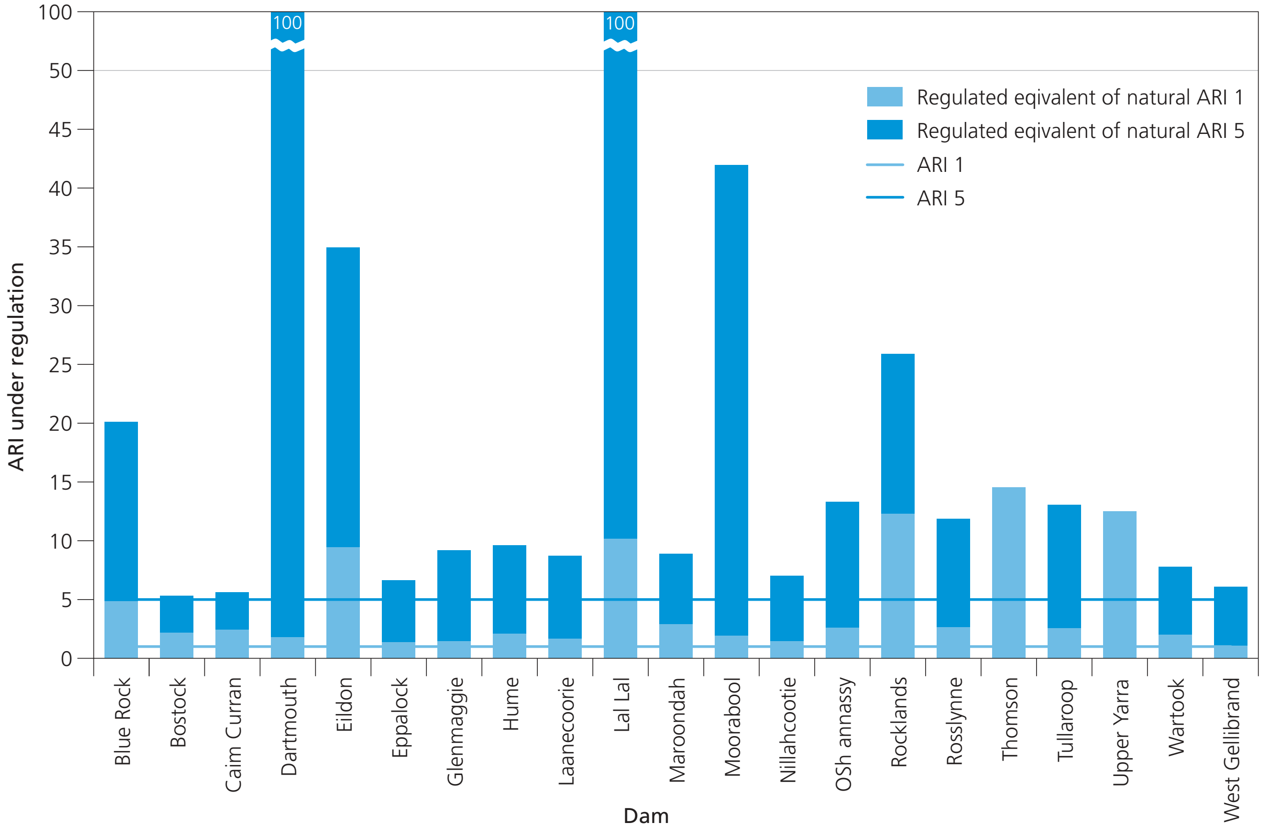


Figure 5.11. Change in the average recurrence interval of the natural (pre-regulation) 1 and 5 year floods in Victorian catchments with large dams. Data from an unpublished Master of Science thesis by Deb Woods, University of Melbourne, former Cooperative Research Centre for Catchment Hydrology.

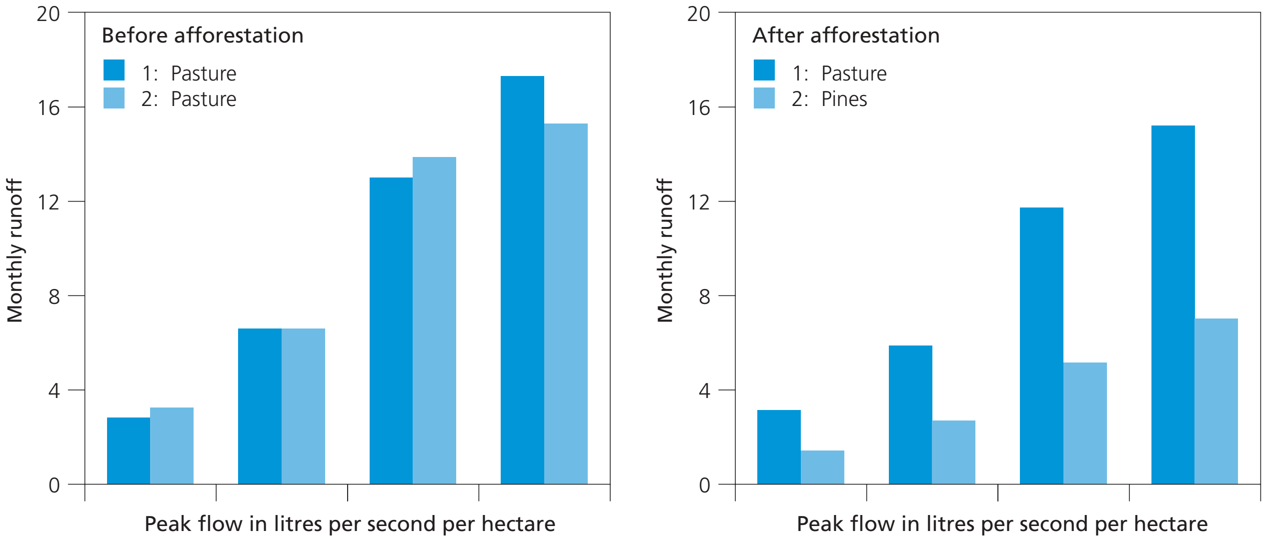


Figure 5.12. Peak monthly runoff per hectare after revegetating the pasture Glendu catchment in NZ with pines (from Fahey and Jackson, 1997).

Principles for managing the effects of riparian vegetation on flooding

To summarise:

~ The major effect of returning vegetation to streams will be through its influence on roughness and flow resistance. Adding or removing large wood (snags) in streams has a very little effect on floods above bankfull capacity.

~ Revegetating riparian zones, or adding large wood to stream channels, will increase the stage of floods at a local reach scale, although in many cases the effects are likely to be small. The effect will be greatest where the vegetation is planted across the full width of a floodplain. But, the effect of increasing flood level at one site is to hold back the flood-waters so that the downstream flood stage will be lower.

~ At catchment scale, the cumulative effect of riparian revegetation is to increase flood stage and duration in headwater streams (where flooding is usually not a problem anyway), but decrease flood stage in larger streams, further downstream, where flooding has in the past often been a major problem.

~ Although the effect of riparian vegetation on flooding is modest in comparison to the effects of dams and regulation, it should be considered in planning major revegetation works. However, the effect is largely positive for downstream catchments, where riparian vegetation will reduce the depth of flooding. The decreased flow depth comes at the cost of slightly longer flood durations at these lower depths.

~ Riparian revegetation should be seen as a catchment scale tool that can have a beneficial effect on flooding in lowland areas. Whilst flow regulation and landuse change affect the amount of water available in floods (magnitude and frequency), riparian vegetation affects the velocity of the flood wave delivered to the stream. All of these interacting aspects need to be considered together when planning changes in catchment land use, including revegetation.

A flood interacting with riparian vegetation. Photo Ian Rutherfurd.

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CHAPTER 6

The influence of riparian management on stream erosion

Ian Rutherfurd (edited by Phil Price)

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

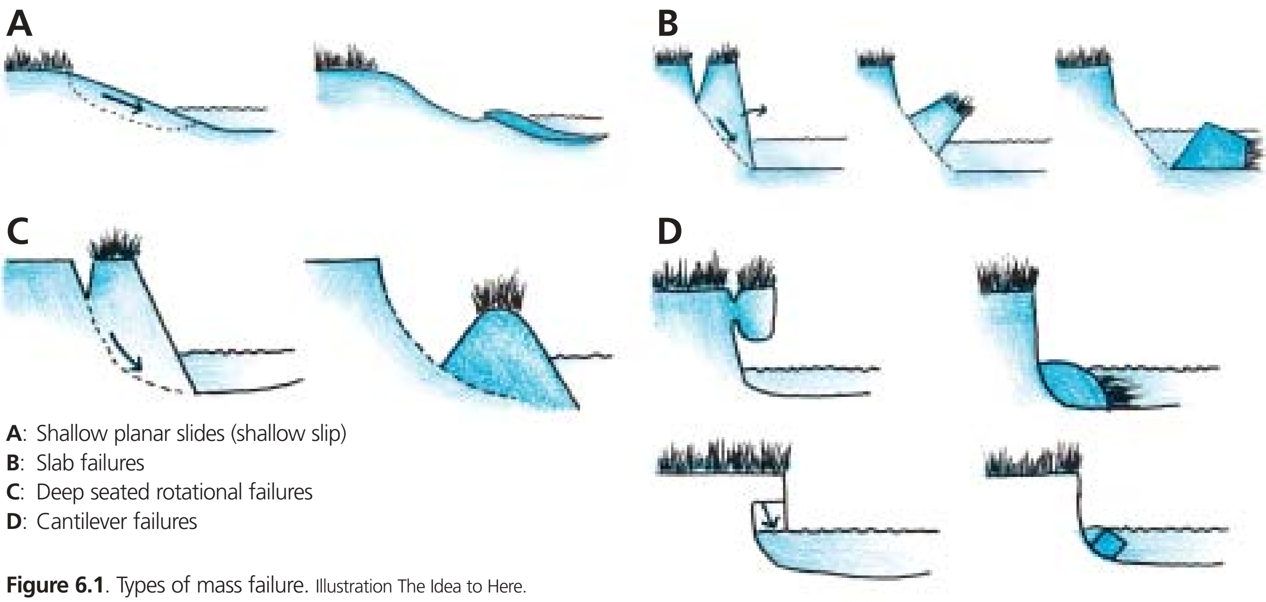
Vegetation on the bank face also reduces the effects of scour by directly strengthening the banks. A dense root mat, such as produced by willows, and several native species (such as river oaks, *Casuarina* and *Melaleuca* spp. and weeping myrtle, *Waterhousia*) directly protects the bank face from scour. 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 substrata 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 &

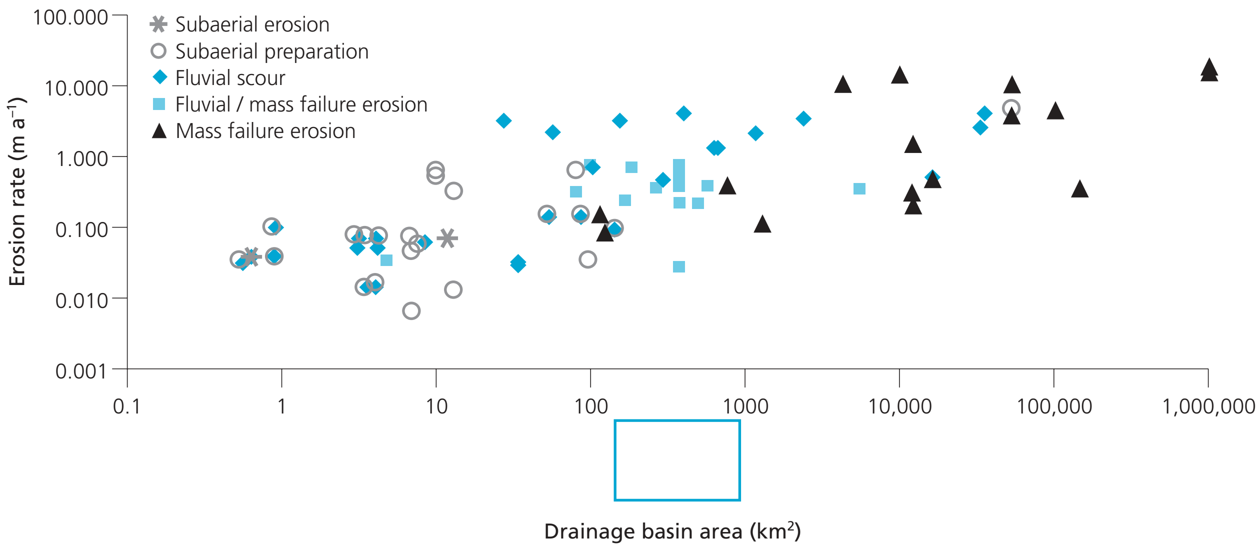


Figure 6.2. Relationship between different erosion processes and catchment area (based on a review of global data by James Grove). The blue rectangle shows the erosion domain for the Kiewa River described below.

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/m^2/a*)
~ Fluvial entrainment = 27% (*0.022 t/m^2/a*)
~ Subaerial erosion = 10% (*0.008 t/m^2/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

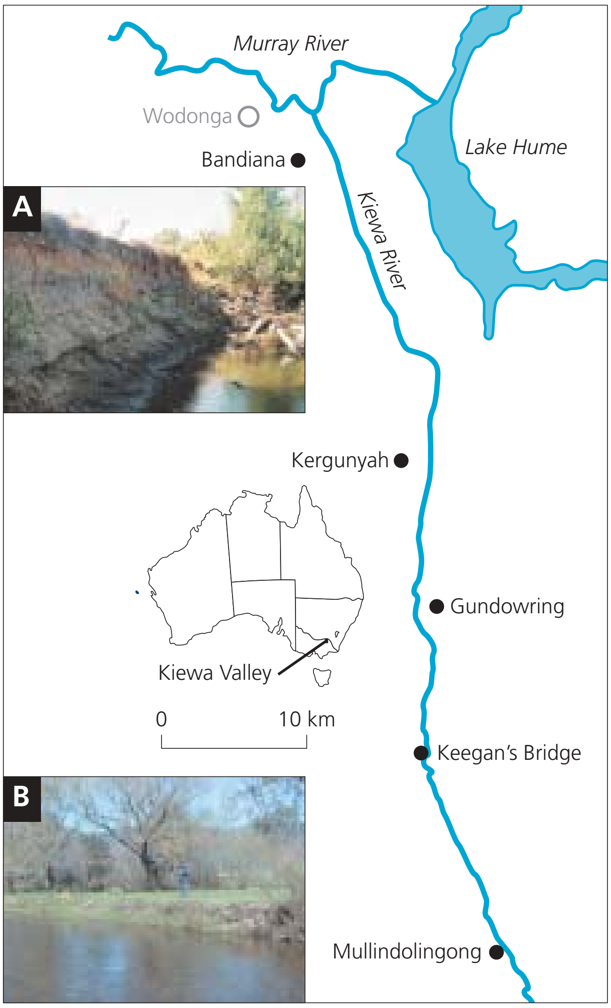


Figure 6.3. Erosion measurement sites on the Kiewa River, Victoria. (A) Bandiana, the most downstream site. Note the increase in bank height downstream. (B) Mulindolingong, the most upstream site.

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).

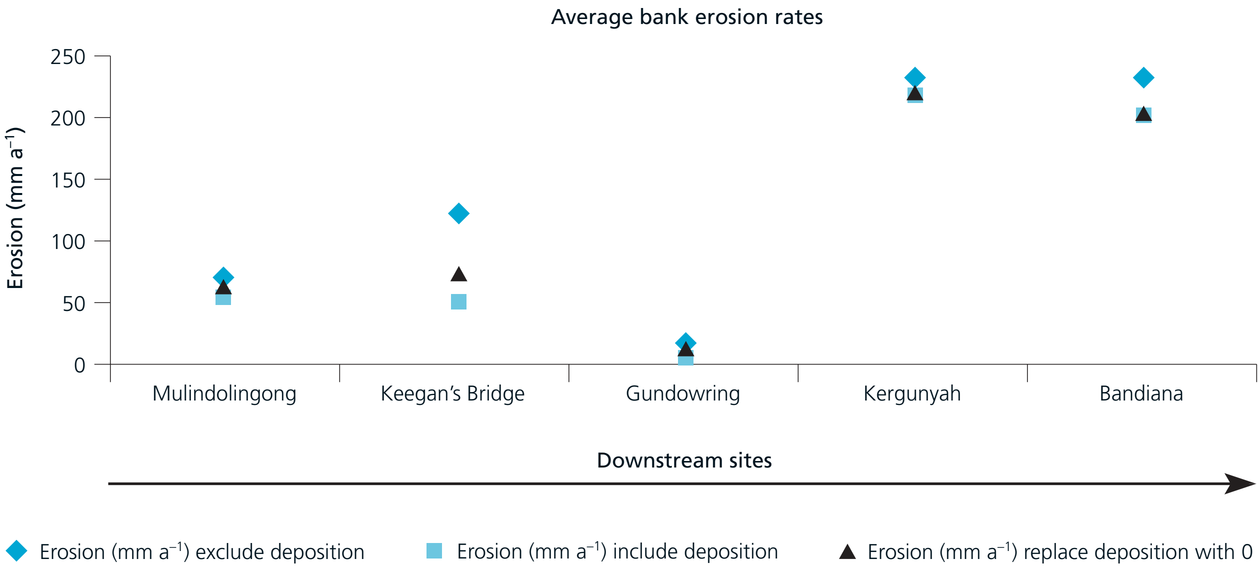


Figure 6.4. Average bank erosion measurements (over the full bank face) at the five sites, over four years of measurement (three sets of erosion measurement are shown, one taking no account of deposition at the site, one subtracting from the measured erosion any deposition, and one using zero for deposition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

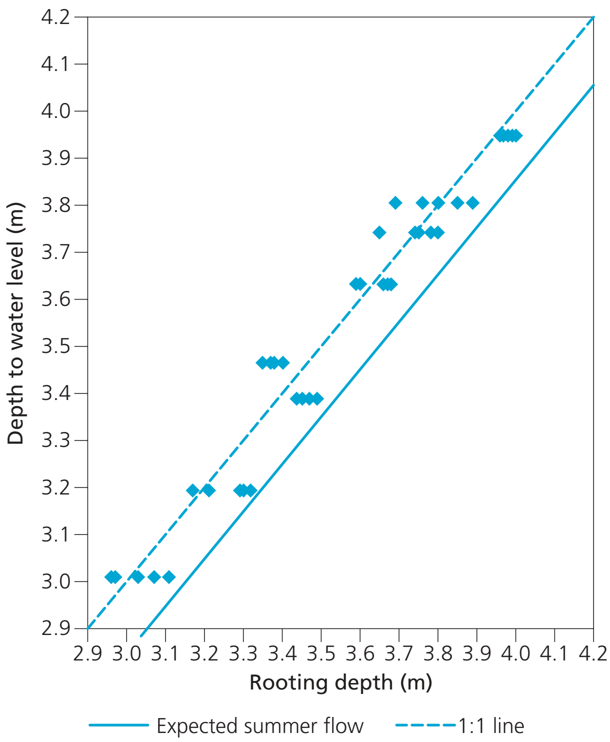


Figure 6.5. Rooting depth versus depth to water level for depths between 300 and 400 centimetres.

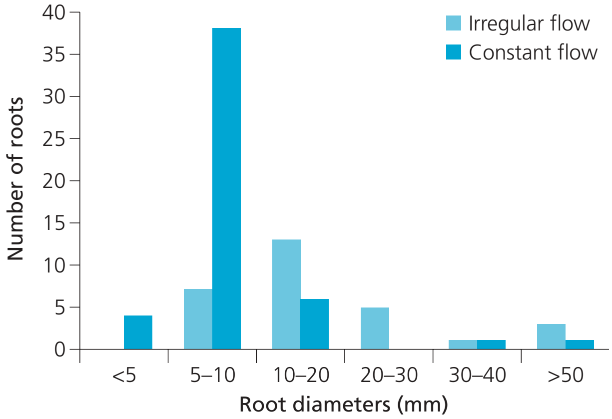


Figure 6.6. Distribution of roots in sites with constant and irregular flow regimes.

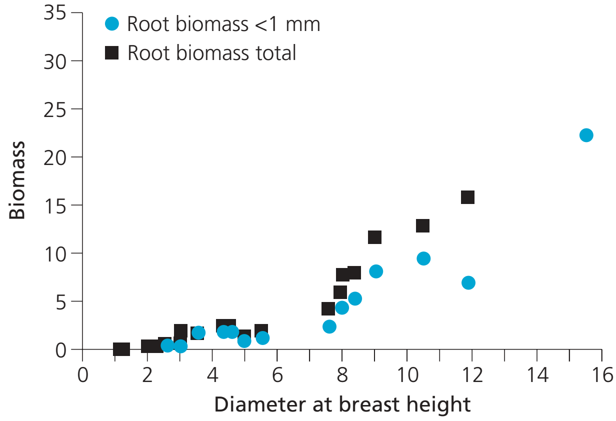


Figure 6.7. Root biomass increases at about the same rate as the size of the tree (diameter breast height).

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.

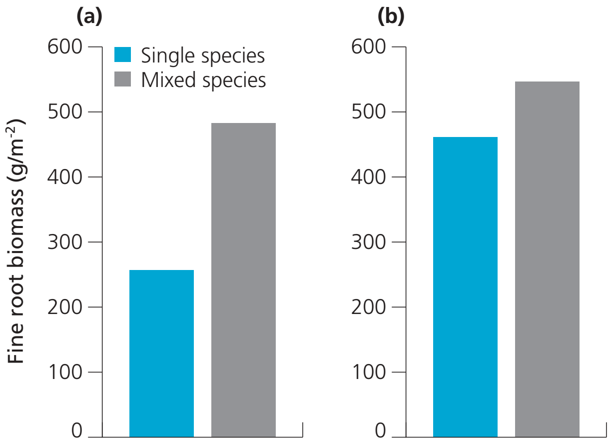


Figure 6.8. Example from North America showing that species in competition have relatively more roots than species that are not in competition. The right hand graph (b) shows a lighter soil than the left hand graph (a), demonstrating the effect of soil clay percentage.

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.

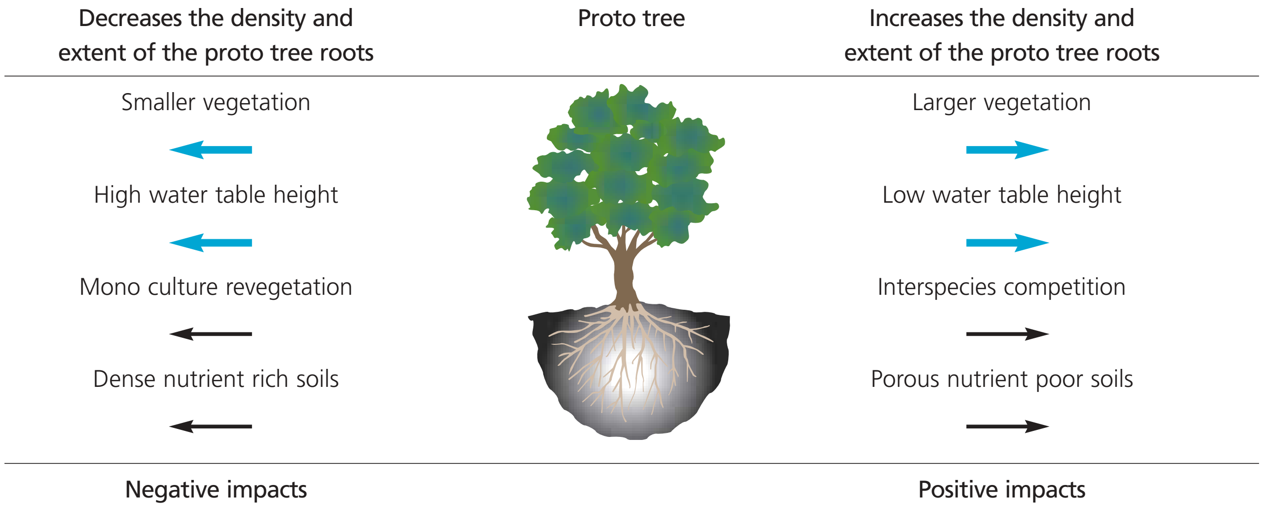


Figure 6.9. The 'proto' tree and the impacts of site conditions that affect root architecture and density are identified with their effects on the root distribution and density of the proto tree.

