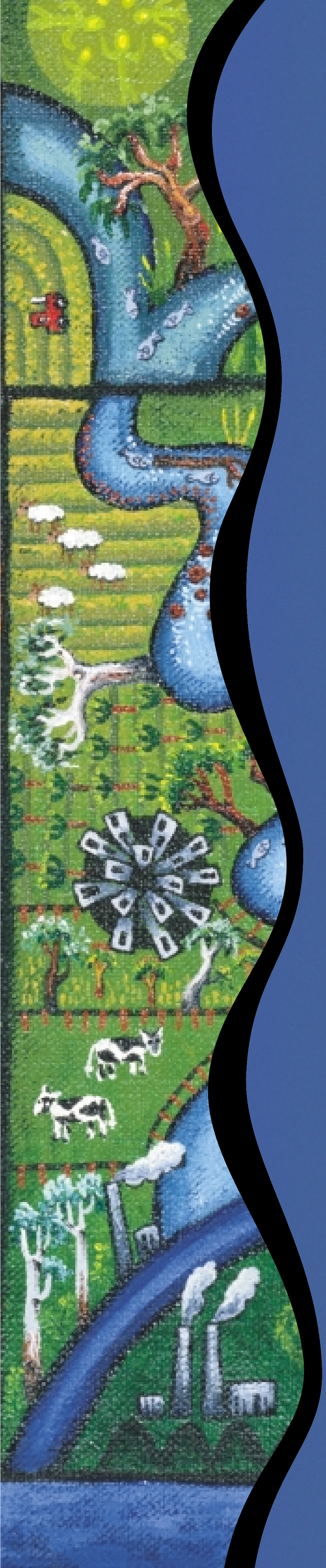

Riparian Land Management Technical Guidelines

Volume One

Part A: Principles of Sound Management

Part B: Review of Legislation Relating to Riparian Management

Land & Water Resources
Research & Development Corporation

RiverLandscapes

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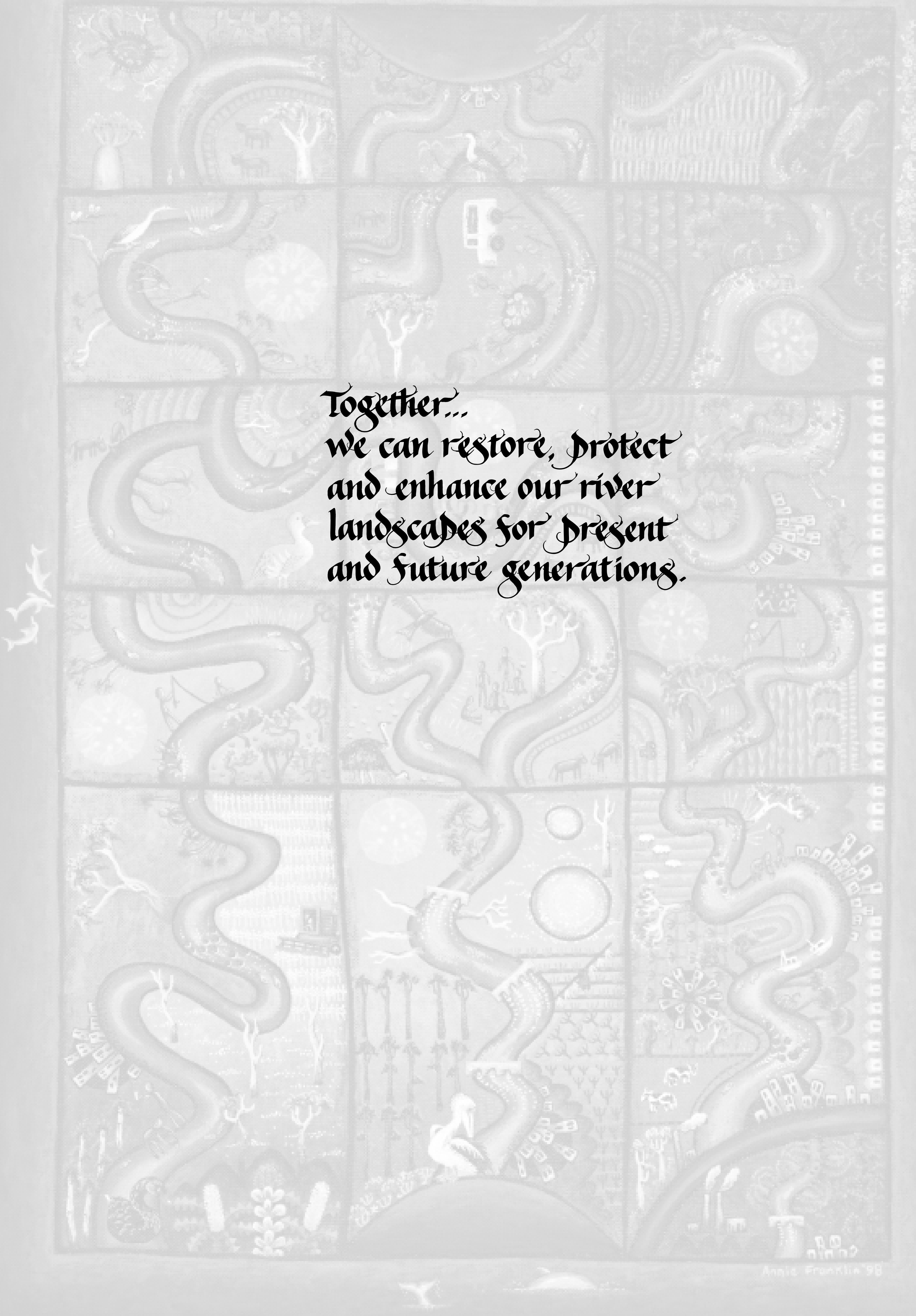