: 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.

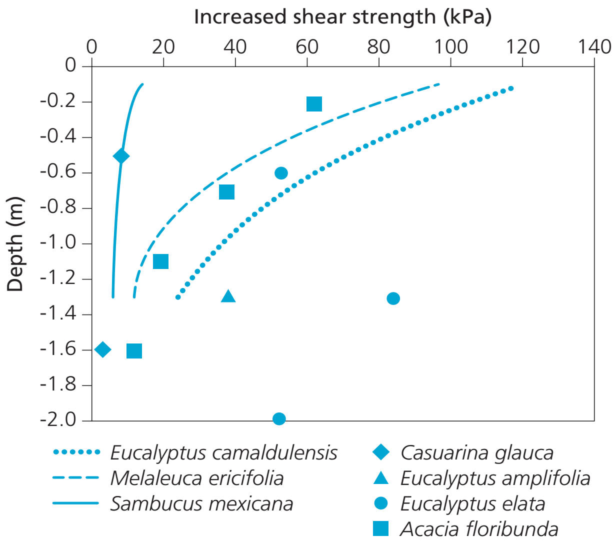


Figure 6.10. Data comparing increased shear strength from various riparian tree species.

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.

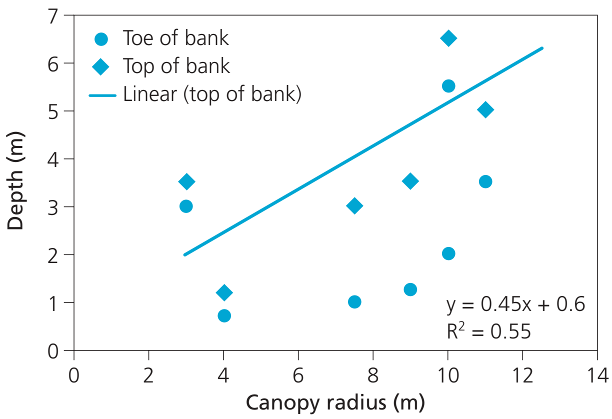


Figure 6.11. Relationship between the radius of the tree canopy (the drip line) and the radius of the abutment along the Acheron River.

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.

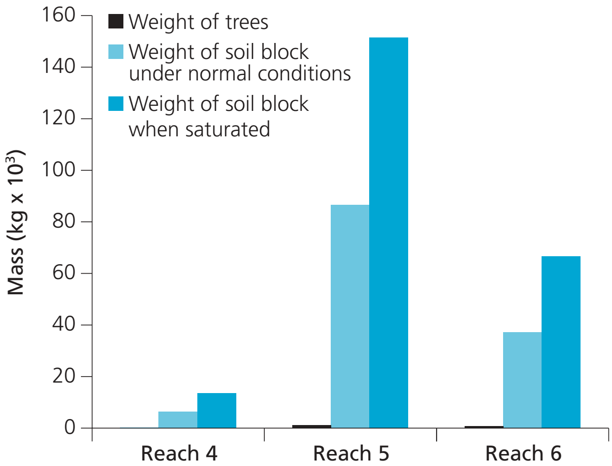


Figure 6.12. Surcharge from wattle trees along three reaches of the Latrobe River (from Abernethy & Rutherfurd, 2000a).

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

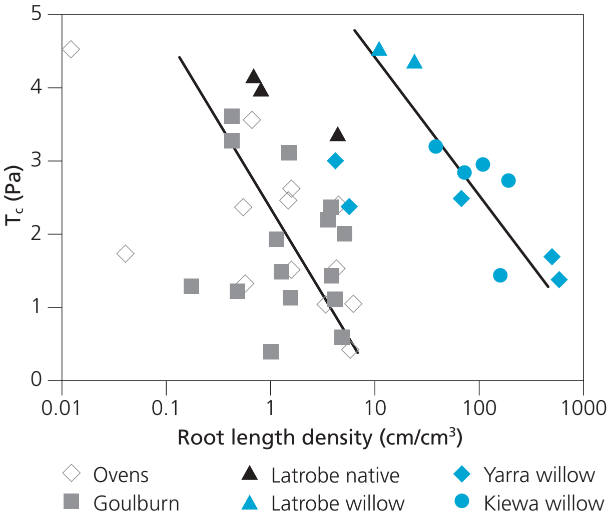


Figure 6.13. Critical shear stress (measured by the hydraulic jet device) required to erode sediment with different root length densities (measured by the root scanner device).

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

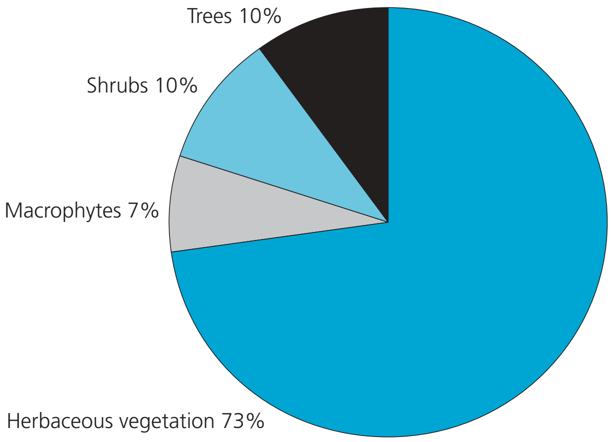


Figure 16.14. Occurrence frequency of vegetation types on vegetated horizontal surfaces in Victorian streams (percentage of vegetated horizontal surfaces with each type of vegetation).

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.

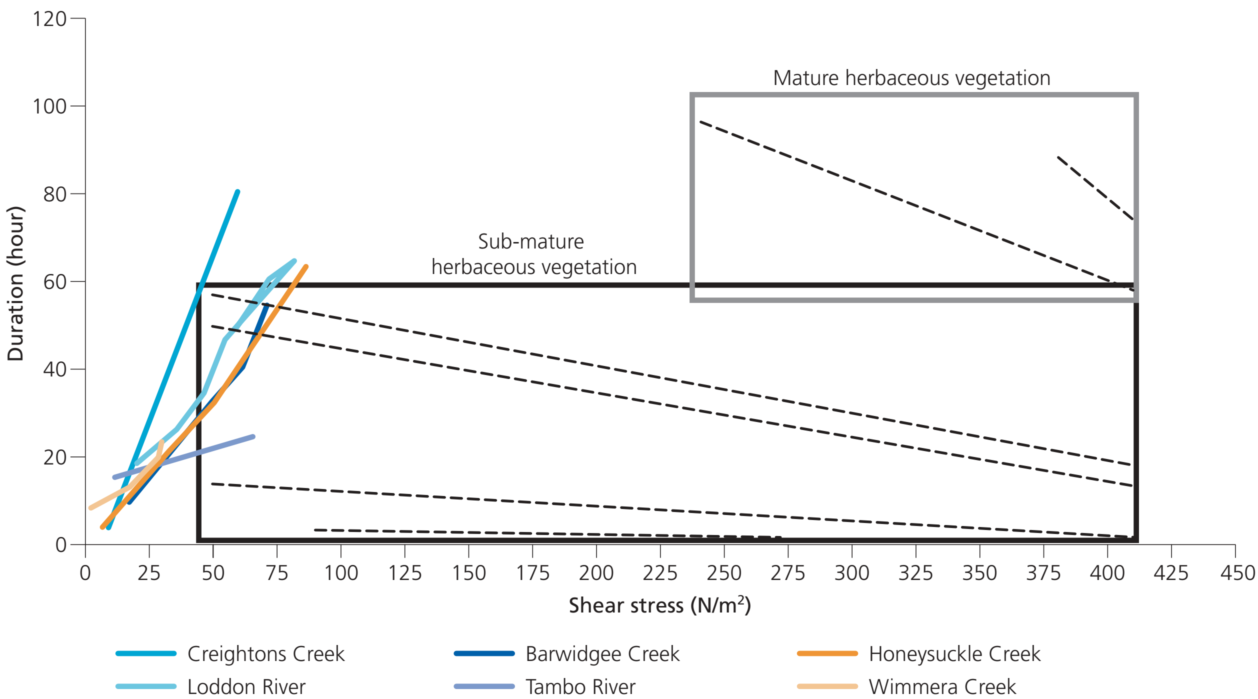


Figure 6.15. Summary graph showing erosion prediction analyses for all combinations of tested herbaceous vegetation and substrate at each study site (the coloured lines show the shear stress and duration of flows experienced in the streams listed, the black dashed lines show the duration and resistance 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 km² (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?

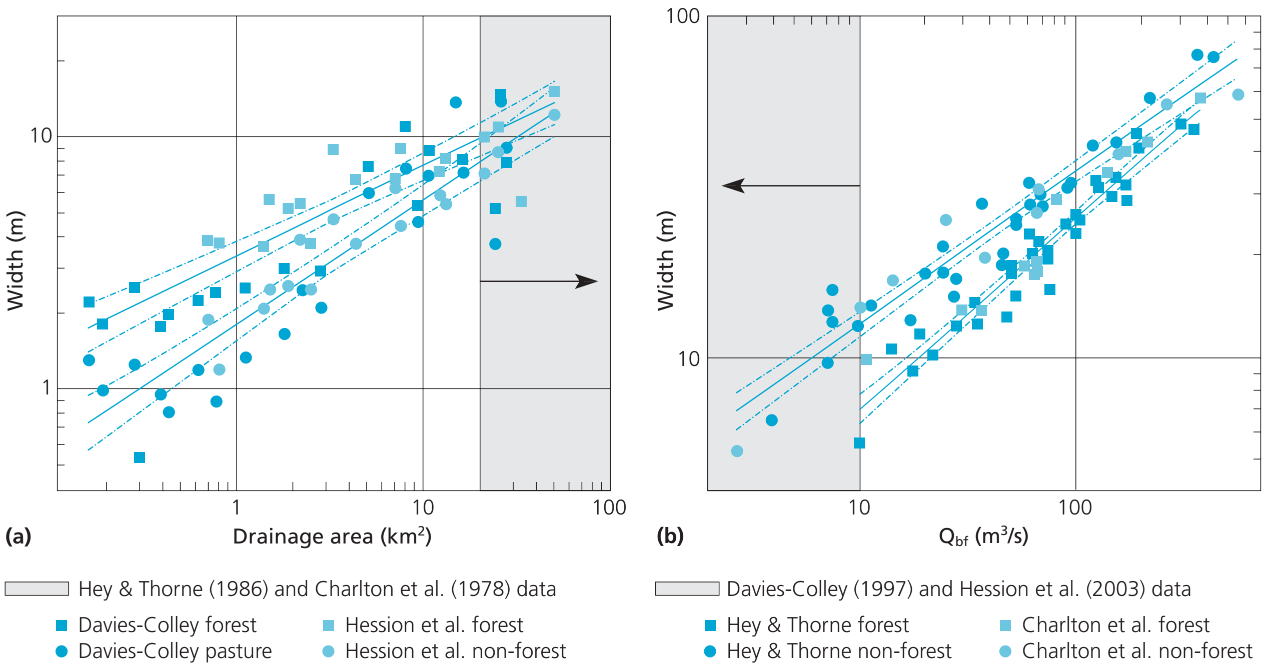


Figure 6.16. Graphs of data from four studies on the effect of vegetation on channel width. Graph (a) shows forested streams with small drainage areas are wider than un-forested streams of the same size. Graph (b) shows that larger forested streams are narrower than un-forested streams with the same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

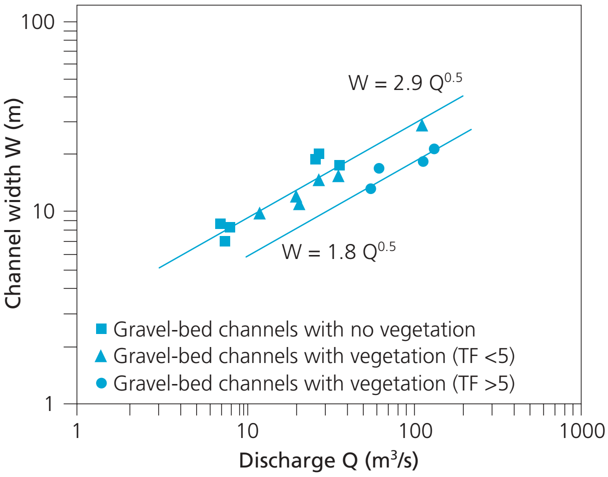


Figure 6.17. At a given discharge, channels lined with Australian Native vegetation were found to be narrower than those with few or no trees (Huang & Nanson 1997b, p. 243).

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.

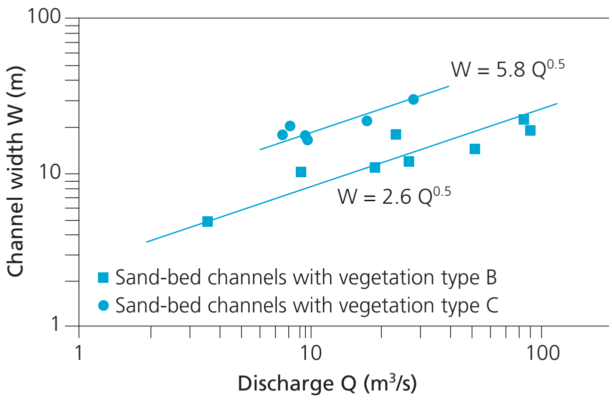
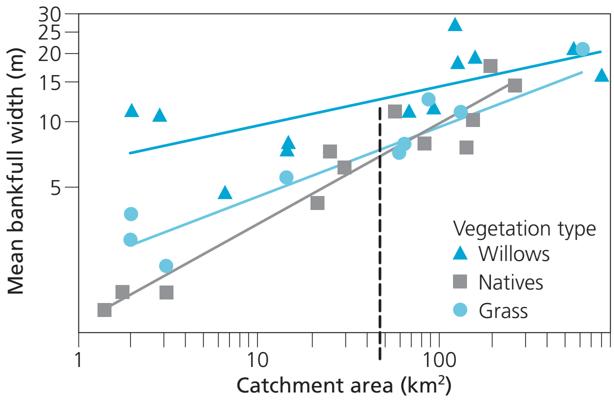


Figure 6.19. Graph showing the results from a study on the width of streams with native Australian trees on the bank (Type B), compared to the width of streams with willows on the bed as well as natives on the bank (Type C) (Huang & Nanson 1997b, p. 245).



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

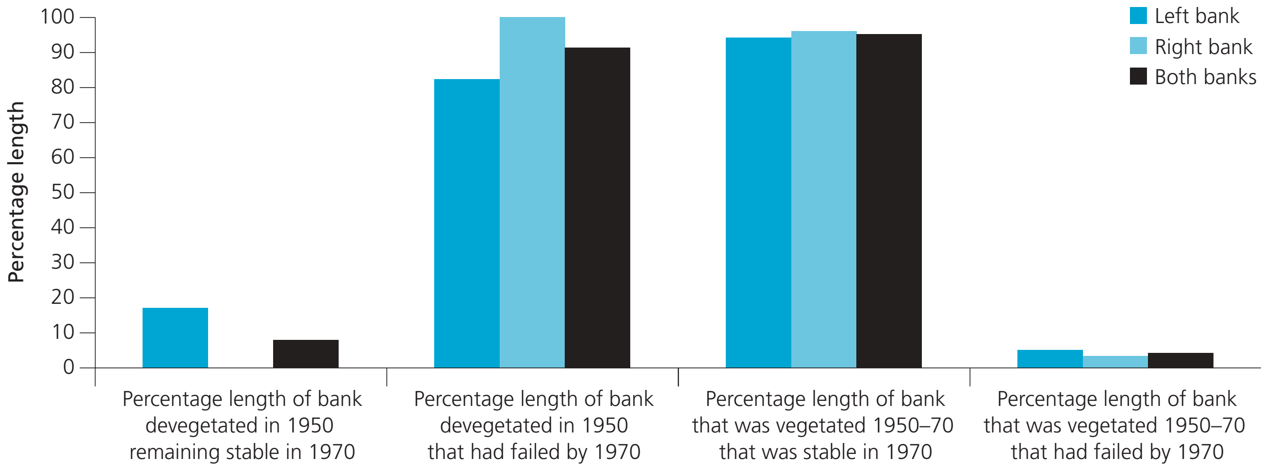


Figure 6.21. Bank failure in vegetated and cleared sections of bank in the Nepean River.

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.

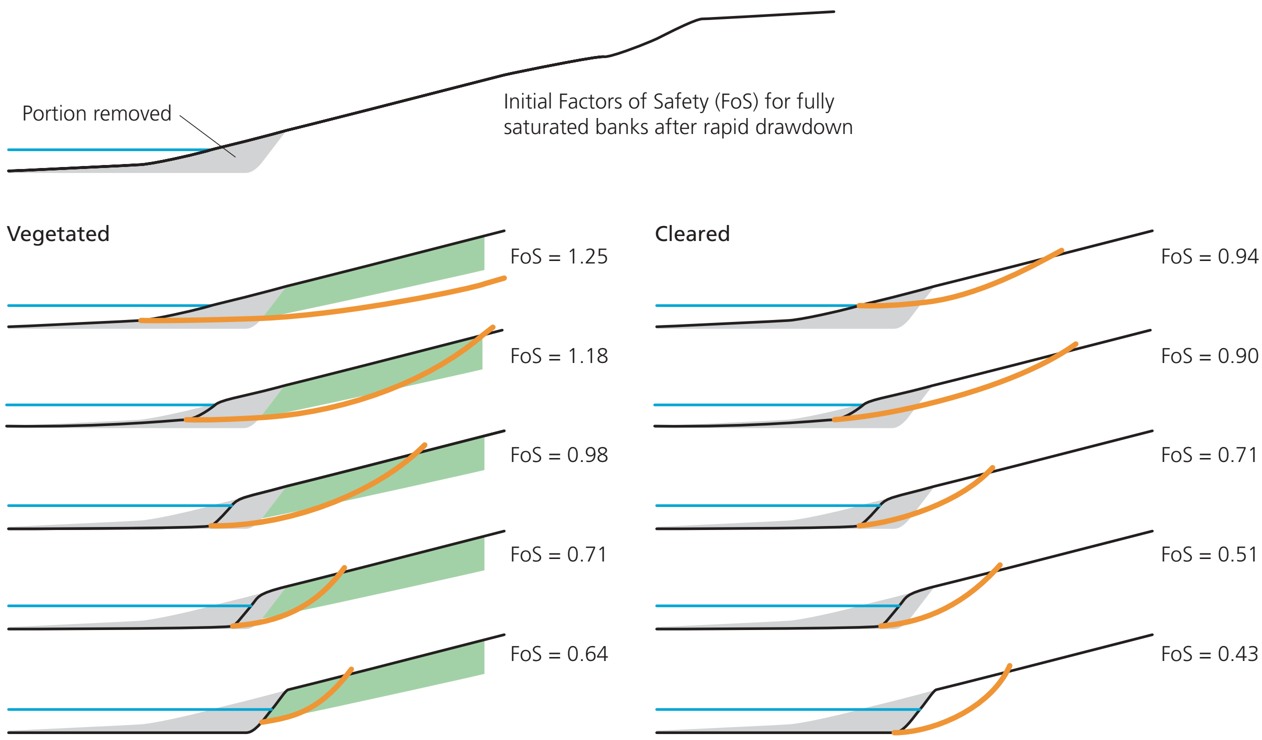


Figure 6.22. Simulation of the effects of channel widening after the onset of an FDR on bank stability for vegetated and cleared banks. Channel widening is assumed to occur due to toe erosion. The bank profile used in the Xslope modelling is shown at the top of the diagram. The consequences of progressive 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

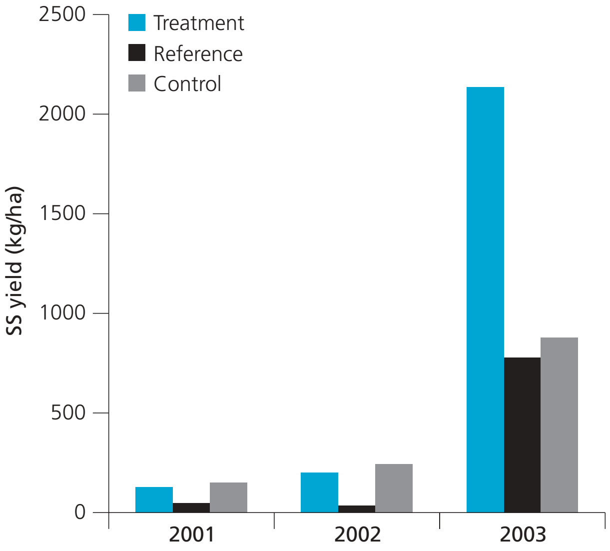


Figure 6.23. Total suspended sediment yield for Echidna Creek, showing that the increase in yield from the treatment stream relative to the control and reference sites.

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.

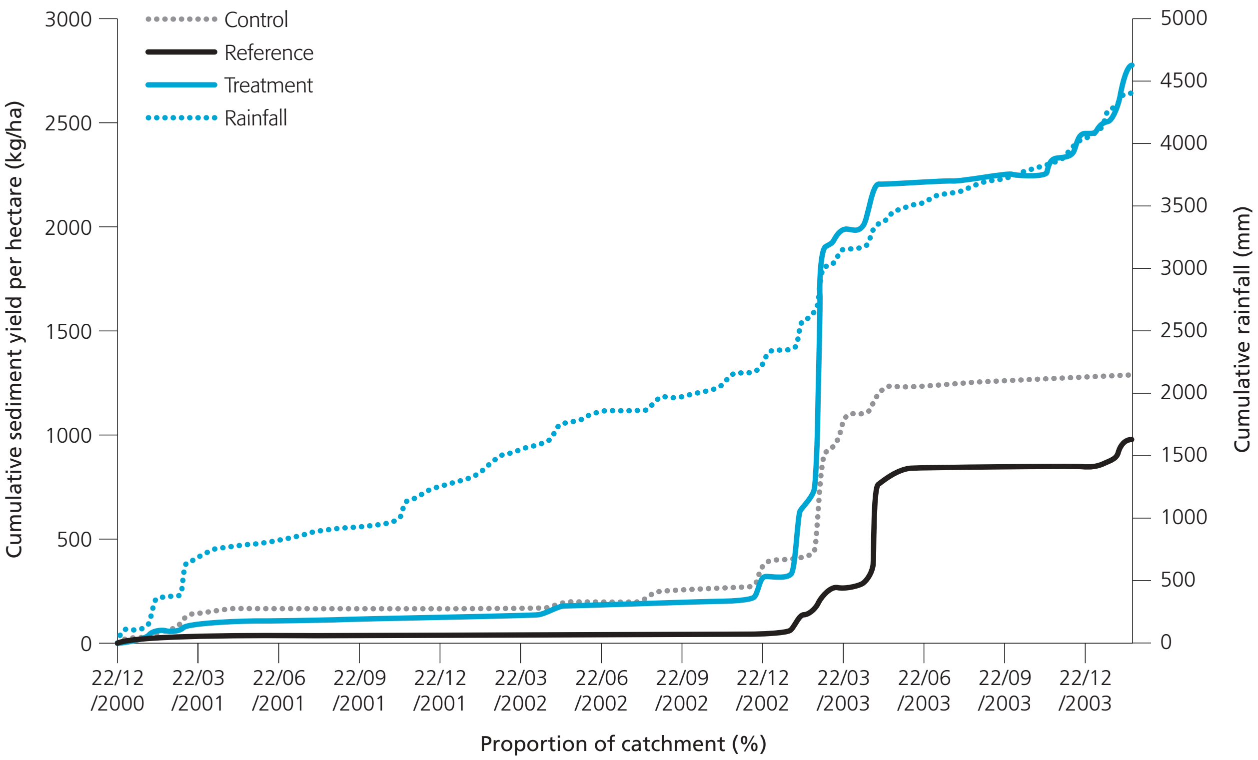


Figure 6.24. Cumulative suspended sediment yield per effective catchment area for the control, reference and treatment catchments.

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
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).

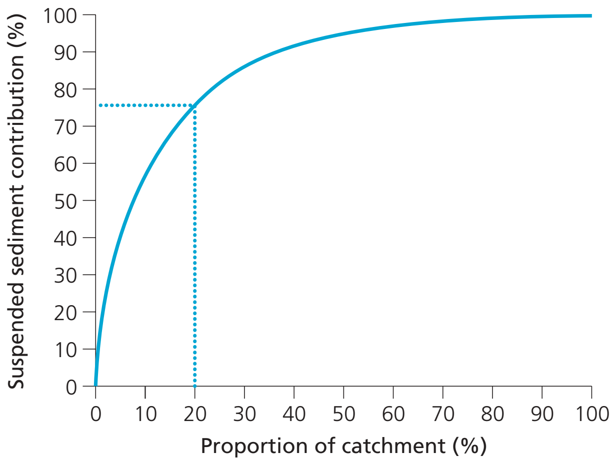


Figure 6.25. Cumulative sediment yield plotted against proportion of total area for catchments of the Murray Darling Basin (data from Sednet modelling). Note that nearly 80% of the sediment comes from only 20% of the catchment area.

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.

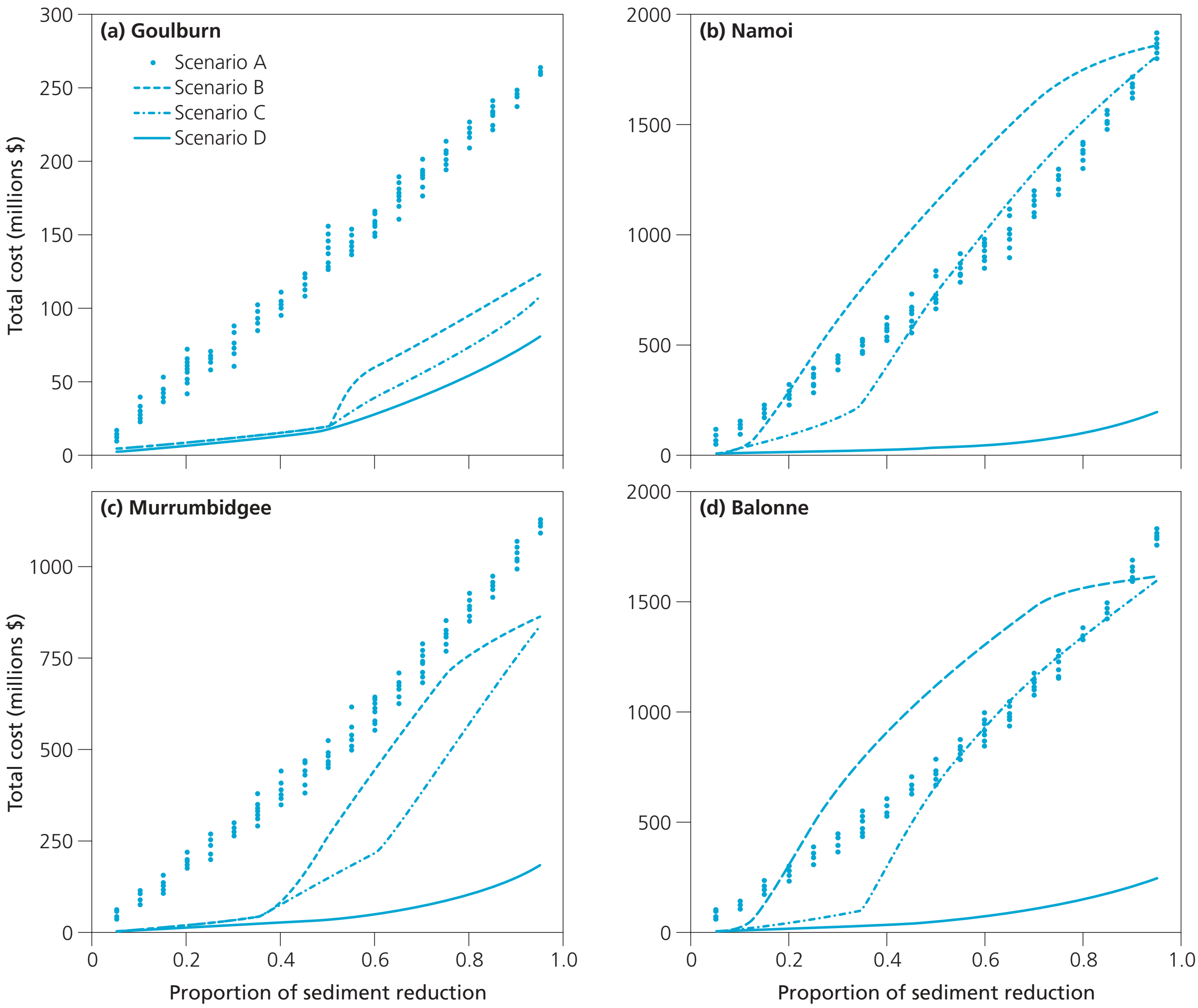


Figure 6.26. Cost versus sediment reduction curves for the four scenarios described above. Scenario A is random distribution of works, scenario B is treating hotspots, scenario C is treating well-connected sites, and scenario D is treating well connected hotspots.

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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CHAPTER 7

Wood and other aquatic habitat

Simon Treadwell, John Koehn, Stuart Bunn and Andrew Brooks

Summary

~ Riparian vegetation increases stream channel complexity and directly contributes to aquatic habitat through inputs of logs and branches. In turn, the provision of complex habitat has a major influence on aquatic biodiversity.

~ Logs and branches can enhance stream stability, regulate sediment transport and exert significant control on channel complexity in bedrock rivers and channel geomorphology in alluvial rivers.

~ Logs contribute to the formation of physical features in streams, such as scour pools and channel bars, which serve as habitat for in-stream biota.

~ Logs provide physical habitat for biota at all levels of the food chain, ranging from microscopic bacteria, fungi and algae, to macroinvertebrates, fish and turtles.

~ Logs also provide sites where bacteria, fungi and algae can process carbon and other nutrients such as nitrogen and phosphorus, thus contributing to ecosystem processes such as productivity and respiration.

~ In alluvial rivers, logs can modify surface water/ground water exchange and enhance nutrient processing.

~ Logs from Australian riparian zones are relatively immobile. Our streams tend to have a low average stream power, the wood has a high density and many riparian trees have a complex branching structure that ensures they are easily anchored in position.

~ Although vast amounts of wood have been removed from many Australian rivers, what does remain provides important habitat for microbes, invertebrates, fish and other animals.

~ Retention and reinstatement of logs should be a priority for river rehabilitation, instead of removal or even realignment.

7.1 Woody habitat

What is woody habitat?

Several interchangeable terms are often used to describe wood material in rivers and streams, which is made up of the sticks, branches, trunks and whole trees that enter the channel from the riparian zone or floodplain. The scientific literature often refers to this material as either coarse woody debris (CWD) or large woody debris (LWD). This is in keeping with the accepted nomenclature for describing organic matter particle-size fractions; that is, dissolved organic matter (DOM), fine-particulate organic matter (FPOM), coarse-particulate organic matter (CPOM) and LWD.

Another term commonly used in Australia is 'snag', although this typically refers to a complex structure that generally consists of very large, highly branched debris. Recently, the term 'structural woody habitat' (Gerhke & Brooks 2003, Koehn et al. 2004, Howell et al. 2004) has been used, in an attempt to encapsulate the structural as well as the ecological attributes of wood in streams. Throughout this chapter we have used the term wood or woody habitat, in line with recommendations made by Gregory et al. (2003) to refer to logs and branches in streams and rivers that have been derived from riparian and floodplain vegetation. We have deliberately avoided the term 'debris' or 'snag' because of their negative connotations (see Cottingham et al. 2003).

Logs and branches are a significant ecological component of streams and rivers, both in Australia (Lloyd et al. 1991, O'Connor 1991a, Gippel et al. 1996a) and overseas (Marzolf 1978, Bilby & Likens 1980, Benke et al. 1985). This material forms an important structural

Photos on these pages Andrew Brooks.

component, influences many ecological processes (see Chapter 4) and provides essential habitat for aquatic and terrestrial organisms. In alluvial rivers, wood plays a critical role in stream morphology, stability and sediment transport. In some perennial sand bed-rivers it has been shown that the majority of morphological complexity is associated with in-stream wood loading (Brooks et al. 2003). Indeed, it has been demonstrated that in some circumstances, the formation of alluvial channels and entire floodplains is dependent on the presence of in-stream wood (Montgomery et al. 1996, Brooks & Brierley 2002). Conversely, wood removed from streams can increase sediment transport capacity by up to three orders of magnitude, thereby exceeding thresholds, which make it very difficult to maintain channel stability (Simon 1989, Simon & Darby 1997, Brooks & Brierley 2004). In mountain rivers, many of the in-stream alluvial features and associated habitat units are directly associated with log steps and log jams (Keller & Swanson 1979, Keller et al. 1995, Montgomery et al. 2003).

Sources, amounts and longevity

Most wood enters streams from adjacent and upstream riparian land. In forested, laterally stable rivers, inputs from riparian land generally occur at a rate similar to that at which live wood is transferred to fallen dead wood in a forest ecosystem (Harmon et al. 1986). However, in many alluvial rivers, lateral channel migration and expansion can increase wood recruitment to rates well above background tree mortality rates (Cohen & Brierley 2000, Benda et al. 2003). In steep headwaters, land-sliding can inject large volumes of timber to the channel network, often in the form of large log jams (Benda 1990, Benda et al. 2003). A river reach wood budget is also influenced by the input of wood transported from upstream (Harmon et al. 1986, Benda et al. 2003). Rare extreme floods that occur in some rivers can have a long-lasting impact on riparian zones and influence the supply of wood to the channel (Jacobson et al. 1995). However, floods can also remove wood from river channels and deposit it on the floodplain (Piegay 2003). Along Australian rivers, self-pruning of *Eucalyptus* species due to osmotic stress in hot weather is often a major cause of input of larger branches (Lloyd et al. 1991). In the Murray River, most river red gum snags are sourced directly from eroding banks (Nicol et al. 2001, Koehn et al. 2004).

Historical records from the Murray–Darling River system indicate that our larger inland rivers historically contained much greater volumes of wood than they do today. Since the 1850s, wood has been removed from streams and rivers under the guise of so-called river-improvement strategies designed to prevent hazards to navigation, reduce damage to in-stream structures, rejuvenate or scour channels, and increase hydraulic capacity to reduce flooding (Strom 1962, Gregory & Pressey 1982, Shields & Nunnally 1984, Gippel et al. 1996a).

Empirical evidence from a number of undisturbed forested systems up the east coast of Australia indicates that wood loadings can be extremely high due to the slow decay of Australian hardwoods in temperate perennial systems (Marsh et al. 2001, Brooks & Brierley 2002, Webb & Erskine 2003). This highlights the fact that those rivers in cleared landscapes that are now largely devoid of wood, once had large wood accumulations falling in from adjoining riparian land and supporting a diverse range of aquatic life.

These photos show the importance of wood in a range of river types. Wood in rivers is vitally important for in-stream health and biodiversity.

These trees are holding the bank together with their roots and when they eventually fall into the river will provide habitat for a host of aquatic organisms. Photo CSIRO Sustainable Ecosystems.

De-snagging of the Murray and Murrumbidgee Rivers commenced in 1855 with a boat captain, Francis Cadell, clearing by hand a little under 160 kilometres of each river (Mudie 1961). Systematic de-snagging was started by the South Australian Government with the launch of a 'snag boat', the *Grappler*, in 1858 (Mudie 1961). Snag boats were capable of removing 300–400 logs per month, and one boat, the Industry, is reported to have removed 3 million logs from the Murray River between 1911 and the late 1960s (Phillips 1972). By 1973 it was estimated that there were about 1200 logs along 330 kilometres of the Murray River between Lock 6 in South Australia, and Wentworth in New South Wales (Hall & Mudie 1975). This is only three logs per kilometre, a far cry from the days when logs were reported as '… standing up like a regiment of soldiers …' (Mudie 1961). Three logs per kilometre is the same density now present in the Willamette River in Oregon, after extensive de-snagging reduced densities from 550 logs per kilometre (Sedell & Froggatt 1984). De-snagging in the Murray River has continued more recently, with 24,500 logs removed between Lake Hume and Yarrawonga over the period 1976 to 1987 (Murray–Darling Basin Ministerial Council 1987).

There is limited historical evidence of wood loadings from other river systems around Australia, although we know that widespread de-snagging has taken place wherever intensive agriculture and irrigation has been developed. For example, rivers of the Swan coastal plain south of Perth were progressively de-snagged from the late 1930s to increase drainage for agricultural land (Bradby & Mates 1995). De-snagging, as part of general 'river improvement' (which also included bank clearance, bank training and relocation of the low-water channel) has been commonly practised throughout Australia under the authority of state government agencies (Strom 1962, Turnbull 1977, Erskine 1990). In some instances this has resulted in increased erosion and flooding and reduced invertebrate and fish populations in the affected reaches (Zelman 1977, Johnson 1978, Gregory & Pressey 1982, Hortle & Lake 1983).

Available data on current wood loads in Australian and overseas rivers are limited. Furthermore, most of the data relate to rivers that have been de-snagged, or to rivers that flow through cleared riparian land. Australian data and some USA data are summarised in Table 7.1 (see page 122). However, natural wood loadings of Australian streams are generally higher than those of streams in the northern hemisphere. This is consistent with the higher proportion of wood recorded in litter fall in Australian forests compared with northern hemisphere forests (Campbell et al. 1992a). Two additional factors also contribute to higher natural wood loads in Australia. These are the relatively low stream power (the ability of moving water to do work) of Australian streams, and the dense, long-lasting nature of Australian timbers. The trees that grow in the riparian zone of Australian rivers tend to be hardwoods that have a higher density and are stronger than the softwoods often occurring along northern hemisphere rivers. For example, tree species from southeastern Australian are, on average, 65% denser and approximately three times the hardness of tree species from the Pacific northwest of North America (White 1998).

Natural wood loads would be expected to vary depending on the climate and vegetation, especially along the riparian and floodplain corridor. For example, many dryland rivers have low wood loads reflecting their sparse riparian tree cover (Davies et al. 1995). Recent research in Australia has highlighted the relationship between the density of vegetation in the riparian zone and wood loading in streams. Although wood varied

Natural wood accumulation. Photo Tim Cohen.

widely both within and between rivers, Marsh et al. (2001) found a linear relationship between riparian tree volume and wood loading in streams across eastern Australia (Figure 7.1). This model assumes that immediate riparian input is the dominant recruitment process, and that the extant riparian vegetation structure and cover is indicative of the long term state. This relationship is described by the following equation:

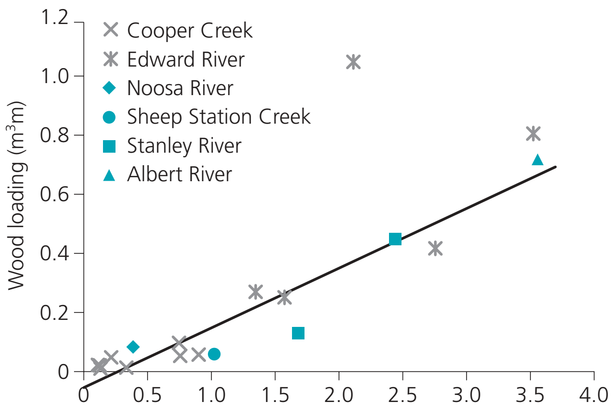
Wood volume (m^3/m) = 0.2*

Overhanging tree volume (m^3/m) — 0.05 ($R^2 = 0.91$)

This not only provides a benchmark for reinstatement of wood in de-snagged rivers, but also reinforces the importance of the riparian zone as the long-term source for this material.

It has generally been considered that as stream size or stream order increases, the volume of wood present relative to channel capacity decreases (Harmon et al. 1986, Robison & Beschta 1990). The data presented in Table 7.1 for some Australian streams tend to confirm this. However, undisturbed low-gradient, high-order streams in the United States have been shown to have comparable wood loadings to headwater streams elsewhere in the United States (except for those streams in the Pacific north west) (Wallace & Benke 1984). Although wood loadings may decrease as stream size increases, some research has indicated that the amount of wood actually located within the wetted channel increases as stream size increases. For example, wood loadings were twice as high in a 4.6 metre wide stream than in a 25.6 metre wide river (Robison & Beschta 1990). However, only 19% of wood fell within the channel of the smaller stream compared with 62% in the larger river. (High-gradient streams generally have a small channel width, so falling wood tends to span the channel, becoming suspended above the stream surface level and not acting directly on the stream.) In effect, the larger river contained twice as much in-channel wood as the smaller stream.

Figure 7.1. Wood loading and fringing riparian vegetation density along six south-eastern Australian streams (from Marsh et al. 2001).



With the realisation of the importance of wood to stream ecosystems, researchers have started to quantify the amounts of wood in streams. Wood loadings can be measured in a number of ways, but this can make comparisons between different systems difficult. A simple measure is the number of wood pieces per length of river bank. This provides an indication of density, but no indication of the amount of surface area available as habitat or of the mass of wood present. Surface area (m^2) and volume (m^3) can be calculated by measuring the diameter and length of pieces and, if wood density is known, mass (kg) can be also calculated. These various measurements can be expressed on an area basis per square metre of stream bed. The proportion of total habitat area available as log surface compared with other benthic surfaces can also be estimated.

Table 7.1. Wood loadings in Australian and some US rivers.

Stream	Catchment size km^2 (stream order)	Wood loading kg.m^{-2} (m^3/m^2)	Density items/100 m (both banks)	Surface area m^2/m^2 stream bed	Proportion of total habitat area available as log surface	Land use	Riparian vegetation	Reference	Comments
Pranjip Creek (Vic)	787	0–5 (0–0.008)		0–0.2		Agriculture	Degraded	O'Connor (1992)	
as above	>787	3.9–42.4 (0.005–0.055)		0.28–0.91	21–47%	Agriculture	Intact	O'Connor (1992)	
Keppel Creek (Vic)	14.3 (4)	4.3 (0.007)	490	0.31	21%	Forested	Intact	Treadwell et al. (1997), S. Treadwell & I. Campbell (unpub.)	
Wellington River (Vic)	122 (4)	(0.0057)		0.097		Forested	Intact	I. Campbell & M. Shirley (unpub.)	
Carey River (Vic)	244 (5)	(0.0004)		0.015		Forested	Intact	as above	
Dolodrook River (Vic)	145 (5)	(0.0056)		0.048		Forested	Intact	as above	
Murray River billabongs (NSW and Vic)					5–15%	Agriculture	Various	M. Shirely (unpub.)	
Murray River Yarrawonga (NSW)			14			Agriculture and forested	Various	J. Koehn (unpub.)	Mature red gum trees along banks
Murray River Barmah Forest (NSW)			9.5			Forested	Intact	Gippel et al. (1992)	Channel de-snagged in past
Murray River Overland Corner (SA)			2.7			Agricultural	Degraded	Lloyd et al. (1991)	Channel de-snagged in past
Goulburn River (Vic)	16 125		23.6			Agriculture and forested	Intact	Anderson & Morison (1988)	Logs and log jams
Thompson River (Vic)	3540	(0.0172)	12.1	0.1184		Agriculture	Intact	Gippel et al. (1996a)	

Johnstone River and Mulgrave River (north Qld)	(1)		9.2					B. Pusey, A. Arthington & M. Kennard (unpub.)	Wood only within 1 m of bank = > underestimate
as above	(2)		22.4					as above	as above
as above	(3)		14.4					as above	as above
as above	(4)		3.8					as above	as above
as above	(5)		4.8					as above	as above
as above	(6)		0.2					as above	as above
Dandelup River (WA)	(4)				0.4%	Agriculture	Degraded	Beesley (1996)	Channel de-snagged in past
Serpentine River (WA)	(4)				1.8–2.4%	Agriculture	Intact	Beesley (1996)	
as above	(4)				1.6–7.9%	Forest	Intact	as above	
Willamette River (Oregon)	29 138		55: before de-snagging 0.3: after de-snagging				Extensive riparian forest now cleared for agriculture	Sedell & Froggatt (1984)	
Walton Creek (Colorado)	26.1 (2)	(0.001)	20				Degraded	Richmond & Fausch (1995)	
Ogeechee River (Georgia)	7000 (6)	6.5 (0.0148)		0.43				Wallace & Benke (1984)	Limited de-snagging
Black Ck (Georgia)	755 (4)	5.0 (0.0168)		0.57				Wallace & Benke (1984)	Limited de-snagging
Satilla River (Georgia)	3100–7300 (5/6)			0.05–0.07	4–6		Cypress–black gum swamp	Benke et al. (1984, 1985)	Extensive de-snagging
Several headwater streams in Oregon	(1 and 2)	8–25						Cummins et al. (1983)	
McKenzie River (Oregon)	1024 (6)	0.5 (0.001)				Forest	Intact forest floodplain	Keller & Swanson (1979)	
Lookout Creek (Oregon)	60.5 (5)	11.6 (0.023)				Forest	Intact	Keller & Swanson (1979)	

Longevity

The slow decay and high stability of wood contributes to its dominance as the major organic matter size-fraction present in undisturbed temperate streams and rivers. An example of the longevity and stability of wood can be found in the Stanley River, Tasmania, where many in-stream logs of Huon pine, *Lagarostrobos franklinii*, and celery-top pine, *Phyllocladus aspleniifolius*, present as individual logs or as part of accumulations, had fallen into the water up to 5000 years ago (Nanson et al. 1995). Wood buried in the floodplain had been there for 3500 to 9000 years, with one buried log (King William pine — *Athrotaxis selaginoides*) having died 17,100 years ago (Nanson et al. 1995). Logs of similar antiquity (up to 13,000 years old) were also dated from floodplains in East Gippsland (Brooks & Brierley 2002). Based on the age of some logs, some accumulations appear to have been stable for up to 2000 years (Nanson et al. 1995), indicating the ability of wood to reduce stream power and stabilise channel beds and banks over long periods (Brooks et al. 2003).

Pattern and structure

The spatial arrangement and physical characteristics of structural woody habitat was examined in the Murray River between Lake Mulwala and Tocumwal using low-level, high-resolution aerial photography (Koehn et al. 2004). It was found that wood occurred in aggregations that were closely associated with eroding banks on meanders. The physical characteristics of the wood in these aggregations varied (basal diameter range 0.44–2.45 metres, length range 1–44 metres), however small to medium-sized trees (basal diameter range 0.7–1.4 metres, length range 5–20 metres) were most common. Most wood was oriented in the 0–90° downstream arc. The association between eroding banks and woody habitat suggests that bank erosion may be an important determinant in the formation of structural woody habitat aggregations. The pattern of wood within the river landscape was also determined at a range of scales (Hughes 2001, Nicol et al. 2001) with the distribution appearing to reflect the energy of meander bends.

7.2 Direct use of wood as habitat

Logs and branches provide habitat over a range of spatial scales for many aquatic organisms. Wood provides a hard substrate for direct colonisation by biofilm and invertebrates, and a surface on which some invertebrates and fish deposit eggs. In a study of wood habitat surface complexity, it was concluded that the more complex the wood surface, the larger the surface area available for colonisation, the greater the resource availability and the greater the invertebrate species richness (O'Connor 1991b).

These fallen trees are providing valuable habitat for aquatic organisms. Photo Tim Cohen.

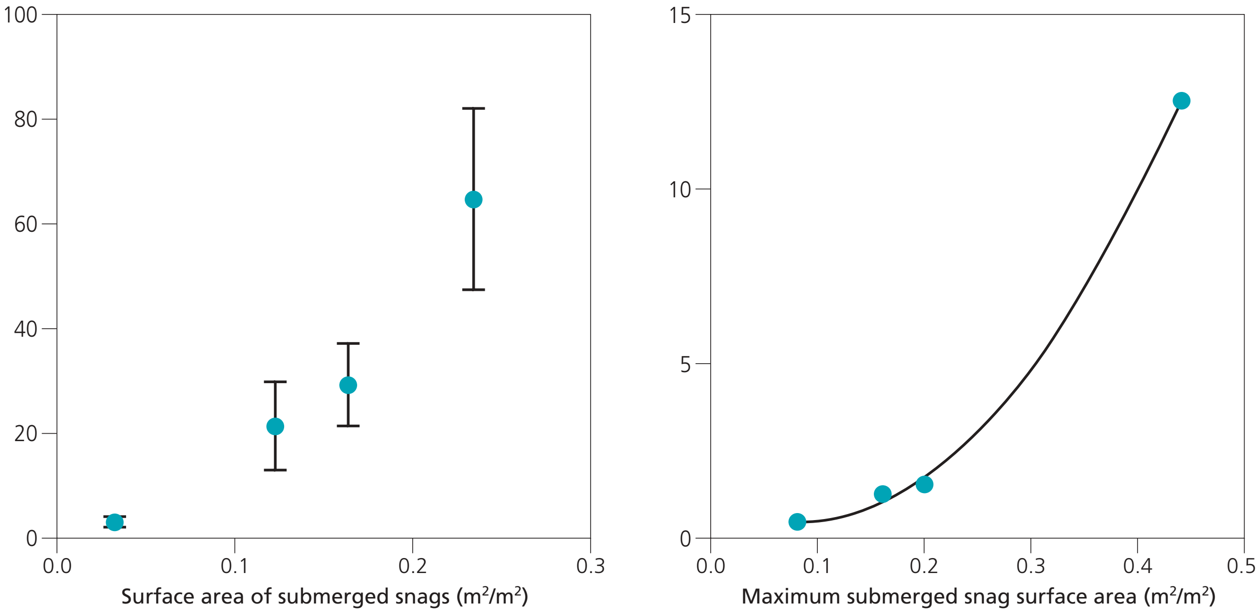


Figure 7.2. Primary production by biofilms growing on wood surfaces as a function of total stream production increases as submerged wood surface area increases. Left: In rivers that have low log surface area, for example rivers that have been desnagged, the amount of primary production by biofilms growing on wood surfaces is low. Right: The greater the log surface area the higher the overall contribution that biofilm primary production makes to total ecosystem production (S. Treadwell, unpublished data for sites in the Ovens and Murray Rivers).

Logs and branches form complex three-dimensional structures in the water column and provide a number of different-sized spaces or habitat zones. The small spaces formed by sticks, twigs and other material trapped against logs provide refuge and feeding areas for small and juvenile fish, as well as invertebrates (Triska & Cromack 1980, Kennard 1995), while the larger spaces around branches and logs provide space for larger species. Hollow logs provide essential habitat for some fish, and branches that extend into the water column and above the water surface provide habitat at different water levels.

Microbes

The complex surface structure of wood provides a suitable substrate for rapid colonisation by a range of microbes, including fungi, bacteria and algae (Willoughby & Archer 1973, Aumen et al. 1983, Sinsabaugh et al. 1991, Scholz & Boon 1993), commonly referred to as 'biofilm'. The activities of these microbes are essential to the generation and processing of organic carbon and nutrients in aquatic environments. Fungal and algal biomass was found to be greater on wood substrates than on an inert substrate (Sinsabaugh et al. 1991). In rivers with unstable sand and silt substrates, wood may provide the only stable substrate for biofilm development.

Wood provides a significant stable substrate for algae (O'Connor 1991), however, its growth can sometimes be affected by fine sediment and changes in river height (as a result of river regulation) that reduce light availability and which favour other organisms. Where algal development is so restricted, fungi and bacteria are likely to constitute the greatest biomass in biofilm on logs and branches, and heterotrophic respiration is likely to be the major process (see Figure 7.2).

Invertebrates

Wood in Australian streams and rivers provides a major substrate for colonisation by invertebrates (Lloyd et al. 1991, O'Connor 1991a, Tsyrlin 1994, McKie & Cranston 1988). Most studies have recorded specific communities existing on wood in preference to other substrates. This highlights the importance of wood in contributing to biodiversity. Most invertebrates that colonise wood graze biofilm and other fine-particulate organic matter on the wood surface (O'Connor 1991b, Tsyrlin 1994) but some, such as freshwater hydras, sponges, and the larvae of blackflies (Simuliidae) and net-spinning caddis (Hydropsychidae), use the hard surfaces as attachment sites to filter feed (Tsyrlin 1994).

In river systems with sandy, unstable substrates, logs and branches provide the only stable substrate for invertebrate colonisation, particularly during high-flow periods (Beesley 1996). In intermittent streams, wood can provide a refuge for invertebrates, enabling them to survive periodic dry periods (Boulton 1989). Certain invertebrate species feed specifically on woody substrate and are instrumental in modifying wood surfaces, thereby

A range of different organisms depend on wood for habitat. Photos (left column) Andrew Brooks, (right column) John Koehn.

contributing to surface complexity and promoting further colonisation (Flint 1996, McKie & Cranston 1988). In-stream wood also traps organic matter (Bilby & Likens 1980) and increases overall biodiversity (Wondzell & Bisson 2003), including macroinvertebrates (Benke et al. 1984, O'Connor 1991).

De-snagging, particularly in rivers where logs and branches are the only significant stable substrate, could significantly reduce invertebrate density and species richness and contribute to a loss of invertebrate biodiversity. De-snagging has been identified as a threat to at least four species of freshwater crayfish found in lowland rivers throughout Australia (Horwitz 1994). Particular threats are faced by the largest freshwater crayfish in the world, the giant Tasmanian freshwater lobster, Astacopsis gouldii (Horwitz 1991), and by the West Australian marron, *Cherax tenuimanus*, a large freshwater crayfish popular with recreational fishers (Morrissy 1978).

Fish

The importance of wood to riverine fish has been illustrated with positive relationships shown between salmon diversity and abundance and instream wood at both larger basin scales (Tchaplinski & Hartman 1983, Reeves et al. 1993, Quinn & Peterson 1996, Cederholm et al. 1997) and micohabitat scales (Flebbe & Dollof 1995, Inoue & Nakano, 1998). There have been similar findings for non-salmonid species with Lehtinen et al. (1997), Angermier and Karr (1984), Todd and Rabeni (1989), Scott and Angermier (1998), Jepsen et al. (1997) and Daugherty and Sutton (2005) all describing fish associations with wood. Wood has been shown to be an important microhabitat component for both adult and age–0 Murray cod (Koehn 2006) supporting previous natural history observations (e.g. Dakin & Kesteven 1938) and for Mary River cod (Simpson & Mapleston 2002) and trout cod (Growns et al. 2004, Nicol et al. 2004, 2006).

Much of the in-stream habitat available for fish originates from riparian zone vegetation (Koehn & O'Connor 1990, Nicol et al 2001). In Australian lowland streams wood is usually the major form of in-stream structural habitat used by many species. Fish need complex structures to hide from predators and to avoid intense sunlight and high current velocities. Woody habitat may also provide cover for predators. For instance, short-finned eels, *Anguilla australis*, in a Victorian stream show preferences for dense log jams. This may be related to their ability to ambush prey, rather than to their own requirements for shelter from predation (Koehn et al. 1994).

Fish also use logs as markers to designate territory and maintain position in the stream. Radio tracking of Murray cod, *Maccullochella peelii peelii*, has indicated they can migrate up to several hundred kilometres during spawning and return to a 'home' log (J. Koehn unpublished data). Providing velocity refuge for fish is a key function of wood in streams (Fausch 1993, Crook & Robertson 1999). Velocity refuges can also be provided by variations in the riverbed substrata caused by wood. Selection of such habitats by Murray cod may reflect this (Koehn 2006), with fish sheltering in substrate 'pockets' created by scour around wood or among the wood itself.

Logs and branches create a diversity of habitats by redirecting flow and forming variations in depth and water velocity. Such a diversity of habitats provides for the needs of a variety of fish species and for fish of various ages. Logs also provide habitat for biofilm and invertebrates that form important links in the food chain for fish. Further, they provide important habitat in deeper, lowland streams, where the benthic substrates are generally composed of finer particles and are more uniform.

Large logs and branches provide spawning sites for species that lay their adhesive eggs on hard surfaces (Cadwallader & Backhouse 1983). River blackfish, *Gadopsis marmoratus*, lay a relatively small number of eggs in the safety of hollow logs (Jackson 1978). Mary River cod, *Maccullochella peelii mariensis*, one of Queensland's most endangered fish species, are thought to require hollow logs for spawning (Simpson & Jackson 1996). Some fish species prefer to live in and around logs, and their numbers can often be directly correlated with the amount of such habitat available. For example, Mary River cod favour slow-flowing pools with in-stream cover in the form of logs, log piles or a combination of logs and bank overhangs, but may also occur in shallower pools where heavy shading and discoloured water provide additional cover (Simpson 1994).

During flooding, logs and branches in floodplain channels provide a substantial increase in available fish habitat (including spawning sites) and may play a major role in factors (such as site selection and post-hatching predation) which influence recruitment (Koehn 2006). Avoidance of predation has been suggested as a reason for fish habitat selection where wood can provide additional shelter.

At least 34 native freshwater fish species from around Australia use wood as a major habitat source or for spawning (see Table 7.2). Given the paucity of knowledge of the biological requirements of many species, it is reasonable to assume that the true figure is much higher. The removal of wood has been widely recognised as a threat to native freshwater fish (Cadwallader 1978, Koehn & O'Connor 1990, Wager & Jackson 1993). In Victoria, the removal of wood from streams and the degradation of native riparian habitat are listed as 'potentially threatening processes' under the Flora and Fauna Guarantee Act 1998 (DCNR 1996a, 1996b). The loss of habitat for any species is likely to lead to a reduction in numbers. This is particularly so for habitat-dependent species and for those species which require a particular habitat for a critical purpose, such as spawning.

Table 7.2. Native freshwater fish species with a documented use of wood as a major habitat or for spawning.

Common name	Species name	Reason for use	Reference
River blackfish	*Gadopsis marmoratus*	Spawning site, preferred habitat	Jackson (1978), Koehn (1986), Koehn et al. (1994)
Two-spined blackfish	*Gadopsis bispinosus*	Likely spawning site, preferred habitat	Robison & Beschta (1990), Koehn (1987, 2005)
Murray cod	*Maccullochella peelii peelii*	Spawning site, preferred habitat	Llewellyn & MacDonald (1980), Cadwallader & Backhouse (1983), J. Koehn (2006)
Trout cod	*Maccullochella macquariensis*	Spawning site, preferred habitat	Cadwallader (1978), Growns et al. (2004), Nicol et al. (2004, 2006)
Eastern freshwater cod	*Maccullochella ikeii*	Spawning site, preferred habitat	Merrick & Schmida (1984)
Mary River cod	*Maccullochella peelii mariensis*	Spawning site, preferred habitat	Simpson & Jackson (1996), Simpson & Maplestone (2002), Merrick & Schmida (1984)
Spotted galaxias	*Galaxias truttaceus*	Preferred habitat includes wood	Williams (1975)

Table 7.2. continued

Common name	Species name	Reason for use	Reference
Tasmanian mudfish	*Galaxias cleaveri*	Preferred habitat includes wood	McDowall (1980)
Mountain galaxias	*Galaxias olidus*	Preferred habitat includes wood	Marshall (1989)
Catfish	*Tandanus tandanus*	Affected by de-snagging	Reynolds (1983)
Australian bass	*Macquaria novemaculeata*	Preferred habitat includes wood	Marshall (1979)
Estuary perch	*Macquaria colonorum*	Preferred habitat includes wood	Sanders (1973), McCarraher (1986)
Barramundi	*Lates calcarifer*	Preferred habitat includes wood	Merrick & Schmida (1984)
Australian smelt	*Retropinna semoni*	Preferred habitat includes wood	Cadwallader (1978)
Tupong	*Pseudaphritis urvilii*	Preferred habitat includes wood	Hortle (1979), Hortle & White (1980)
Southern purple-spotted gudgeon	*Mogurnda adspersa*	Spawning	Allen (1989)
Striped gudgeon	*Gobiomorphus coxii*	Spawning	Cadwallader & Backhouse (1983)
Western carp gudgeon	*Hypseleotris klunzingeri*	Spawning	Lake (1967), Llewellyn (1971)
Golden gudgeon	*Hypseleotris aurea*	Preferred habitat includes wood	Merrick & Schmida (1984)
Empire gudgeon	*Hypseleotris compressa*	Spawning	Allen (1989)
Barnett River gudgeon	*Hypseleotris kimberleyensis*	Preferred habitat includes wood	Allen (1989)
Prince Regent gudgeon	*Hypseleotris regalis*	Preferred habitat includes wood	Allen (1989)
Midgeley's carp gudgeon	*Hypseleotris* sp. A	Preferred habitat includes wood	Allen (1989)
Northern trout gudgeon	*Mogurnda mogurnda*	Spawning	Allen (1989)
False-spotted gudgeon	*Mogurnda* sp.	Preferred habitat includes wood	Allen (1989)
Snakehead gudgeon	*Ophieleotris aporos*	Spawning	Allen (1989)
Sleepy cod	*Oxeleotris lineolatus*	Spawning	Allen (1989), Merrick & Schmida (1984)
Giant gudgeon	*Oxeleotris* sp. A	Preferred habitat includes wood	Allen (1989)
Flat-head gudgeon	*Philypnodon grandiceps*	Spawning	Allen (1989)
Dwarf flat-head gudgeon	*Philypnodon* sp.	Preferred habitat includes wood	Allen (1989)
Swan River goby	*Pseudagobius olorum*	Spawning	Allen (1989)
Lake Eacham rainbowfish	*Melanotaenia eachamensis*	Preferred habitat includes wood	Merrick & Schmida (1984)
Westralian pygmy perch	*Edelia vitata*	Preferred habitat includes wood	Merrick & Schmida (1984)

Wood provides an important component of habitat for many animals, not only those that live in the stream. Photo Ross Digman.

Other animals

Logs and branches provide habitat for other aquatic and terrestrial species. Birds, reptiles, amphibians and mammals use logs and branches for resting and foraging and as lookout sites (Harmon et al. 1986). Birds commonly use the exposed branches of logs as perch sites, while turtles climb out of the water using log surfaces. Partially submerged logs provide habitat for both terrestrial and aquatic organisms and also allow small terrestrial animals to approach the water surface to drink and bathe. Logs spanning channels may provide stream-crossing points for a range of animals. Riparian vegetation along streams and rivers also provides significant habitat for many terrestrial species, as do logs and branches on riparian land and on larger floodplains.

7.3 De-snagging and river 'improvement'

Clearing the riparian zone and de-snagging rivers under the guise of 'river improvement' has undoubtedly contributed to channel degradation in many Australian rivers (Brooks et al. 2003, Brooks 1999a), and the decline of aquatic species that depend on these structures for shelter and food (e.g. Koehn et al. 2000, Crook & Robertson 1999, O'Connor 1992). De-snagging can have a catastrophic effect on channel stability, especially when combined with channelisation. Altered hydraulic roughness associated with wood removal can increase sediment transport capacity by an order of magnitude in sand-bed streams (Brooks et al. 2003). This can then lead to increased bank and bed erosion, especially in sandy-bed rivers (Bird 1980, Brookes 1985, Erskine 1990, Gippel et al. 1992, Shields & Gippel 1995, Brooks et al., 2003), which in turn leads to further increases in stream power and hence channel instability. Brooks et al. (2003) outlined a case in which an autocatalytic response induced by wood removal led to in increase in sediment transport capacity of three orders of magnitude.

Furthermore, the removal of timber from the riparian zone and floodplains means that future sources of wood are now greatly diminished. For example, preliminary estimates provided by MacNally and Parkinson (1999) suggest that the amount of fallen wood remaining on the floodplains of the southern Murray–Darling Basin is approximately 15% of that present prior to European settlement. Wood on the floodplain is likely to play a significant role in maintaining local biodiversity given that fish and aquatic macroinvertebrates are known to utilise this habitat during inundation (e.g. MacNally 2000). The loss of wood on the floodplain and the patchy distribution of that which remains means that we have also lost potential habitat for birds, invertebrates, reptiles and mammals, in addition to aquatic organisms.

'River improvement', which in many cases in the past was a euphemism for desnagging, appears to have been implemented in an uncoordinated manner, with little regard for the impact of the works on upstream and downstream reaches or for cost–benefit analysis (Zelman 1977, Warner 1984). In fact, the consequences of river-improvement practices are often the opposite of those intended. A particular example is the report of an increase in the severity of flooding of the Ovens River around Wangaratta, Victoria, following river-improvement activities that were designed to reduce flooding (Zelman 1977).

Elevated log sill structure has trapped flood debris that will later provide valuable habitat. Photo Andrew Brooks.

Recent recognition of the role wood plays in river structure has resulted in several recommendations to restore woody habitat to Australian streams (Gippel et al. 1996a, 1996b, Cottingham et al. 2003, Brooks et al. 2004, Brooks et al. 2006). It is now widely acknowledged that flooding and erosion are essential components of a healthy riverine ecosystem. Rivers will flood irrespective of the presence of wood, and the minor erosion that occurs around logs is a natural process and contributes to the diversity of habitat available to riverine biota. Thus the focus of river management over the past decade has moved from one of actively removing logs to retaining or reinstating them as part of river rehabilitation efforts. Wood retention in the mid and upper reaches of rivers can indeed be an effective strategy for reducing flooding in downstream reaches, through attenuation of flood hydrographs (Anderson et al. 2004, and Chapter 5 of this document). Desnagging has been recognised as a major threat to many native species and a cause for the decline of populations (Cadwallader 1978, Koehn & O'Connor 1990, Murray-Darling Basin Commission 2004).

7.4 Other riparian influences on aquatic habitat

Undercut banks and tree roots

The roots of riparian trees stabilise stream banks and allow them to become undercut without collapsing (Cummins 1986). (See also Chapter 6.) Undercut banks provide shelter from predators and high flows for a wide range of aquatic invertebrate and vertebrate species. For example, glass shrimps (Atyidae) tend to congregate under banks, large submerged boulders, and amongst aquatic vegetation (Williams 1980). The fibrous root mats of some riparian species exposed in undercut banks also offer a complex habitat for aquatic invertebrates.

The spotted galaxias, *Galaxias truttaceus*, is usually found behind boulders and under logs and undercut banks (Hortle 1979). Freshwater catfish adults, *Tandanus tandanus*, in the Logan River, south-east Queensland, are collected most often from undercut banks and root masses (Kennard 1996). Binding and roughening of banks by abundant riparian vegetation allows the development and maintenance of lateral scour pools and related features. These are thought to benefit salmonid fishes and other drift feeders by putting the main drift of food close to prime concealment cover (White 1991).

Many species of fish actively seek shelter among the roots of overhanging trees (Koehn & O'Connor 1990). For example, sleepy cods/gudgeons, *Oxyeleotris* spp., usually inhabit slow-moving water and tend to live near the cover of roots, rocks or logs (Herbert & Peters 1995). Smaller gudgeons prefer leaf litter or bank-side roots for cover. The Tamar River goby, *Favonigobius tamarensis*, and blue-spot goby, *Pseudogobius olorum*, may construct burrows beneath rocks or tree roots (Koehn & O'Connor 1990).

Platypus, *Ornithorhynchus anatinus*, construct their burrows where the roots of native vegetation consolidate the banks and prevent the burrows from collapsing (Serena et al. in review). The distribution of burrows in streams is clearly associated with the presence of intact riparian vegetation and stable earth banks.

Overhanging and fringing vegetation

Overhanging vegetation can provide resources such as large instream wood, smaller wood and organic material that provides shelter for small fish and invertebrates. It has been shown to be an important habitat component for both adult and age–0 Murray cod (Koehn 2006). Southern pygmy perch, *Nannoperca australia*, juveniles and adults occur in shaded, weedy, slow-flowing waters and are most common among dense bank-side vegetation away from fast currents (Koehn & O'Connor 1990).

Macrophytes provide important habitat for pygmy perch, *Edelia vittata*, in south-western Australia (Pusey et al. 1989). However, shading of streams by riparian vegetation, particularly of the shallow littoral margins, is likely to decrease the extent of aquatic macrophyte cover (see Chapter 3) for some species of fish.

Overhanging and trailing vegetation also provides shade and cover for stream organisms. Species richness of invertebrate fauna in streams is clearly related to riparian cover. In a recent study of 29 New Zealand streams, it was found that the number of mayfly, stonefly and caddisfly taxa was significantly correlated with the proportion of native forest cover in the riparian zone (Collier 1995). The importance of riparian cover for trout and other salmonids is also well documented (Barton et al. 1985, Wesche et al. 1987). Similar observations have been made for many species of native Australian fish. For example, the mountain galaxias, *Galaxias olidus*, and broad-finned galaxias, *Galaxias brevipinnis*, are both found in the headwaters of small, fast-flowing, clear mountain streams which have overhanging vegetation and a good forest canopy (Hortle 1979). Overhanging vegetation also provides important cover from predators for platypus as they enter and leave their burrows.

Emergent macrophytes and other fringing vegetation are sometimes used for spawning and for recruitment by some species of fish. Duboulay's rainbowfish, *Melanotaenia duboulayi*, (a species found in coastal drainages in northern New South Wales and southern Queensland), deposits adhesive eggs amongst aquatic macrophytes and submerged overhanging vegetation within 10 centimetres of the water surface (Kennard 1996). Similarly, the fire-tailed gudgeon, *Hypseleotris galii*, attaches adhesive eggs to the underside of submerged structures such as leaf litter, logs, branches and rocks (Kennard 1996).

In the upland forested streams of the northern jarrah forest (south-western Australia), trailing vegetation is an important habitat for the larvae of filter-feeding insects. The most common of these, *Condocerus aptus* (Trichoptera), attaches its case to emergent or trailing vegetation at the air–water interface. From these perches, individuals filter the water surface, catching and ingesting detritus and prey items. Vegetation which is situated or suspended in regions of intermediate velocity (approx. 20 cm $^{-1}$) supports the greatest larval abundances.

Inundated riparian vegetation

During high flows, fish and other aquatic animals may move into inundated riparian vegetation to avoid downstream displacement or to feed or spawn. For example, the inanga, a primary species in New Zealand's whitebait fishery, spawns in riparian vegetation near the upstream extent of saltwater penetration in river estuaries (Mitchell & Eldon 1991). Some banded kokopu populations spawn in flooded riparian vegetation (Mitchell & Penlington 1982).

In Australia, spawning sites of the common galaxias, *Galaxias maculatus*, are often among grasses and vegetation on river estuary margins which are inundated by high spring tides (Koehn & O'Connor 1990). The pygmy perch, *Edelia vittata*, migrates out onto the floodplain (into riparian vegetation) during winter to spawn (Penn & Potter 1991). Submerged riparian vegetation provides habitat for Murray cod at higher flows (Koehn 2006).

Overhanging vegetation is vital for shelter and providing habitat for fish and other organisms. Photo Andrew Brooks.

7.5 The geomorphic role of wood in rivers

Until recently, many river managers considered that logs were significant contributors to channel instability (e.g. bank erosion) and flooding. We now realise that logs contribute significantly to stream stability and their role in flooding has been overstated. The presence of wood can exert significant control on channel complexity in bedrock rivers and channel geomorphology in alluvial rivers (Figure 7.3), and ultimately the long-term evolution of river channels and floodplains. For example, a comparative study of the Cann and Thurra Rivers in East Gippsland, Victoria, highlighted the importance of wood to stream geomorphology. Europeans settled the floodplain of the Cann River in the 1860s, while the floodplain of the adjacent Thurra River remains relatively undisturbed. Both catchments have been subject to logging and wildfire. The defining difference between the catchments was the widespread clearance of the riparian zone and the removal of wood from the Cann River (Brooks et al. 2003, Brooks & Brierley 2002, Brooks 1999a, b). When compared with the contemporary Thurra River and palaeo-channel condition of the Cann River, the contemporary Cann River has:

- a wider channel width,
- deeper mean depth,
- greater bankfull discharge and velocity,
- greater stream power,
- larger median grain size (suggests increased export of fine sediment and greater downstream transport of coarse material),
- greater likelihood of bank failure,
- no stable riffle-pool sequences (see photos below), and
- greater lateral migration.

The significance of wood in rivers and its control on channel geomorphology has also been described overseas, particularly in North America (e.g. Abbe & Montgomery 1996, Montgomery et al. 1996, 2003).

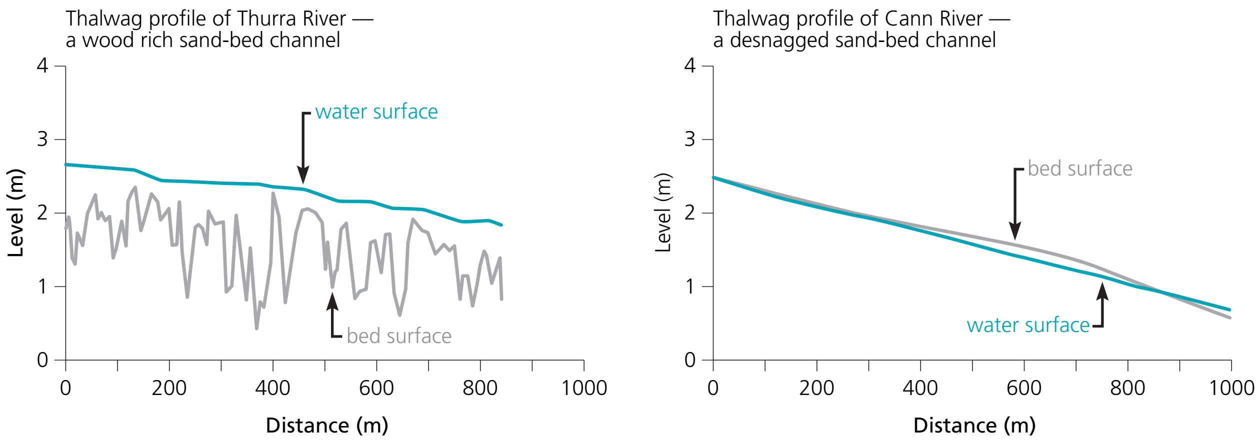


Figure 7.3. The effect of desnagging on channel complexity in forested sand-bed channels. Note. A palaeo-reconstruction of the Cann channel suggests it was previously very similar to the Thurra. The photos below show the difference in channel geomorphology when wood is taken out of a river. Left: A wood rich stream (Thurra) and right, a desnagged stream (Cann). Photos: Andrew Brooks.

Orientation to flow	Habitat formed	
	Upstream	*Downstream*
Parallel	Scour pool	Bar or island
Angled	Combination pool and bar	Combination pool and bar
Perpendicular: on bed	Depositional zone	Scour pool
Perpendicular: above bed	Scour pool	Scour pool

Table 7.3. Habitat development as determined by log orientation.

The control on channel geomorphology imparted by in-stream wood can have profound implications for stream ecology and river rehabilitation. For example, the presence of wood can provide macro- and microhabitat (Figure 7.2), and effect attributes such as stream power, channel dimensions and wood transport potential. Bed substrate microhabitat has been shown to be finer and spatially more complex in streams with high wood loads compared to those without (Buffington & Montgomery 1999).

As well as providing direct habitat, accumulations of logs and branches affect channel morphology and can modify habitat formation by initiating and accelerating the formation of major in-stream habitat types such as scour pools, bars, islands and side-channels (Keller & Swanson 1979, Montgomery et al. 1995, Abbe & Montgomery 1996, Richmond & Fausch 1995, Wallace et al. 1995).

The type of channel structure formed by logs and branches depends on the orientation of key pieces (see Table 7.3). Scour pools formed by logs and branches contribute to an increase in residual pool volume — the volume of water that would remain in pools if stream surface flow stopped (Skaugset et al. 1994). This contribution is greatest in smaller streams (Skaugset et al. 1994, Andrus et al. 1988). Residual pool volume is important in streams that have low summer flows with the associated potential for low surface flow. If these streams stop flowing, the pools associated with logs and branches provide the only available habitat for all aquatic species. These residual pools also provide a source of recruitment for new colonisation. It has been reported that the lower the stream gradient and the greater the amount of wood in the stream the bigger the pools (Carlson et al. 1990).

Log induced pool, Allyn River NSW. Photo Tim Abbe.

As is discussed in Chapter 5, at European settlement streams in the humid to semi-arid regions of Australia were full of fallen timber. Deflection around this material certainly caused local bank erosion, but this effect was moderated by the densely vegetated banks. There are numerous reports of dense layers of wood incorporated in the sandy beds of lowland streams (Brooks & Brierley 2002). De-snagging crews often removed several layers of large logs from sandy beds, which led to dramatic deepening (Strom 1962). It is now recognised that that timber was playing a critical role in stabilising the bed of channels, acting as a reinforcing matrix in the sediment. It is difficult to isolate the influence of de-snagging from the numerous other human impacts on streams. Certainly, though, the loss of this reinforcing has led to much of the dramatic river instability that we see today.

Wood and channel erosion

In natural systems that possess good riparian vegetation cover as well as a high in-stream wood load, the overwhelming effect of wood is to reduce net erosion and increase channel stability. Even in highly altered riparian landscapes, the net effect of in-stream wood at the reach scale is to increase channel stability. However, at the scale of individual logs, there may be either a net increase or decrease in erosion, associated with one or more of the following mechanisms:

~ by providing flow resistance in the channel, which reduces average flow velocity, *decreasing* sediment transport capacity and thereby erosion,

- ~ by deflecting flow onto the stream banks, thereby directly *increasing* bank scour,
- ~ by deflecting flow away from the banks, thereby directly *decreasing* bank scour,
- ~ by directly protecting the banks and *decreasing* erosion,
- ~ by increasing local bed depth and consequently *increasing* local bank erosion (because scour pools develop around logs and branches even though the overall effect of the wood is probably to reduce bed scour).

Whether a given piece of wood will increase or decrease erosion depends on:

- ~ the orientation and size of the obstruction,
- ~ the velocity and depth of flow,
- ~ the character of the bed and bank material,
- ~ the height of the bank as a function of its sediment composition (i.e. whether the bank is constrained by mass failure or fluvial particle entrainment),
- ~ whether the bank is subject to other coexistent disturbance factors — e.g. stock trampling.

Most of these variables are in some way controlled by the size of the stream. There has been some research into the effects of wood on bed scour (Cherry & Beschta 1989, Marsh et al. 2001) but almost none into its effects on bank erosion. This is because it is difficult to isolate the effects on erosion of a single piece of timber in a stream from the numerous other processes that are operating. Monitoring and modelling programs have now begun in Australia and the points discussed in this section are preliminary. At present, the best way to consider the effect of wood on erosion is by analogy with engineering structures in rivers (such as groynes, weirs and deflectors).

Wood in river rehabilitation

Wood reintroduction projects and experiments are now underway in numerous locations around the world (see Reich et al. 2003, Abbe et al. 2003, Brooks et al. 2006, Borg et al. 2004). An assessment of these projects is beyond the scope of this chapter, and a full overview of these works can be found in the *Design guideline for the reintroduction of wood into Australian streams* published by Land & Water Australia in 2006 (see www.rivers.gov.au). Experiments currently underway in Australia have demonstrated that wood can be safely and effectively reintroduced into rivers, however, the initial results suggest that large volumes will be required over extensive lengths of rivers to have a measurable response at the system scale. Brooks et al. (2006) have demonstrated that channel degradation can be reversed through the reintroduction of logs, with results from the first 5 years of monitoring showing that sediment storage can be increased on average by 40 m^3/1000 m^2 of bed area. This equates to around 3.5 m^3 of additional sediment storage (i.e. reduced erosion) per m^3 of wood added.

Instream wood is seen as an important habitat component for fish and its reinstatment of has been suggested as an important rehabilitation measure for fish populations (Murray-Darling Basin Commission 2004, Lintermans et al. 2005, National Murray Cod Recovery Team 2006). Techniques and technical guidelines for such works are now available (Nicol et al. 2002) and indeed, the reintroduction of wood into river channels in two major studies (Koehn et al. 2000, Brooks et al. 2003, Nicol et al. 2004) has found increases in fish populations, including Murray cod and the endangered Trout cod (Nicol et al. 2004).

Left: Constructing a log jam. Right: Stream with hydraulic changes as a result of wood reintroduction. Both photos Dan Keating.

River rehabilitation using an engineered log jam. Photo Tim Howell.

Some general principles

When considering the influence of wood on channel morphology, the following general rules should be kept in mind.

- Not all erosion is bad. Scour of the bed and undercutting of the banks are essential for producing the 'hydraulic diversity' required for habitat in a healthy stream. Natural streams are lined with undercut banks.
- By the time erosion around a fallen tree is noticeable, there is a good chance the bank erosion from the wood is almost complete. It is probably reasonable to assume that the erosion around wood follows a negative exponential curve. This means that if the same-sized flood occurred on a given stream twice in a row the second flood would cause much less erosion around the same piece of wood than did the first flood. Put another way, the flow velocity or duration of the second flood would probably need to be much greater to generate the same amount of erosion as occurred in the first flood.
- There is an infinite variety of log sizes and orientations. The variables include the relative size of the log to the stream, the length and diameter, and its vertical and horizontal orientation.
- As a rough guide, erosion around an obstruction will usually remove an amount of material equivalent to no more than one or two times the projected area of the obstruction (that is, the area of the obstruction as seen from the front) from the cross-section. For example, if a log has a projected area of 5 m^2, then the erosion around the log is much more likely to remove a total of 5–10 m^2 of the cross-section than, say, 50 m^2.
- It is likely that at low flows a log will deflect flows in the opposite direction to that at high flows.
- Flows passing over a log will be deflected across the top of the log, roughly at right angles to it.
- The common perception that a log oriented with its tip pointing upstream will cause more scour on the adjacent bank may seldom be true. In fact, at high flows it is likely that a log oriented upstream will deflect flow away from the adjacent bank. Scour of the adjacent bank is usually caused by mechanisms which are not strictly influenced by flow deflection.
- The amount of flow deflection produced by wood in a channel is often over-estimated because of what appear to be 'deflection lines' flowing away from the end of a log. These lines of flow often extend right across the channel. In fact, these surface flows do not reflect the true deflection around the obstruction, which is much less than the flow lines would suggest. This has been confirmed in recent flume experiments on groynes (Dyer et al. 1995).
- The effect of logs on a bend will differ from that of the same log in a straight reach because of the effect of secondary circulation in the bend.
- As a general rule, in most Australian streams the effect of wood on erosion decreases with the size of the channel. This can be demonstrated by considering the general planform of the channel. Although wood is often randomly distributed in larger stream channels, and often at high natural densities, larger channels retain their general meandering characteristics. That is, the planform is not controlled by the wood, which is, at most, a secondary impact on erosion processes. The same is not true of wood in smaller streams. There is much literature (admittedly from North America) that demonstrates how wood accumulations control the morphology of small headwater streams by producing large jams and accumulations of wood.

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CHAPTER 8

Riparian wildlife and habitats

Carla P. Catterall, Romeny J. Lynch and Amy Jansen

Summary

- Riparian lands are among the most productive ecosystems on earth. They occupy only a small proportion of the landscape but frequently support a greater variety and abundance of animal life than adjacent habitats.
- Important habitat components include vegetation (often taller, denser, more diverse, and more complex in riparian lands), food, standing water, shelter from predators, sites for nesting and roosting, and a local microclimate with less extreme temperatures and more humid conditions than adjacent areas.
- Wildlife species differ in their dependence on the riparian zone: some are confined to it throughout their lives; others may use it only occasionally, although their long-term persistence depends on access to intact riparian habitats.
- Riparian areas are often corridors for wildlife movement. This occurs naturally in dry regions, where stream-side vegetation forms distinctive networks across the landscape. In regions where most native vegetation has been cleared for human use, vegetated riparian zones also provide habitat for many species.
- Degradation of riparian lands by clearing and grazing has negative impacts on a range of wildlife species which depend on these riparian areas.
- Restoration of riparian lands, including fencing to exclude livestock and re-instatement of native vegetation, can lead to improved riparian habitat for a variety of wildlife species. There may also be benefits to other aspects of farm productivity, such as reduced impacts of pest species.

8.1 Wildlife ecology in riparian lands

Riparian lands occupy only a small proportion of the landscape, but they frequently have a much higher species richness and abundance of animal life than adjacent habitats. Research in Australia has documented the importance of riparian lands to a variety of wildlife across many habitat types.

The majority of this work has been on birds, and mostly in eastern and northern Australia, but the results are likely to be applicable to wildlife in general across the country, since work in other countries has provided similar conclusions (e.g. Knopf et al. 1988). In savanna landscapes in northern Australia, it has been found that the number of species of birds, mammals, reptiles, frogs and spiders (Williams 1993, Woinarski et al. 2000, Woinarski et al. 2002, Woinarski & Ash 2002), and the total abundances of birds (Woinarski et al. 2000, Woinarski & Ash 2002) were significantly higher in riparian areas than away from creeks and rivers. The adult forms of aquatic insects were much more abundant close to creeks and rivers than further away, and even terrestrial insects were more abundant in riparian areas (Lynch, Bunn & Catterall 2002). Likewise, in the forests and woodlands of eastern Australia, birds were significantly more abundant and diverse in riparian areas than upslope (Bentley & Catterall 1997, Mac Nally, Soderquist & Tzaros 2000, Catterall et al. 2001, Palmer & Bennett 2005, Martin & McIntyre, submitted) while leaf litter-dwelling invertebrates (Catterall et al. 2001) and ground-dwelling and arboreal mammals (Soderquist & Mac Nally 2000) were more abundant in riparian areas than upslope. In the mulga lands of south-western Queensland, the abundance and number of species of birds was higher in riparian than non-riparian areas (Kingston, Catterall & Kordas 2002).

As well as supporting disproportionately high species richness and abundance of many faunal groups, riparian areas are also critical habitat for many individual wildlife species. For example, Woinarski et al. (2000) listed 17 species of birds which were only found in riparian areas in an extensive survey of birds across the savanna of northern Australia, while Kingston et al. (2002) listed 16 species of birds in the mulga lands of south-western Queensland which were only found

Arboreal: living in trees.

in riparian sites. Williams (1993) found 31 species of birds, the water rat, five species of reptiles and 11 species of frogs which were only recorded in riparian areas in savanna woodlands west of Townsville in North Queensland. In the wetter eucalypt forests of eastern Australia, there are generally few species of birds and mammals which are found only in riparian areas, but for many species, abundances are much higher there (e.g. Bentley & Catterall 1997, Mac Nally, Soderquist & Tzaros 2000, Soderquist & Mac Nally 2000, Catterall et al. 2001, Palmer & Bennett 2005).

These differences occur because riparian land provides the habitat features needed by many terrestrial wildlife species. For some species this habitat is critical. Habitat components include food, water, shelter from predators and from harsh physical conditions, and safe sites for nesting and roosting. Some animals rely on such resources from the riparian zone for their entire lifetime, whereas others may only need them at particular times of the day, in certain seasons, or during specific life stages.

The extent to which these resources are available to the full range of riparian-dependent wildlife species within a region depends on the structure and composition of vegetation within the riparian zones. When a waterway bordered by native vegetation runs within cleared or more open land, this vegetated riparian zone provides the only suitable habitat for many species, and is also a potential corridor for their movements. Riparian areas which have been cleared or degraded by grazing or other human impacts have significantly lower habitat value than those supporting native vegetation. Throughout Australia, riparian lands are one of the most highly impacted, reduced and fragmented habitat types.

Range of riparian environments providing habitat for wildlife.

Photo Ian Dixon.

Photo Jenny O'Sullivan.

Photo Land & Water Australia.

Photo John Dowe.

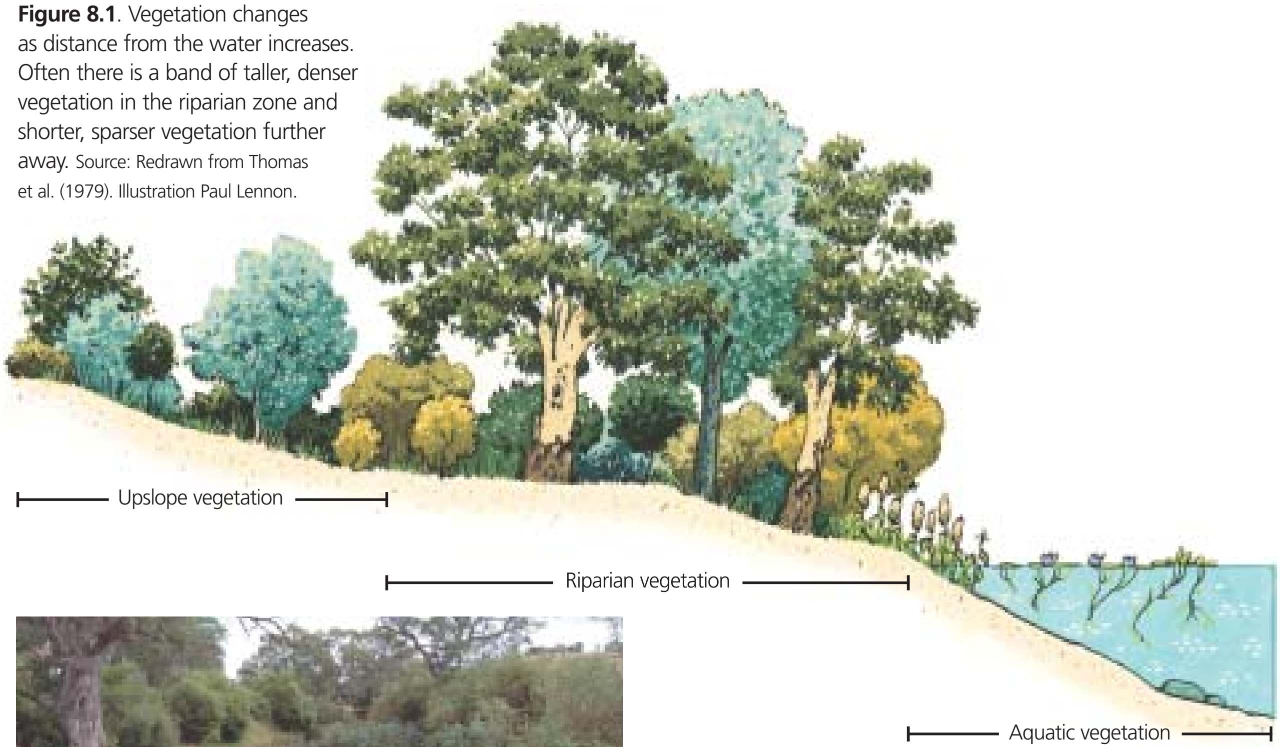
8.2 Habitat features of riparian lands

Vegetation structure and diversity

Riparian vegetation dynamics were discussed in detail in Chapter 2. A number of features of riparian vegetation are important for wildlife. Firstly, riparian vegetation is often taller, more dense, and structurally more complex in riparian lands than in upslope areas. Secondly, riparian lands are a zone of transition in plant communities from aquatic or semi-aquatic species adjacent to the waterway, through communities which are often specifically riparian in composition, to fully terrestrial species on higher ground (see Figure 8.1). Riparian vegetation communities are also spatially and temporally variable, due to the interacting effects of environmental gradients both along and across the riparian zone, as well as temporal changes due to the effects of flooding. For example, a survey of riparian vegetation of the Murray River identified three vegetation zones (an inner floodplain, an outer floodplain, and rises within the floodplain) with a total of 37 floristic communities (Margules et al. 1990). On the floodplain of Cooper Creek in inland Australia, Capon (2005) found that plant communities were structured according to flooding regimes, with less frequently flooded sites being very variable and quite different to frequently flooded sites. Flooding clearly created a diversity of vegetation communities across the floodplain. Heterogeneity in vegetation structure and plant communities provides a diversity of wildlife habitats.

Trees such as this one are 'living ecosystems' and vital for wildlife. Photo Jim Puckridge.

Figure 8.1. Vegetation changes as distance from the water increases. Often there is a band of taller, denser vegetation in the riparian zone and shorter, sparser vegetation further away. Source: Redrawn from Thomas et al. (1979). Illustration Paul Lennon.



Left: An example of vegetation zonation adjacent to a stream. Photo Roger Charlton.

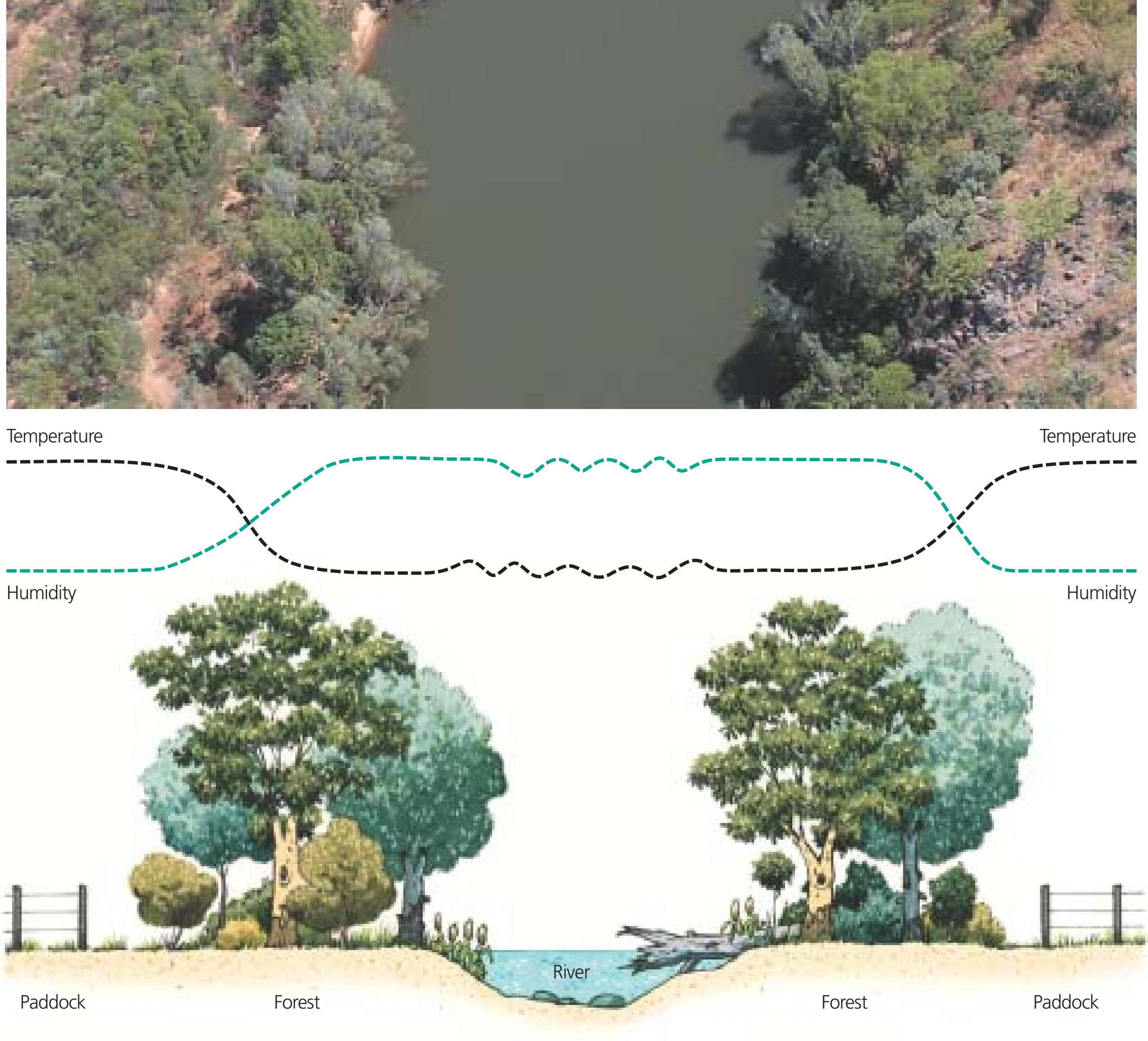


Figure 8.2. Riparian vegetation has a moderating effect on local microclimatic parameters such as air temperature and humidity. Source: Redrawn from Malanson (1993). Illustration Paul Lennon. Photo at top Ian Dixon.

Water and microclimate

Moisture is an important habitat feature of riparian lands, and occurs in a variety of forms: surface water in the channel and in wetlands; groundwater, including sub-surface flow when the channel appears dry; and soil moisture (Malanson 1993). Water is directly important to a large proportion of riparian wildlife both as drinking water (particularly important in arid and seasonally dry environments), and as habitat for larval stages of semi-aquatic organisms such as frogs and dragonflies. When wetlands in riparian lands in the arid zone of Australia fill with floodwaters from the Cooper Basin, they provide habitat for large numbers of waterbirds which move in from other regions (Roshier, Robertson & Kingsford 2002). Wetlands can also be a focus for the activity of terrestrial birds, with sites containing wetlands supporting more species and higher abundances of birds than non-wetland sites within a floodplain woodland (Parkinson, Mac Nally & Quinn 2002).

The water available in riparian areas is also indirectly important to riparian fauna, because it supports the special vegetation communities which provide them with food, refuge and breeding sites. Riparian vegetation reduces the impact of wind and lowers solar radiation reaching understorey vegetation and the forest floor. Together with evaporation from surface water and evapotranspiration by plants, this creates a local microhabitat with less extreme temperatures and more humid conditions than adjacent areas (Malanson 1993, see also Figure 8.2). As a result, riparian habitats are the only part of the landscape that can support some species which are sensitive to desiccation, and may be used as retreats by other species when conditions elsewhere are unfavourable (too hot, too cold or too dry).

The width of a band of riparian vegetation is a major determinant of the extent to which it will moderate the local microclimate. The effect of forest on microclimatic parameters increases with distance from the edge (Saunders, Hobbs & Margules 1995). In North American forests, soil moisture reaches a maximum at a distance from the edge of about half the height of the tallest trees; incoming radiation and soil temperature levels stabilise where the riparian forest width is about equal to the height of the tallest trees; and air

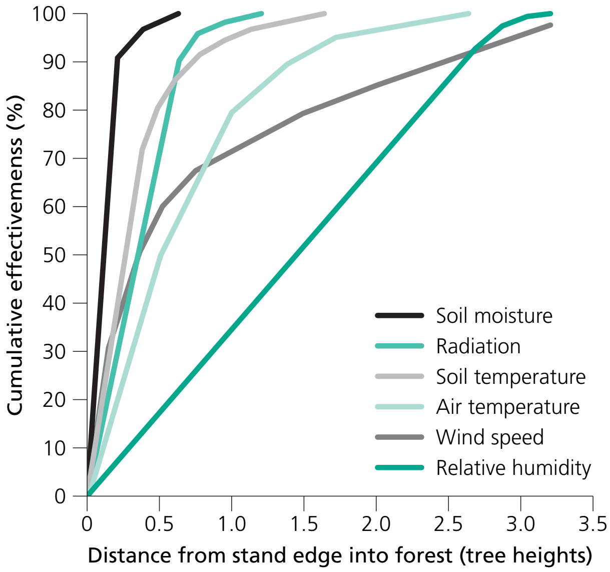


Figure 8.3. These generalised curves indicate the distance from the edge of a forest at which the effect on microclimate attributes is maximised. Source: Redrawn from Collier et al. (1993).

Right: Comb-crested jacana. Photo Ian Dixon.

temperature, wind speed and relative humidity stabilise where the forest width is two to three times the tallest tree heights (Collier et al. 1995, see also Figure 8.3). A study of the effects of riparian buffers in the north-western USA recommended a 45 metre buffer adjacent to small streams to maintain a natural riparian microclimate (Brosofske et al. 1997).

Food and productivity

Riparian lands are among the most productive ecosystems on earth (Croonquist & Brooks 1991). The high primary productivity of riparian lands is the result of a greater availability of water and the presence of soils which are richer in nutrients than those further upslope. Riparian soils receive nutrients from both the land and water: by surface runoff from upslope areas after rain and by deposition along stream banks during floods (Cummins 1993).

High primary production leads to a larger and more reliable supply of plant products such as leaf litter (Malanson 1993). Riparian vegetation may also contain a greater number or greater diversity of flowering and fruit-bearing plants, or these plants may flower or fruit more consistently as a result of the availability of water and nutrients. This productivity creates conditions that promote higher abundances of terrestrial invertebrates which, in turn, are food for riparian insectivores. This means there are food resources present for a wide range of animal feeding groups.

The stream environment also contributes to the diversity and abundance of food resources available in the riparian zone. The nutrient and energy dynamics of riparian ecosystems are linked with cycles in both adjoining aquatic ecosystems and the wider landscape. Transfer of nutrients and energy from in-stream to terrestrial habitats can occur in a number of ways, although little specific research has been done in this area. Aquatic organisms may be eaten by semi-aquatic predators such as kingfishers and water rats, resulting in a transfer of nutrients to terrestrial soils in these animals' dung and urine. Water birds that prey on aquatic invertebrates and fish may, similarly, be vectors for substantial nutrient movements from lowland floodplain rivers to their fringing riparian habitats.

Many 'aquatic' insects have adult stages that emerge from the stream and move into adjacent riparian or terrestrial habitats. The abundance and biomass of these adult aquatic insects is highest close to the water in riparian habitats, and declines with distance from the edge of the water (Lynch, Bunn & Catterall 2002). These aquatic insects may die and enter the riparian detritivore food web or fall prey to riparian insectivores, thus moving aquatic nutrients and energy into riparian food webs. Terrestrial species that forage in riparian habitats may in turn move nutrients and energy into adjacent non-riparian habitats. In this way, the productivity of the riparian zone may be important in supporting a wider area.

Nest and retreat sites

Riparian vegetation may provide a greater variety of perches, roosts, rest sites and nest sites, or these may be of a better quality than those available in adjacent habitats (that is, they may offer greater protection from predation or climatic extremes). For example, flying foxes in the Northern Territory preferentially roost in riparian forests in the dry season, when these areas are likely to provide the coolest, dampest microhabitats (Palmer & Woinarski 1999). Large riparian trees are a source of nest hollows for birds, bats and arboreal mammals. The density and structural complexity of riparian forest also provides numerous protected perch, nest and roost sites for mobile species which feed in surrounding habitats. For example, riparian habitats are very important for nesting of the threatened Regent Honeyeater in New South Wales, even though these birds range over large areas to find flowering trees for foraging (Geering & French 1998, Oliver, Ley & Williams 1998).

Leaf litter, fallen timber and flood debris accumulated in the riparian zone provide foraging sites and retreats for invertebrates, small mammals, reptiles and amphibians. On the floodplain of the Murray River, experimental accumulations of dead wood provided new foraging habitat for birds such as brown treecreepers (Mac Nally, Horrocks & Pettifera 2002) and yellow-footed antechinus (Mac Nally & Horrocks 2002). Riparian soils are often more loose and friable than those of adjacent upland habitats and, therefore, provide ideal conditions for burrowing and nesting by ground-dwelling fauna, ranging from insects to mammals.

Above: Crimson rosella. Photo Andrew Tatnell.
Photo (below) CSIRO Sustainable Ecosystems.

8.3 Modes of use of riparian lands by wildlife

Riparian lands support both fully terrestrial wildlife and some aquatic organisms during particular stages in their life cycles. Three broad groups of riparian fauna can be recognised: riparian-dependent aquatic species; riparian specialists; and riparian-dependent terrestrial species. A given species' riparian-dependence may vary among bioregions. For example, a study in the mulga lands of south-western Queensland found that the pied currawong was entirely restricted to riparian areas (Kingston, Catterall & Kordas 2002), whereas in coastal regions this bird commonly occurs in upslope areas.

Many different types of wildlife are found in riparian lands. Ecological groupings include soil fauna, litter fauna, ground-surface dwellers, bark and foliage dwellers, and aerial species. The most prominent and best known groups are the insects and vertebrates.

Detritivore: animal that feeds on dead plant or animal matter, e.g. leaf litter, woody debris, dead grass, dead insects.

Examples of animals dependent on visiting riparian land. Photos: (top) Ian Dixon, (middle) Peter Davies, (bottom) Michael Douglas.

Within each of these groups there are many species, which differ in their lifestyle, life-history, and ecological roles. Some will be tolerant of changes and degradation in riparian vegetation, but many will not. The latter will depend in various ways on the continued existence of adequate native vegetation cover on riparian land.

Riparian-dependent aquatic fauna

Many fully aquatic organisms are dependent in various ways on stream banks and riparian habitat. Fish and turtles within the stream often depend on riparian inputs (such as fruit and insects) for food, and riparian plant material (such as fallen submerged logs and branches) for shelter. Animals such as crocodiles, turtles and platypus feed in the water but use stream banks and riparian lands for resting, moving and nesting. Many insects and frogs are aquatic for part of their life cycle, and may be riparian-dependent for the remainder.

Water in the stream and riparian wetlands provide habitat for the larvae of many 'aquatic' insects. The adult stages of these insects are often particularly dependent on riparian vegetation, which influences the quality of their aquatic larval habitat and provides resources and shelter for adults. Natural stream-side vegetation may be important to such taxa during pupation, emergence, reproduction and egg-laying (Erman 1981). For example, alderflies and dobsonflies, *Megaloptera*, lay their eggs close to the water, often on overhanging vegetation. When the eggs hatch, the larvae fall or crawl into the water. The larvae of many aquatic insects leave the water to pupate in soil, moss and leaf litter or around stumps and logs on riparian land. Some aquatic insects, such as mayflies, shelter on stream-side vegetation immediately after emerging from an aquatic pupal stage. Adults of some aquatic insects, such as caddisflies and male mosquitoes, cannot feed on solid food, and nectar from riparian plants may be an important source of energy for these species.

The larval (tadpole) stages of most frog species are aquatic and, though the adults may not always live in riparian habitats, some species congregate in these areas to mate and lay their eggs. On the floodplain of the Murrumbidgee River in New South Wales, several frog species are strongly associated with wetlands, and more species and individuals are found at wetlands with better quality fringing and aquatic vegetation (Jansen & Healey 2003).

Top: Platypus. Photo Andrew Tatnell. Above: Water monitor. Photo Ian Dixon.

Riparian specialists

Riparian specialists require specific riparian conditions throughout their life-cycles (Collier 1994). These species may be either terrestrial or semi-aquatic. Some regularly use both aquatic and riparian habitats. For example, the water rat (a semi-aquatic riparian specialist) forages in the water for large aquatic insects, crustaceans, freshwater mussels, fish and frogs and also along stream banks for terrestrial insects (Woollard et al. 1978). Other mammals which are riparian specialists include *Rattus lutreolus* and *R. colletti*. *Eulamprus quoyii*, a small riparian skink found in eastern Australia, is primarily terrestrial and usually forages along the banks of streams but may also capture surface-swimming aquatic prey such as damselfly nymphs, water beetles and tadpoles (Cogger 1992). Several semi-aquatic reptiles are also riparian specialists, exploiting both terrestrial and aquatic food resources. These include two water monitors, *Varanus mertensi* and *V. mitchelli*, the water dragon and the water python (e.g. Shine 1986). Some frogs are also riparian specialists; for example, three terrestrial frogs of the genus *Geocrinia* are restricted to small strips of riparian habitat in south-western Australia (Wardell-Johnson & Roberts 1991).

Little is known about the dependence of terrestrial insect species upon riparian lands. However, many taxa are associated with terrestrial habitats bordering waterways. For example, about one-quarter of all Australian carabid beetle species occur on the edges of waterways or waterbodies (CSIRO 1991). Some groups of insects are associated with mud and moist or decaying vegetation at the margins of waterbodies. For example, limnichid beetle larvae and heterocerid beetles burrow in mud or sand on the margins of ponds and streams where they feed on organic matter (CSIRO 1991). Toad-bugs (*Hemiptera: Gelastocoridae*) are found at the edges of creeks and waterholes where they prey on small invertebrates that venture near the water's edge (Williams 1980). Many groups of flies have some species which require damp sand, mud or rotting vegetation as larval habitat (CSIRO 1991) and in drier regions these conditions exist mainly in riparian and floodplain areas. Adults are frequently found in vegetation bordering waterways.

Australia has many examples of birds that are riparian specialists. For example, bitterns hide in dense riparian vegetation by day and forage at night for aquatic prey. The azure and little kingfishers are riparian specialists that favour well-vegetated creeks and streams. A survey across savanna landscapes in the Northern Territory identified 17 species of birds only found in riparian habitats; these included seven aquatic and fish-eating species, a raptor and an owl, two species of honeyeaters, and six insectivorous species (Woinarski et al. 2000). In box-ironbark forests in southern Australia, a survey identified seven species of birds which were only found in riparian habitat (Mac Nally, Soderquist & Tzaros 2000).

Riparian-dependent terrestrial fauna

Many mobile animals inhabit riparian land during a part of their lifetime, while spending the rest of their lives elsewhere in the landscape (Catterall 1993). Some of these species depend on access to riparian areas, whereas others may benefit from the riparian habitat but still persist without it. Terrestrial animals may travel to riparian lands on a daily basis (for activities such as drinking, feeding and roosting), on a seasonal basis (for activities such as foraging or breeding), or during a particular stage of the life cycle (such as when they are juveniles). For example, in the arid zone, ground-feeding granivores such as pigeons, finches and parrots, fly to waterholes on a daily basis to drink, especially during hot weather. Kangaroos and wallabies often retreat to the denser shady cover of riparian vegetation in the heat of the day. Rufous and powerful owls (genus *Ninox*) roost during the day in riparian forest, although they forage widely for small mammals at night in eucalypt forest and woodland. In eastern Australia, the regent parrot nests only in large hollows found in mature, senescent or dead river red gums within 60 metres of a waterway or waterbody (Burbidge 1985), while in the Riverina, superb parrots also only nest in river red gums adjacent to water (Blakers, Davies & Reilly 1984). Insectivorous bats visit riparian areas to drink and feed, but spend much of their time elsewhere in the landscape (Strahan 1983).

Many terrestrial herbivorous insects are likely to be associated with plant species that occur primarily in riparian habitats, though few Australian examples have been documented. The role of riparian forests in the conservation of butterflies has been recognised overseas (Galliano et al. 1985). In Australia the Richmond birdwing butterfly, once widespread in subtropical lowland rainforest, now occurs mainly in riparian remnants as a consequence of clearing other habitats.

In many drier environments, riparian areas may also provide 'refuge habitat' during dry seasons, drought, or after fire. Narrow bands of river red gum along watercourses are significant habitat for koalas in drier parts of their range, especially during drought (Gordon et al. 1988). In the wet–dry tropics, riparian rainforest vegetation may be an important source of dry-season food and shelter for amphibian species which are found mainly in eucalypt forest and woodland during the wet season (Martin & Freeland 1988). Also during the dry season in the wet-dry tropics, brown honeyeaters move from eucalypt woodlands into riparian forests as paperbarks begin to flower (Morton & Brennan 1991), and fruit bats tend to shift their roosting sites into riparian forests, while during other seasons they roost more frequently in non-riparian rainforest (Palmer & Woinarski, 1999).

Granivore: animal that feeds on seeds.
Senescent: old trees with some dead limbs.

Yellow-bellied sheathtail bat. Photo Angus Emmott.

Many species that occur in riparian habitats may also be found in a range of other habitats. These species are not dependent on riparian lands, but may occur in higher abundances there because of the concentration of resources. For example, the crucifix toad *Notaden bennetti*, a burrowing frog of inland eastern Australia, is found in savanna woodland and mallee areas, but is especially abundant on the black soil flood plains of the large river systems throughout its range (Cogger 1992). Reptiles that are commonly found in riparian zones, but also occur in other habitats, include six species of *Eulamprus* skinks and the semi-arboreal *Lophognathus* dragon lizards (Cogger 1992). Bird species that are common in riparian areas but that also occur (although often at lower density) in a wide range of habitats include many honeyeaters, fairy wrens, flycatchers and others (see Bentley & Catterall 1997, Loyn 1985, Recher et al. 1991). Many other studies have shown higher abundances of wildlife species in riparian than non-riparian areas: frogs, reptiles and mammals (Williams 1993); leaf litter invertebrates (Catterall et al. 2001); and birds (Williams 1993, Bentley & Catterall 1997, Mac Nally, Soderquist & Tzaros 2000, Woinarski et al. 2000, Catterall et al. 2001, Kingston, Catterall & Kordas 2002, Palmer & Bennett 2005).

8.4 Riparian lands as habitat corridors

Animals move for a variety of reasons and over a range of time scales and distances, in order to use resources that are patchily distributed, exploit different seasonal environments, accommodate different life stages, and colonise new areas (Harris & Scheck 1991, Merriam & Catterall 1991). Small isolated populations are at risk of local extinction as a result of unpredictable events such as fires or drought. Movement and recolonisation can be aided by a network of riparian corridors across the landscape. There are two main situations in which riparian lands may function as movement corridors: first, as a distinctive habitat network in uncleared landscapes; second, as connections among the remnant forest patches in cleared landscapes.

Riparian corridors in uncleared landscapes

In drier areas of the continent, where riparian vegetation forms both a discrete habitat which differs greatly from that of surrounding habitats and an extensive natural network across the landscape, fauna may use riparian lands as movement corridors. For instance, in the semi-arid Riverina in south-eastern Australia, riparian forests along the Murray and Murrumbidgee Rivers provide corridors for colonisation by many species characteristic of higher rainfall areas to the east, such as the feathertail glider, the frog *Crinia signifera* (Robertson et al. 1989), the white-browed scrubwren and white-throated treecreeper (Jansen & Robertson 2001b). In tropical savanna landscapes in the Northern Territory, birds typical of wetter forests extend their distributions into drier areas only along riparian corridors (Woinarski et al. 2000).

Riparian corridors in cleared landscapes

Most terrestrial wildlife species show preferences for particular types of habitat, and many show a strong aversion to areas cleared of native vegetation, such as agricultural and urban landscapes. In many parts of Australia the formerly continuous forest cover has been cleared and converted to pasture, cropland or urban development, leaving only remnants of native forest. The conservation of many species of forest-dependent wildlife may rely on linking remnants into networks by means of habitat corridors (Merriam & Saunders 1993, Saunders et al. 1995, Saunders & de Rebeira 1991).

In cleared landscapes, the retention of continuous bands of riparian vegetation provides primary habitat for riparian specialists and other species, as well as corridors for wildlife to move between patches of remnant vegetation (Figure 8.4). Studies in fragmented landscapes of southern and northern Queensland, and central NSW, have shown that forest-dependent birds and mammals use riparian corridor remnants as habitat even if these are isolated from other forest patches (Crome, Isaacs & Moore 1994, Bentley & Catterall 1997, Fisher & Goldney 1997).

Riparian areas are ideally suited to form the basis of linked wildlife habitat networks because they: form a hierarchy of natural corridors throughout the landscape; are used by most forest-dependent species; and also act as buffers to protect water quality and aquatic ecosystems (Naiman & Decamps 1997). Riparian corridor connections should help to sustain wildlife populations in remnant forest patches by allowing movement between patches, while also increasing wildlife diversity within the riparian areas since, without connections to larger remnants, the riparian corridors themselves are small, narrow habitat fragments.

In the drier areas of Australia riparian corridors are vital for wildlife. Photo Michael Douglas.

The remaining riparian corridor is clearly visible in this agricultural landscape. Photo CSIRO Sustainable Ecosystems.

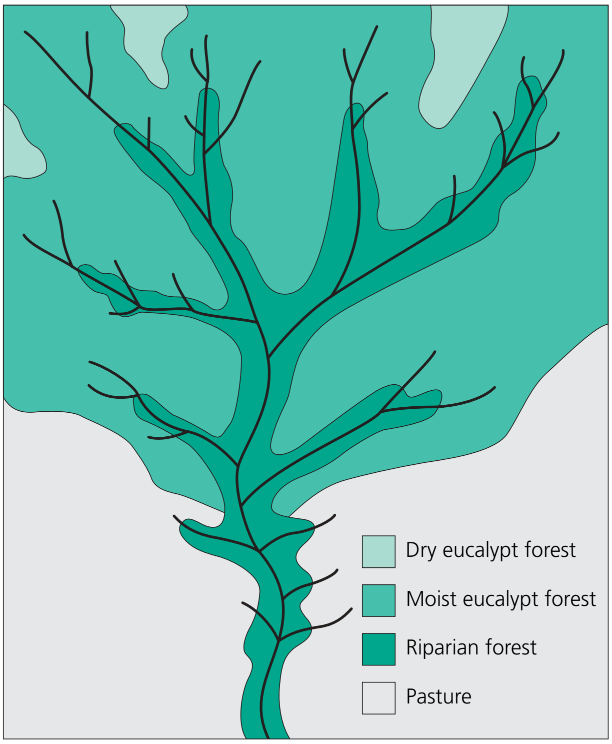


Figure 8.4. Riparian vegetation can provide a distinct habitat network in undisturbed landscapes and potential movement corridors within human-modified landscapes. Source: Adapted from Thomas et al. (1979).

This landholder has set the fence back from the river to restore a riparian area that will not only stabilise the streambed but provide valuable habitat for a range of different organisms. Photo Michael Askey-Doran.

Corridor width

Within both cleared and uncleared landscapes, the width of natural riparian vegetation needed for either primary habitat or movement depends on the wildlife species concerned and the habitat type and landscape. Some smaller animals may require only a narrow band of natural habitat, perhaps no more than 10 metres wide. Larger species generally forage over larger areas and will often require wider corridors. Unfortunately, little hard data exist regarding exactly how wide a corridor needs to be in any given situation (Saunders & de Rebeira 1991). A study in the eastern United States found that minimum corridor widths varied with the stream and with the species of bird or mammal in question, making definition of a single minimum width for riparian corridors meaningless (Spackman & Hughes 1995). The values to wildlife of narrow corridors of riparian forest within cleared lands are likely to be degraded by edge effects, including altered microclimate, invasion by weeds, and altered interactions among species (Saunders & de Rebeira 1991, Saunders, Hobbs & Margules 1995, Wilson & Lindenmayer 1995).

In many landscapes, natural riparian corridors may not be very wide; in forested catchments small low order streams have a narrower zone of influence than larger watercourses. In landscapes where much of the former vegetation cover has been cleared, the width of riparian vegetation is likely to be an important determinant of the corridor's effectiveness for different taxa, and riparian corridors would often need to be wider than the riparian zone itself. Edge effects may reduce the habitat value of narrow corridors, but even narrow strips of riparian vegetation will be useful to some species.

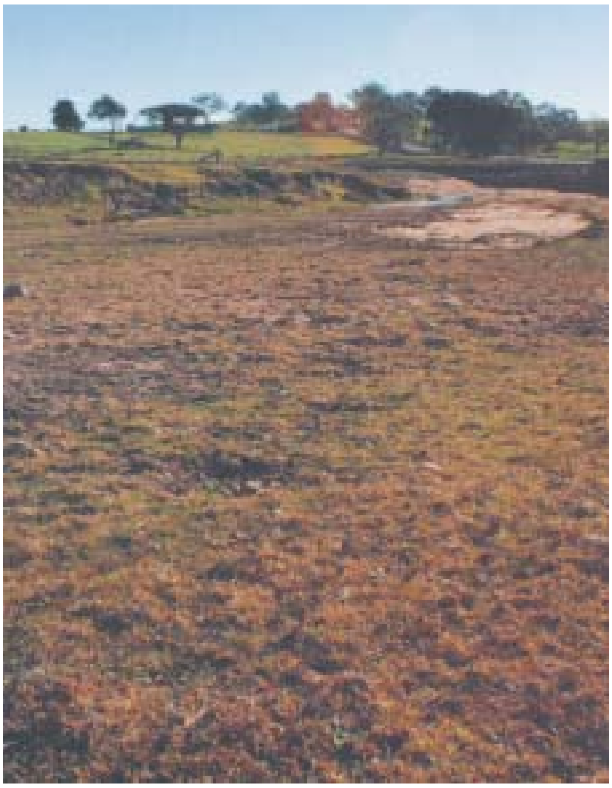
8.5 Influences of habitat degradation on riparian wildlife

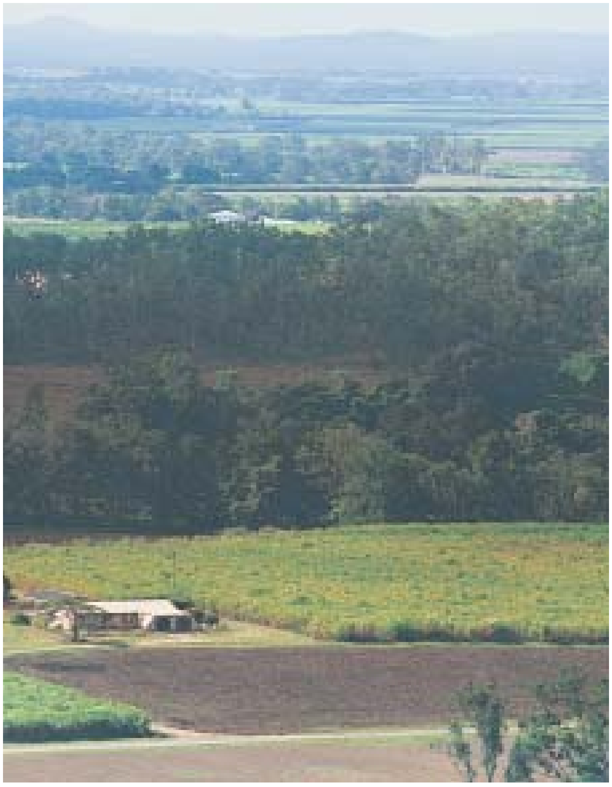
Degradation of riparian lands can occur through removal and fragmentation of native vegetation, or through the removal of particular components of the vegetation cover (usually the understorey, involving removal of shrubs, woody debris and native ground cover). Riparian land degradation is widespread in Australia, and has mostly been caused by either clearing for agriculture or impacts on the understorey resulting from domestic livestock grazing (Wilson 1990, Walker 1993). Changes to the frequency of fire, and invasion by exotic weeds and feral animals, are frequently a part of the degradation syndrome. These factors interact with grazing, clearing, and understorey changes in ways that may be complex, and poorly understood.

Riparian specialist species will be particularly sensitive to such degradation of riparian areas, and protection of riparian habitats is a priority for their conservation (see Geier & Best 1980, Pearce et al. 1994, Wardell-Johnson & Roberts 1991). Degradation of riparian habitats is also likely to have a major impact on many riparian-dependent aquatic species, which rely directly or indirectly on the vegetation as a food supply or as habitat, and on mobile terrestrial fauna which depend on access to riparian lands on a daily, seasonal or life-history basis. Additionally, population reductions are likely to occur in species which, although able to survive without access to riparian lands, are typically most common there.

Clearing of native woody riparian vegetation will result in the replacement of a diverse wildlife community composed of species that are typically found in riparian forest or woodland by a different, often less diverse, set of widespread "open-country species", which are typically common in pasture or cropland. Furthermore, small patches and narrow strips of remnant riparian vegetation are likely to experience similar trends; some woodland or riparian species will persist in these remnants, but others will be lost, and replaced by open-country species. For birds, this phenomenon has been described from a variety of bio-regions (Crome, Isaacs & Moore 1994, Bentley & Catterall 1997, Fisher & Goldney 1997, Jansen & Robertson 2001b).

Studies in uncleared savanna and grassy eucalypt woodlands in eastern Australia have linked livestock grazing to declines or disappearances in riparian wildlife, including species of ants and spiders (Woinarski et al. 2002), frogs (Jansen & Healey 2003), reptiles and mammals (Woinarski & Ash 2002) and birds (Jansen & Robertson 2001b, Woinarski & Ash 2002, Martin & Possingham 2005). In most of these studies, the changes in wildlife were related to changes in vegetation structure caused by grazing. At least in the case of birds, loss of woodland and riparian specialist species such as the brown treecreeper, eastern yellow robin, and speckled warbler are typically accompanied by their replacement with common pasture birds such as the Australian magpie and crested pigeon (e.g. Jansen & Robertson 2001b, Martin & Possingham 2005). The loss of large woody debris from the floodplain of the Murray River has been associated with declines in numbers and diversity of ground-dwelling mammals and birds (Mac Nally et al. 2001). On the floodplain of the Murrumbidgee River, studies of ants found that seed predators became more common in heavily grazed sites (Meeson, Robertson & Jansen 2002). This in turn may cause further degradation in future years, because the seed predators consume river red gum seeds, which cannot then germinate and grow to replace aging trees.





Contrasting riparian areas where one has been degraded and cleared and the other has been retained as a buffer and habitat for wildlife.
Photos: (left) Siwan Lovett, (right) Canegrowers.

8.6 Restoration of riparian vegetation and wildlife

Works aimed at restoring riparian vegetation in areas grazed by livestock generally involve fencing to remove or control stock access. In areas which have been cleared for pasture or agriculture, it is also necessary to replace the lost riparian vegetation. This has been most commonly attempted by planting seeds or seedlings of locally-occurring trees, shrubs and grasses, and frequently also involves the removal and on-going control of weeds. Fenced-off areas of cleared land may also be allowed to regenerate naturally, although weeds may dominate the initial regrowth. Because mature vegetation develops slowly, other habitat elements, such as large woody materials, have sometimes been added.

There have been few studies of the effects of riparian restoration on wildlife, and most have been conducted over relatively short time frames, when compared with the time necessary to re-establish the large trees and associated habitats typical of riparian lands. However, replanting of cleared riparian lands can produce rapid improvements in wildlife communities. In the wet tropics of north Queensland, where plants grow rapidly, rainforest and riparian birds began to use a replanted and fenced riparian corridor within three years (Jansen, 2005). A survey of a large number of differently restored rainforest sites (both riparian and upslope) in the Australian tropics and sub-tropics concluded that reforestation can lead to moderate colonisation by rainforest wildlife within 5–10 years (Catterall et al. 2004), although many factors will affect its extent, including the density and diversity of plantings and the presence of other forest nearby (Kanowski, Catterall & Wardell-Johnson 2005). Restoration of rainforest along waterways in north Queensland cane fields has been shown to benefit not only riparian wildlife but also the cane farmers, since replacement of tall weedy riparian grasses with forest vegetation leads to a significant decline in numbers of rats which damage sugar cane (Anonymous, undated).

In the upper Murrumbidgee catchment, fencing of remnant riparian vegetation influenced bird community composition and the abundances of indicator species such as superb fairy-wrens and brown treecreepers, with shifts towards more grazing-sensitive species and fewer grazing-tolerant species as time since fencing increased from 1–5 years to greater than 10 years (Thompson, Jansen & Robertson 2002). The area fenced was also important to some species, for example brown treecreepers only used fenced patches larger than 4 hectares.

Top: Natural regeneration once stock are removed. Above: Assisted planting following willow removal. Below: Brown treecreeper. Photos: (top to bottom) CSIRO Sustainable Ecosystems, Lizzie Pope, Andrew Tatnell.

Photo Peter Walton Photography.

Although many wildlife species show rapid responses to restoration, some will be much slower, because they depend on particular microhabitats that may take centuries to develop fully, such as tree hollows and dead wood, or require certain plant species or certain forms of local vegetation structure. For example, in the wet tropics, corridors of secondary-growth riparian rainforest, several decades after regeneration began, had around half the number of regionally-endemic bird species (of high conservation value) as similarly-sized corridors of intact riparian rainforest (Hausmann 2004). Adding the missing habitat elements can help some species establish more rapidly. For example, studies on the floodplain of the Murray River have found that replacing large woody debris resulted in increased abundances of *Antechinus* and brown treecreepers (Mac Nally & Horrocks 2002, Mac Nally, Horrocks & Pettifera 2002).

Weeds and feral or pest animals are an on-going issue in the restoration of riparian lands in a number of respects. Fencing to exclude livestock can often result in the growth of many weeds (e.g. Jansen & Robertson 2001a). This creates a management dilemma: weeds are typically considered undesirable, and the control of some, such as lantana and blackberries, may be required by law in particular regions. But this weedy regrowth can provide good habitat for riparian wildlife, especially in the absence of native shrubs (e.g. Crome, Isaacs & Moore 1994, Jansen & Robertson 2001b). Therefore, weed removal in some circumstances may lead to declines in riparian wildlife. Solving such dilemmas, and finding the best methods for cost-effective restoration of wildlife habitat, requires more real-world experimentation with different forms of restoration and management, coupled with scientifically-designed monitoring programs which can evaluate and compare their outcomes.

Current research

Although riparian lands are clearly very important to wildlife, and some research has been carried out in the last few years in Australia, there is little current research. A PhD on birds has recently been completed and is being written up for publication which examines responses of birds to grazing in riparian (and non-riparian) lands in south-eastern Queensland. This study has looked at both the effects of habitat degradation within riparian sites, and also the landscape context of sites: increasing intensity of land use surrounding riparian lands can also influence the birds found there. A PhD project in western Queensland has investigated the importance of riparian vegetation and water availability to the regional avifaunas of the mulga lands. Work in the Murray-Darling Basin is examining responses of ants to changed grazing regimes in river red gum forests, using an experimental approach with grazing exclusion plots and different seasonal grazing regimes. The aim of this work is to determine grazing management practices suitable for use in state forests to maintain biodiversity values. Experimental work on the effects of replacement of large woody debris on the Murray floodplain is also on-going, examining effects on invertebrates, birds and mammals.

White-breasted woodswallows. Photo Angus Emmott.

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CHAPTER 9

Impacts of land management practices on riparian land

Amy Jansen, Michael Askey-Doran[1], Neil Pettit[1] and Phil Price

Summary

- Land management practices on and surrounding riparian land can lead to its degradation if they are not compatible with its special properties and functions. Land uses on riparian land, whether for agriculture, other commerce, or for urban development, need to be planned and managed carefully.
- When allowed uncontrolled access to riparian land, domestic stock can degrade riparian vegetation by grazing and trampling, leading to consequent increases in rates of erosion, to changes in floral communities by way of preferential grazing, and to invasion by exotic weeds.
- Uncontrolled grazing, especially by cattle which favour riparian areas, often results in increased stream turbidity, as well as increased input of nutrients and bacteria into the stream. Such disturbance of the stream has deleterious effects on aquatic ecosystems and on the quality of water available to downstream users.
- Exclusion of stock from riparian land can allow riparian vegetation and riparian habitats to recover, although a return to pre-disturbance conditions does not always occur.
- Altered fire regimes also have major impacts on the functioning of riparian ecosystems.

1 Michael Askey-Doran and Neil Pettit wrote this chapter for the previous edition.

9.1 Grazing by domestic stock on riparian land

Riparian land is often a very productive part of the landscape. Human settlement has always been focused on rivers, and the activities of people are often a major determinant of riparian structure and function (e.g. Dynesius & Nilsson 1994). The introduction to Australia of domestic livestock has also had a particularly pervasive influence on riparian habitats (see Fleischner 1994, Trimble & Mendel 1995), with grazing management practices among the most widespread agents of chronic modification to land-water interfaces (McComb & Lake 1988, Wilson 1990, Walker 1993, Morton, Short & Barker 1995, Robertson 1998). In a recent assessment of biodiversity values of riparian zones in Australia, grazing has been identified as the most extensive threatening process (Sattler & Creighton 2002). As a result, this chapter focuses mainly on the impacts of grazing by domestic stock on riparian land, with some information on the effects of fire. Other human activities such as cropping and urban land use also have major impacts on riparian land since they generally involve complete removal of riparian vegetation and loss of the riparian ecosystem, and they are also briefly discussed.

Since European settlement, riverine landscapes and wetlands have been used by Australian farmers as watering points for stock, as well as valuable sources of feed. Riparian and wetland habitats, as well as areas around artificial watering points in pastoral regions, suffer greater impacts from domestic and feral grazing herds than do dryland habitats because stock concentrate around water sources (Robertson 1997, James, Landsberg & Morton 1999). Riparian land is typically more fertile and moist than adjacent lands and consequently supports a higher quality and more diverse forage than do upland areas (Gillen, Krueger & Miller 1985, Platts & Nelson 1985). In the hotter seasons, stock are attracted to the cooler microclimates that characterise riparian lands and (especially for cattle) may spend extended periods loafing in the shade or standing in pools found there. These effects are exacerbated during drought years, when water becomes scarce in the landscape (Robertson, 1998, James, Landsberg & Morton 1999).

A comprehensive review of livestock impacts on riparian ecosystems in the western United States found that stock can have negative impacts on stream geomorphology and hydrology, riparian soils, in-stream water quality, and aquatic and riparian vegetation (Belsky, Matzke & Uselman 1999). Along floodplain rivers, livestock can also have impacts on the soil, water and vegetation of wetlands in the riparian zone (Robertson 1997). In the following section we summarise the findings of work on the impacts of stock on the physical characteristics of streams, including riparian soils, stream geomorphology, hydrology and in-stream water quality; this is mainly based on overseas studies as little work on this topic has been done in Australia. We discuss in more detail work on vegetation, some of which has been done in Australia, and include information from work in non-riparian areas. The impacts of grazing by livestock on riparian wildlife were discussed in the previous chapter. Finally, we will discuss the effects of exclusion of stock from riparian areas that have previously been degraded by grazing.

Bank undercutting caused by cattle impact. Photo John Dowe.

The impacts of stock

The impacts of stock on physical characteristics of streams

Livestock consume vegetation and remove ground cover from the soil surface through trampling, leading to increased amounts of bare ground and compaction of the soil. These factors in turn lead to increased erosion and delivery of sediment to streams, as well as lower infiltration rates and reduced fertility of riparian soils (Belsky, Matzke & Uselman 1999).

Decreased infiltration rates, combined with increased erosion in catchments as a result of livestock grazing, lead to greater runoff into streams and riparian zones during rainfall events. This changes the nature of flooding in streams with generally bigger flood events and more variable flows, as less water is stored in the soil to be released during drier periods (Belsky, Matzke & Uselman 1999). These changes, as well as the trampling of stream banks by livestock, alter channel shape (deepening and widening), causing siltation of pools and depositional areas of the stream, and loss of stream bank stability (Belsky, Matzke & Uselman 1999). The impacts of stock on these processes depend on:

~ soil type,
~ soil moisture content,
~ size of stream,
~ regional climate,
~ intensity, season and duration of grazing,
~ type of stock,
~ grazing history,
~ condition and type of vegetation.

Research has shown that grazed stream banks may erode three to six times faster than those that are ungrazed (Trimble & Mendel 1995). This erosion mainly occurs along the tracks that stock create in accessing streams, and can result in losses of about 40 m³ of bank material

Cattle at a restricted water access point but are still content to stand in the water rather than moving back out to pasture. Photo Peter Hairsine.

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These publications are available from the website www.rivers.gov.au

Cows and Fish, a Canadian program to assist ranchers better manage cattle in riparian areas that has fact sheets and information resources of very high quality — website www.cowsandfish.org

Channel widening and bank collapse with removal of riparian vegetation by uncontrolled grazing. Photo Amy Jansen.

Soil bared by overgrazing is easily eroded. Photo Land, Water & Wool.

a year along a single reach. Australian work on the effects of ground cover on soil loss has shown that when ground cover of pasture and litter is greater than 70%, little runoff and soil loss occur in most rainfall events (Costin 1980). Stock also wear tracks through riparian vegetation, and these become pathways for sediments and nutrients to enter streams (Hairsine, Bormann & Brophy 2001). Tracks created along the edges of stream banks are eroded quickly, and parts of the undercut bank may eventually slump into the stream.

Stream size has an important bearing on the degree to which stock affect stream banks. Stock have a greater impact on small streams than they do on large streams (Williamson, Smith & Quinn 1992). Small streams have low stream banks and shallower water, allowing easier stock access at many points. Larger streams have steeper banks, which tends to limit stock access to a few, heavily-used places. Here, much of the erosion occurs as undercutting. Stream banks on the Murray River show signs of undercutting and subsequent collapse, with losses of up to 900 m^3 of bank material along 150 metres of stream bank (Frankenberg 1994). By contrast, ungrazed banks protected by the reed *Phragmites australis* show only minimal erosion and no undercutting.

In addition to those changes that can be seen at the individual stream reach scale, it has also been suggested that grazing has been a major cause of landscape-scale changes in the geomorphology of Australian rangelands (Pringle & Tinley 2003).

Erosion by scour (left hand side of photo) and mass failure (right hand side) along a large river. Photo Ian Prosser.

The impact of stock on water quality

In the Kimberley region of north-western Australia cattle overgrazing of the native vegetation has caused major erosion and river siltation problems (Williams et al. 1996, Winter 1990). Increases in nutrient concentrations from stock excrement, high bacterial and protozoan loads, as well as large sediment loads and high turbidity from trampling near the water edge all cause poor water quality. This situation is made even worse when riparian areas are cleared and grazed so that there is no shade over the stream. High water temperatures and increased light combine with the high nutrient conditions to reduce oxygen concentrations in the stream (Kauffman & Krueger 1984, Belsky, Matzke & Uselman 1999). This situation develops in the following way:

~ nutrient concentrations increase as a result of runoff from disturbed stream banks and direct deposition of livestock urine and manure,

~ bacteria and protozoa increase due to direct contamination by livestock faecal material in streams and in runoff, and toxic algae may grow in-stream in response to the increased light, temperature, and nutrient availability,

~ sediment loads and turbidity increase due to in-stream trampling, erosion from denuded banks, reduced filtering capacity of the riparian vegetation, and increased peak flows due to the compaction of upslope soils,

~ water temperatures and light levels increase as a result of the loss of riparian shade,

~ dissolved oxygen levels decrease as a result of the higher water temperatures, and greater biological demand for oxygen as a consequence of high nutrient loads leading to increased organic matter.

The "ecotrough" developed by woolgrowers David and Ruth Read showing reeds planted in a restricting container to provide shade and reduce the water temperature, keeping the water highly palatable for sheep. Photo David and Ruth Read.

Livestock wastes contaminate streams, while the faecal organisms contained in the wastes can lead to health problems for humans (Miner et al. 1992). Streams contaminated with faecal material can be the source of a range of diseases, such as giardiasis, salmonellosis, gastroenteritis, typhoid fever, hepatitis A, amoebiasis and viral gastroenteritis (Splichen 1992). The good news is that the use of riparian buffers and the exclusion of stock from the riparian zone can reduce by up to 90% the faecal inputs that create the conditions for these diseases.

Impacts of livestock on in-stream water quality can also have major effects on in-stream fauna such as fish and aquatic invertebrates (Larsen et al. 1998, Belsky, Matzke & Uselman 1999). Stock effects on water quality and in-stream life can be particularly severe during periods of low flow, for example in the tropical dry season, as animals congregate at the few remaining waterholes in the landscape (Burrows & Butler 2001).

Stock not only affect water quality but are also affected by it. Work in Canada has demonstrated that gains in stock productivity of up to 25% can be achieved through the provision of watering systems such as troughs based on a clean and uncontaminated water source (Willms et al. 1994). In Australia, this may have important implications for streams which have reduced seasonal flows and which are freely accessed by stock. Trials in Western Australia demonstrated that wethers which drank from polluted dam water lost 1.7 kilograms more body weight and consumed 33% less water than those drinking solely from fresh water (Parlevliet 1983).

The impacts of stock on vegetation

Livestock have a variety of impacts on vegetation. The most obvious is the direct grazing and trampling of ground covers, shrubs and saplings. Undisturbed riparian vegetation usually contains a diverse range of species, including trees and shrubs of various ages, height and form, as well as ground covers (including grasses, sedges and herbs). This contributes not only to the site's biodiversity but also to its structural diversity. The presence of a range of different plants influences the nature of the root zone and the depths to which roots penetrate and this, in turn, affects the water table in stream banks and their stability (see Chapter 2). Plant

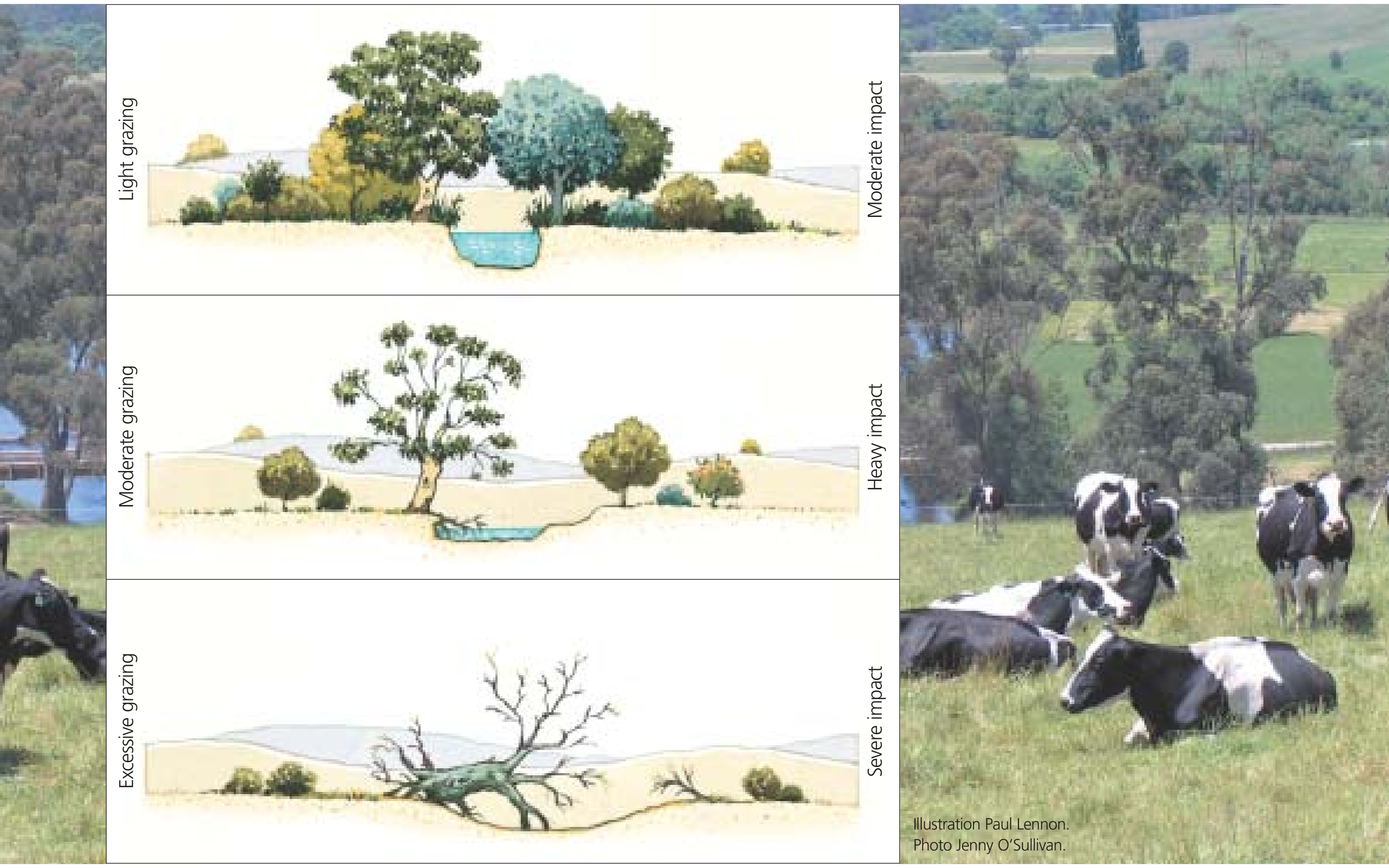


Illustration Paul Lennon.
Photo Jenny O'Sullivan.

diversity supports enhanced nutrient cycling and uptake, soil aeration, soil structure and levels of microbial activity (Earl & Jones 1996). As discussed in the previous section, riparian vegetation is a major controller of geomorphological processes occurring in the riparian zone, and also has strong influences on water quality in-stream. In the previous chapter the importance of intact riparian vegetation to wildlife was discussed.

Table 9.1 summarises the major influences of livestock grazing on riparian vegetation, the causes of these effects, and their impacts on riparian ecosystems. When stock graze they remove plant parts from ground cover vegetation, shrubs and saplings, and also damage them through trampling. These changes lead to loss of ground cover and biomass of vegetation, and through the loss of grazing-sensitive species, to declines in native plant diversity. Soil compaction due to trampling reduces the macrospore space in soil and this reduces infiltration, root growth and overall plant production (Bohn & Buckhouse 1985). The loss of important species or functional groups within riparian vegetation affects the diversity at a particular site and can thereby result in changes in microclimate, nutrient cycling and soil structure. These changes can lead to disruption of ecosystem function and degeneration of the system which cannot be easily reversed.

Stock preferentially graze more palatable plant species, either removing them from a site or reducing them to compact, low tussocks, coppices or rosettes. Plants with different life forms respond to grazing in different ways. Grazing may favour sedges, grasses and other species whose growing point is protected from grazing animals (for example, by being at or below the soil surface and thus able to survive, albeit with reduced vigour) over other life forms. These processes lead to shifts in plant community composition towards species more tolerant of grazing (Fleischner 1994). In Australia, these shifts tend to involve loss of native specialist riparian species and replacement with exotic annual species (Pettit 1999, Jansen & Robertson 2001a, Jansen & Robertson 2005), something that has also been recorded as occurring in North America (Fleischner 1994, Belsky, Matzke & Uselman 1999). Livestock can also promote invasion of weeds (usually annual, ruderal

Above: Uncontrolled stock access degrades riparian lands and allows establishment of exotic weeds. Photo Guy Roth. Below left: Ungrazed riparian areas have a diversity of small native perennial plant species. Below middle: Native perennial tussock ground cover. Below right: *Poa labillardierei*, an example of a large tussock grass found in riparian areas. Small photos Amy Jansen.

Table 9.1. Impacts of livestock grazing and trampling on vegetation and riparian ecosystems (Summarised from Belsky, Matzke & Uselman 1999).

Influence on	Response	Causes	Impacts
Cover, biomass, productivity and native diversity of herbaceous vegetation	Decline	Grazing and trampling by livestock, selective grazing of palatable species, loss of grazing-sensitive species, changed microclimates	Lowered food inputs for aquatic organisms, degraded habitat for aquatic and riparian fauna, reduced biodiversity, replacement of riparian specialists with weedy generalists, loss of ecosystem resiliency
Species composition	Altered	Preferential grazing of palatable species, loss of grazing-sensitive species, changed microclimates, increased disturbance	Replacement of riparian species by upland and exotic weeds, reduction in riparian area
Overhanging vegetation	Declines	Grazing and browsing by livestock	Less shade, greater fluctuations in water temperature, lower food inputs into stream
Tree and shrub biomass and cover	Decline	Browsing and trampling of shrubs and saplings	Loss of complex vegetation structure for wildlife
Structure (vertical and horizontal)	Simplified	Loss of trees and shrubs	Loss of sensitive bird species, reduction in wildlife habitat
Plant age-structure	Becomes even-aged	Reduced recruitment and survival due to grazing and trampling	Reduced riparian habitat, loss of riparian-dependent wildlife

species), which can bring about changes in vegetation structure (Fleischner 1994). The creation of open sites by grazing or trampling provides a perfect opportunity for weed species to become established. Weeds are also spread by the movement of stock, either in their faeces or by attachment to the animal. Stock faeces and urine also contribute large quantities of nutrient to the soil (especially nitrogen and phosphorus), that further encourages the growth and spread of weed species.

Shrubs and trees may be only moderately affected by grazing in the short term but over longer time frames become increasingly degraded. Overgrazing restricts the recruitment of most riparian plants, particularly overstorey plants, and so prevents the replacement of plants as they mature and senesce. This occurs because new seedlings are grazed, or because trampling leads to changes in the soil structure which prevent germination. The reduced tree or shrub canopy may then favour the development or expansion of ground covers (Trimble & Mendel 1995) especially of annual plants that require higher light levels, further restricting germination of woody species (Kirkpatrick 1991). In addition to the direct impacts that livestock have on shrubs and saplings through browsing and trampling, grazing in Australia usually goes hand-in-hand with the clearing of overstorey vegetation. This means that heavily grazed sites tend to have a very simplified vegetation structure, with few trees and shrubs and little recruitment of either (e.g. Pettit 1999, Robertson & Rowling 2000, Jansen & Robertson 2001a). Over time, heavy grazing can result in the development of even-aged stands of vegetation, a reduction in species diversity, or both. These changes to vegetation structure have significant consequences for riparian wildlife (see previous chapter).

In addition to direct impacts of grazing on vegetation, there can be much more subtle effects. For example, Meeson et al. (2002) found that heavily grazed sites had more seed-eating ants than lightly or ungrazed sites, and that rates of predation of river red gum seeds were higher in the heavily grazed sites. Thus, recruitment of river red gum trees was potentially limited in more heavily grazed sites by the availability of seeds. Another complication to this finding is the influence of changed flooding regimes. It was found that sites which flooded less frequently (as is often the case on regulated rivers), were more strongly influenced by the effects of grazing, having greater populations of seed-eating ants, than those which flooded regularly (Meeson, Robertson & Jansen 2002). Hence, grazing may interact with altered flooding regimes to have even more significant impacts on riparian vegetation than would be the case for either effect on its own.

Buffalo Brook, 1986.

When stock are excluded from riparian land

While it is clear that grazing livestock can have profound effects on riparian vegetation and other aspects of riparian zone function, exclusion of grazing from riparian zones can have mixed results. Certainly exclusion of stock can result in rapid recovery of physical functions such as prevention of erosion. For example, after stock were excluded from riparian land in Ohio in the United States, average annual soil loss from streams was 40% lower and sediment concentrations in storm flows 60% lower (Owens, Edwards & Van Keuren 1996). On the Murrumbidgee River in south-east Australia, exclusion of livestock led to decreases in the amount of bare ground in the riparian zone, thus improving riparian zone function (Robertson & Rowling, 2000).

Responses of vegetation to exclusion of livestock grazing can vary due to a number of factors. These include:

- prior adaptation of the vegetation to grazing by livestock,
- availability of seed sources for recruitment,
- extent of degradation of the vegetation,
- other factors such as floods, weeds, etc.

At sites that have had a long history of grazing and where the riparian vegetation has adapted to this form of disturbance, the exclusion of livestock may result in changes to the vegetation structure, such as invasion by woody plants and a reduction in species diversity (Milchunas & Lauenroth 1993). Experiments with grazing exclusion in riparian vegetation have shown a reduction in species richness and an increase in plant cover (Kauffman, Krueger & Vavra 1983). These studies advocate management which excludes grazing for some period of the year (or in particular years) so that vegetation can recover and recruitment can take place. In Australia, however, riparian vegetation is not pre-adapted to grazing by hard-hooved grazing animals. Here, it is unlikely that grazing will be beneficial to

The extent of natural regeneration that has occurred in a 20-year period of stock exclusion, Buffalo Brook, Tasmania. Photos Lindsay Nicolson.

riparian zone function, except in situations where the vegetation is so degraded that grazing can be used as a tool to manage weeds and fire risk.

Fencing out stock can lead to a variety of outcomes. For example, in Tasmania stock were excluded from Buffalo Brook in 1986. In the 11 years to 1997 there was extensive regeneration of native trees (*Acacia dealbata* and *A. melanoxylon*), shrubs (*Leptospermum lanigerum* and *Micrantheum hexandrum*) and ground covers (*Poa labillardierei* and *Lomandra longifolia*). Adjacent grazed sections of the stream failed to regenerate to the same extent. Conversely, riparian land fenced out along the Elizabeth River in the Tasmanian Midlands has become overrun with woody weeds, including *Ulex europaeus* and *Crataegus monogyna* (Askey-Doran et al. 1999). Past land-use history, present practices, availability of propagules (seed bank and proximity to native vegetation), regeneration characteristics of the vegetation, and the composition of the vegetation (introduced versus native) will all influence the progress of regeneration.

Other research has shown that there has been no recovery of ground cover plant communities after 10 years of exclusion of livestock grazing from river red gum forests at Barmah-Millewa in south-east Australia (Kenny 2003). Past degradation, lack of seed sources and resource limitation due to the continuous canopy cover may all have contributed to this lack of recovery. On the Murrumbidgee River, however, exclusion of grazing from riparian zones for periods between one and 30 years has led to significantly different plant communities, with fewer exotic annual grasses in ungrazed than grazed sites. Lower stocking rates were also associated with more native annual grasses, tall perennial forbs and small perennial sedges (Jansen & Robertson 2005). Exclusion or partial exclusion of grazing from riparian zones in the Goulburn-Broken Catchment has also been associated with increased native plant biodiversity, increased abundance of native grasses and decreased numbers of introduced species, including noxious weeds (Goulburn Broken Catchment Management Authority and Land & Water Australia 2002).

Predicting which particular species are most affected by livestock grazing and which species are likely to return after stock exclusion is important for the rehabilitation of degraded riparian areas. This may depend on particular traits of individual species — such as life form, ability to resprout after defoliation, seed production, seed dispersal techniques, seed dormancy and the ability to

This creek is seasonally wet or dry and occasionally burnt. The mix of riparian species present is dependent on this wetting and drying cycle. Photos Michael Douglas.

form a seed bank. After one year of excluding stock in a grazing exclusion experiment on riparian land on the Blackwood River in Western Australia, native perennial herbs showed the greatest increase in vegetation cover. There was also successful recruitment of the overstorey species *Casuarina obesa* in the exclosure plots, which did not occur in the grazed plots (N. Pettit, unpublished data).

Germination studies of Tasmanian riparian land indicate that the recruitment of woody species after exclusion of grazing is a lengthy process. After almost three years of exclusion there was only limited recruitment of woody species in the monitored plots (Askey-Doran et al. 1999). Marsupial grazing is likely to be influencing this, but other factors (such as suppression by the grass layer, unsuitable germination conditions, and a depauperate seed bank) may also be implicated. Successful recruitment of many species may be episodic, relying on the coincidence of several factors (such as winter flooding, early receding of floodwaters corresponding with seedfall, and some summer rainfall). Recruitment requiring particular environmental conditions has been documented in some plant communities (e.g. Askey-Doran et al. 1999, Pettit & Froend 2001, Pettit, Froend & Davies 2001), and grazing may interfere with any such 'window of opportunity' for recruitment.

9.2 Other impacts

Unmanaged or poorly controlled grazing by domestic stock is a major cause of continuing degradation of riparian land in agricultural areas and is therefore the primary focus of this chapter. However, there are a range of other activities that impact upon riparian areas, and these are covered here.

Fire

Parson (1991) cites several references to the use of fire by Aboriginal people along rivers, including the Namoi, Gwydir, Barwon, Bogan, Macquarie and Narran Rivers. Similarly, the use of fire to stimulate regrowth of grass along watercourses in Central Queensland has been reported (Parson 1991). Aboriginal use of fire would have impeded regeneration of river red gum but favoured woodland development and the maintenance of forest grassland boundaries (Chesterfield 1986). The impact of fire on riparian communities depends on their floristic and structural composition and on the intensity, season and frequency of burning. Different species respond differently to fire. In general, riparian communities are generally not adapted to frequent burning, with many species sensitive to fire. Young river red gums are examples of a species sensitive to even low-intensity fires (Dexter 1978); their lack of lignotubers making them more susceptible to death from fire than many other eucalypts (NSW Forestry Commission 1986, cited in Parson 1991). The vulnerability of river red gum to fire means that very little control burning occurs in these forests (Parson 1991). Low fuel loads and depauperate shrub layers limit the need to reduce fuel loads. Other species, such as *Callitris oblonga*, may be killed outright by fire, but the death of the parent facilitates seed fall and regeneration (Harris & Kirkpatrick 1991).

Fire regime (frequency, season and intensity) can have a major influence on the composition and health of riparian vegetation. Photo Ian Dixon.

Frequent fire can encourage fire-tolerant species and discourage fire-sensitive species, leading to changes in the composition and structure of plant communities. In the south-western United States, *Populus* spp. were missing from burnt stands whilst *Salix* spp. were able to persist (Busch 1995). Fire in these communities encouraged the invasion of the exotic species *Tamarix* and *Tessaria*. In Australia, 'bush run' country is regularly burnt for 'green pick' for stock. If these fires are of low intensity and well controlled they should not affect riparian vegetation. However, escaping fires do burn into riparian areas and can lead to the death of plants. The common practice of controlling weed species with fire poses a threat to riparian land. For example, some

Examples of development on or near riparian land that affect its functions and water quality or river health. Photos: (top left and right) Guy Roth, (bottom left) Phil Price, (bottom right) David Morgan.

fires burn intensely and produce embers which can be blown into riparian areas or the fires can burn into the riparian zone (Askey-Doran et al. 1999).

Work in the savanna country of the northern territory has shown that early dry season burns are much less damaging than late dry season burns to riparian zone vegetation (Andersen et al. 2005) and to stream water quality during early wet season run-off events (Townsend & Douglas 2000). However, late dry season burns lead to flushes in growth of aquatic vegetation and associated aquatic fauna which are absent from unburnt sites and those burnt early in the dry season (Andersen et al. 2005).

Cropping

As noted elsewhere in this document, riparian land is often a very productive part of the landscape, and may therefore be cultivated for agricultural or horticultural crops. Removal of the native vegetation and cultivation of the soil leads to complete loss of many important riparian functions, with consequent deleterious impacts on both the terrestrial and aquatic ecosystems. As cropping land is valuable, the temptation is strong to crop up to the edge of the channel, and sometimes into the channel itself. Careful planning of the paddock layout, for example, to incorporate a track and area for turning machinery, a grassed filter strip, and thin band of shading riparian vegetation, can restore some of these functions.

Urban development

Urban development can be equally deleterious, even when some riparian vegetation is retained. Increased run-off from impervious urban surfaces has been dealt with in the past by converting the natural channel into a straight concrete drain to maximise flood conveyance (Ferguson, Hardie & Miller 2004). This process is being reversed in some areas, at considerable expense, but other problems remain of weed invasion, contamination with nutrients and rubbish, and erosion and modification of vegetation from over-use.

River regulation

Changes to stream flow regime can have large impacts on riparian vegetation, and these are outlined in Chapter 5. Channel straightening and 'de-snagging' undertaken in the past with the aim of increasing flood conveyance and reducing the inundation of riparian land, can also impact directly and indirectly on riparian zones. Both can lead to increased flow velocity and enhanced erosion of the channel bed and banks, with potential for channel avulsion, flood-outs, head-cutting and loss of riparian vegetation and land. Loss of important in-stream habitat can have flow-on effects to the adjacent riparian land as explained in Chapter 8. Even where native riparian vegetation has been retained it may take many decades for the natural level of in-stream wood to be restored, and where the vegetation has been cleared or lost there is no likelihood of restoration to more natural flow conditions.

Construction of weirs, dams and reservoirs can also have a major impact on the health and functions of riparian land (Ogden & Thoms 2001). A large impoundment can greatly reduce the frequency and extent of the flood peaks required by some riparian plants for reproduction or survival, and releases timed to meet the needs of downstream irrigators (summer and early autumn) may reverse the natural flood season (spring in Southern Australia). Frequent releases may result in rapid changes in water level that increase bank erosion but do not provide the conditions necessary for successful recruitment of riparian species. Massive alteration to disturbance regimes is an important contributor to declining condition of riparian lands in many regulated catchments.

Sand and gravel extraction

Rivers have been used as important sources of materials for road base and concrete, often with little thought given to the potential effects of their removal. Changing the balance between flow/erosive power and sediment supply can lead to episodes of bed or bank erosion and channel widening, establishment of nick points and head-cuts, and loss of water quality and in-stream habitat. Sand and gravel extraction is another activity that can have direct (at stream access points) and indirect (through changes to the channel and flow) impacts on riparian land and its functions. The need for restoration of extraction sites should be incorporated into the permitting process.

Weed invasion

For many people, an important deterrent to changing stock management in riparian areas is the fear that they will become havens for weeds and pest animals, as well as posing a fire risk. These are issues that must be taken into account in planning the management of riparian areas. Fortunately many landholders have found ways to improve their management of riparian areas without significant invasion or establishment by weeds. An important principle of weed management is that most weed species find it difficult to invade and establish into intact riparian vegetation. In general, if vigorous pasture and healthy native vegetation is maintained or established in riparian areas, weeds will find it harder to compete and establish. Managing grazing so that plant cover of established pasture and native vegetation is maintained is the key management practice to prevent weeds becoming a problem.

Bamboo grass and artichokes shown here, can be difficult weeds to contain in riparian areas once they take hold. Photo Phil Price.

On riparian land that has become degraded by past land use and management, and on areas that are affected by flood, frost, or wildfire, it is vital to promote natural regeneration or to deliberately revegetate as soon as possible after the disturbance, otherwise weed invasion is almost certain and it will be much harder to bring the area back to a natural condition.

However, even with this careful approach to management, some weed species especially suited to riparian areas may become established. Weeds can be brought in through wind dispersal of seeds, seeds passing through the droppings of birds and other animals, or seeds and pieces of vegetation arriving from upstream during peak flows. Where these invaders are successful, carefully-managed and selective grazing in the riparian area can be used, as well as selective control with herbicide or hand-weeding. Pulling individual weeds out by hand or grubbing out with a hoe can be effective when numbers are low.

In many regions, riparian areas have already been invaded by woody weeds. These plants, which might include willows, pepper trees, olives, desert ash, tamarisk and other species, may provide some benefits (for example, they may shade the stream or help strengthen banks against erosion), but overall their influence is negative, and in the long run they should be replaced with local native species. Willows, for example, will

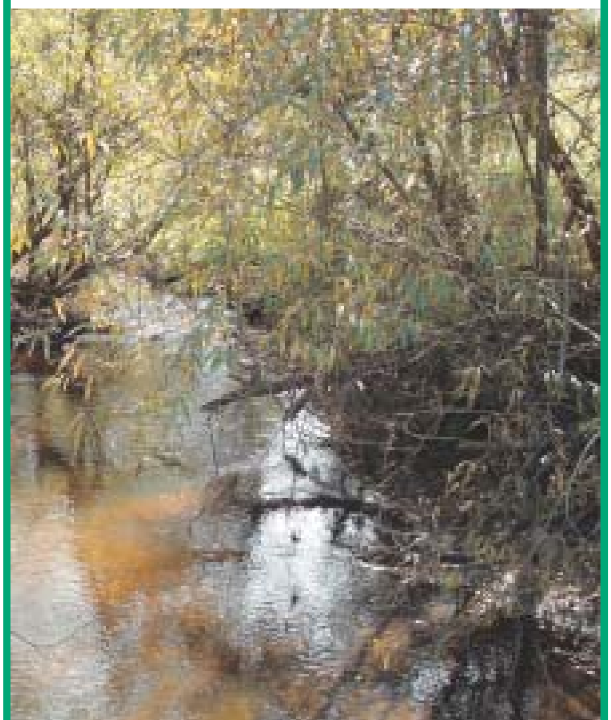
The problem with willows in riparian areas

In many high rainfall areas, willows have been used extensively to help stabilise many stream banks. Willows establish easily, grow rapidly, produce fine matted roots ideal for stabilising soil, and require little attention after planting. However, over time the consistent use of willows (and the planting of male and female plants of most species that successfully spread by seed), has caused changes to the ecology and flows of rivers and streams. Some southern rivers are now completely choked by invasive willows. Willows have displaced native riparian species and colonised sand and gravel bars in streams, diverting floods and causing erosion on vulnerable banks. The soft textured leaves that are all dropped at the same time do not provide a year-round food source for native in-stream animals. This, together with the extreme shade provided by willows has reduced biodiversity wherever willows dominate riparian areas. Willows are also prodigious users of water, and en masse can reduce natural water flow. Some of these features also apply to other invasive species found in the riparian zone including poplars, she-oaks, olives and desert ash.

Willows are now listed as a weed of national significance. For more information see the website www.weeds.org.au/WoNS/willows/.

For more on how to manage willows see: 'Controlling willows along Australian rivers', *River and Riparian Technical Guideline*, no. 6, Land & Water Australia. Available in hard copy and on the web at www.rivers.gov.au.

Text source: Department of Land & Water Conservation. Photo Lizzie Pope.



Foxes are a major threat to livestock production and to wildlife. Photo Jan and Neville Lubke.

gradually grow into the stream, blocking the channel, and causing additional flooding. They can be highly aggressive, and now that both sexes in most species are present in Australia there have been some huge seeding events, with millions of seedlings becoming established downstream, completely choking some channels. Willows also use a lot of water, and are harmful to native in-stream animals as they drop all their leaves at once into the stream where they decompose and create anoxic (no oxygen) conditions.

Pest animals

The development of catchments for agriculture or urban use has disturbed natural systems and forced or enabled some animal species to become pests. Loss of natural habitat combined with greater availability of water and quality food (in the form of crops) has led to some species increasing their population while others declined. There is a risk that unmanaged or revegetated riparian areas may provide harbour for pest animals, which can include both native and feral species. Wallabies, kangaroos, possums and some bird species can cause significant damage to native vegetation. Feral species, including pigs, foxes, rabbits, deer, wild dogs and cats, are also deleterious to native plants and wildlife, can be predators of farm animals and may pose a disease risk. In closely-settled areas, where riparian areas are likely to include grazed pasture and small areas of native vegetation, the eradication of these pests is normally not a problem. However, over larger areas, particularly in pastoral country, this is an issue that must be considered as part of overall riparian management strategies and eradication programs put in place.

Current research

Long-term exclusion of livestock from riparian land in the Burdekin Catchment

Four sites at which cross-stream fencing separates areas with stock access and without were studied. Stock had been removed from riparian zones one side of the fence for at least 15 years. Results indicated that the dominant trees species had a greater density and cover in the unstocked areas. This was most likely not through greater levels of regeneration following removal of stock, but due to the degradation and/or loss of the dominant tree species through the activities of stock. Additionally, the time frame is too limited for the germination, establishment, and growth to maturity of large slow growing species such as broad-leaved *Melaleuca* spp. and *Eucalyptus camaldulensis*. The life span of dominant trees may be significantly reduced by soil compaction, erosion generated by trampling and track formation, and the input of faecal materials into the soil below the trees. Conversely, at the study sites at least, there was a greater cover and abundance of deleterious weeds in the unstocked area, but overall there was no significant differences of species adundances or species composition between the stocked and unstocked sites. It was concluded that stock have a significant detrimental impact on the persistence of established dominant trees in riparian zones.

Researcher: John L. Dowe, Australian Centre for Tropical Freshwater Research, James Cook University, Townsville

Exclusion experiments in the Burdekin Catchment

Nine stock exclosures each with an average cover of 1500 m^2 were constructed at three sites in the Burdekin catchment in late 2002. The sites have been monitored bi-annually since November 2002 on a pre wet season (November) and post wet season (May) basis. Each site consists of three exclosure plots and two to four control plots. The sites are also graded as steeply sloping, moderately sloping and gently sloping. In the first surveys following establishment, grass cover was significantly greater within the exclosures compared to the controls, primarily because of no grazing. Levels of grass cover have more or less remained at a high level within the exclosures, whilst in the controls levels of grass cover reflected seasonal rainfall patterns and subsequent levels of grazing. In most exclosures, one or two exotic pasture grass species have come to be dominant at the expense of others, including native grass species, that were initially of greater abundance. There have been no significant changes in species composition at any of the sites, although abundance (as determined by percentage cover) has altered for many grass species. There was no evidence of greater weed occurrence within the exclosures, and no change in the number of species present in any plot. It was concluded that in the short term, some grass species respond to not being grazed, and are able to out-compete others that may benefit from grazing.

Researcher: John L. Dowe (as previous)

Exclusion experiments in the Riverina

Grazing experiments were established at three sites which were continuously grazed prior to 2001. Starting in 2001, Millewa was only grazed in summer, Cuba North was only grazed in winter, and Cuba South continued to be continuously grazed. Five fenced and five unfenced plots were established at each site and baseline monitoring of plants occurred in the spring of 2001. All sites were virtually ungrazed throughout 2002, due to the drought, and baseline monitoring of ants occurred in the late spring of 2002. Some grazing occurred at Millewa and Cuba South but not at Cuba North in 2003, and all sites had some stock in 2004. Plants were resampled in spring of 2003 and 2004, and ants in late spring of 2004. While there have been changes from year-to-year in the plant and ant communities, no differences have developed over time between the fenced and unfenced plots at any site, for either plants or ants. There are three possible explanations:

1. The time frame has been too short to allow differences to develop (this seems unlikely, given that ants, at least are known to respond relatively quickly to changes in land management).
2. The sites have reached a level of degradation where recovery in response to the removal of grazing is unlikely (again this seems unlikely as the sites chosen, especially Millewa, are in relatively good condition).
3. The stocking rates adopted by state forests for these sites, and particularly the extremely low stocking during the drought, may be so low that there is no detectable effect.

The main conclusion is that stocking rates and grazing regimes used in state forests in the Riverina floodplain in recent years are unlikely to cause any more degradation of riparian habitats than has already occurred. There is also no evidence that any recovery of riparian habitats is likely to occur, either under light grazing or with total exclusion of grazing.

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