Together...
we can restore, protect
and enhance our river
landscapes for present
and future generations.

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GPO Box 2182
Canberra ACT 2601
Tel: 02 6257 3379
Fax: 02 6257 3420
E-mail: public@lwrrdc.gov.au
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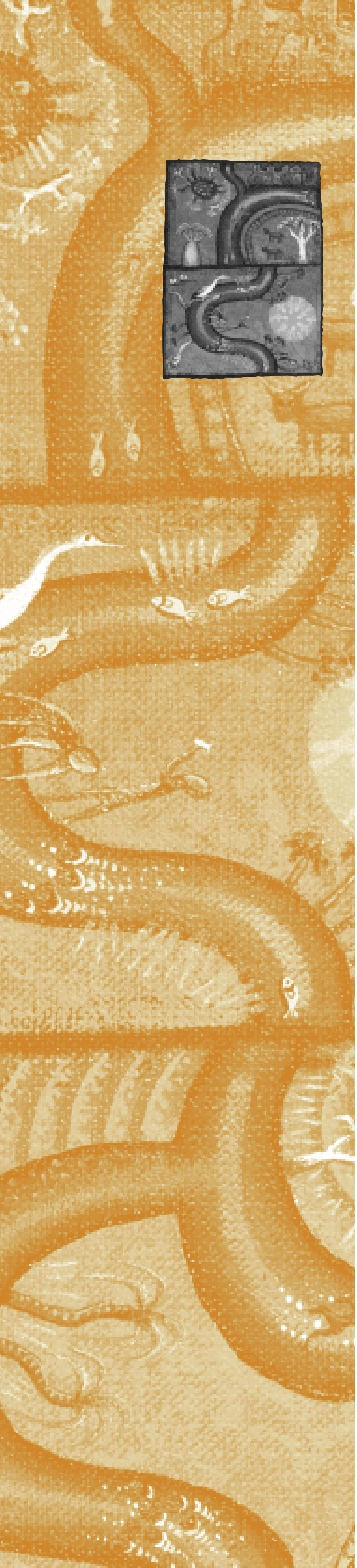

PREFACE

In 1993, shortly after its establishment, the Land and Water Resources Research and Development Corporation commissioned a brief review of riparian management issues in Australia. It quickly became apparent that there was a growing recognition of, and participation in, active riparian management by landholders, community groups and government agencies. However, it was also apparent that there was little quantitative data that could be used to develop management methods likely to deliver the desired results. As a result, the Corporation, in collaboration with the Cooperative Research Centre for Catchment Hydrology and the Centre for Catchment and Instream Research at Griffith University, established a national research and development program into the rehabilitation and management of riparian lands. The program operates Australia-wide, with several experimental and demonstration sites established in collaboration with State agencies, local government and catchment management groups, rural industry bodies and individual landholders. The aims of the program are to achieve a much improved understanding both of the processes operating in riparian lands, and of the interactions between riparian land, vegetation and aquatic ecosystems.

In early 1997, the Corporation and its partners released a series of issues papers on riparian management. These were designed for a non-technical audience, to promote awareness of riparian functions. They discussed a range of riparian management issues and techniques for stabilising banks, trapping sediment, improving the ecological condition of streams, and managing stock access. There was a huge response to the issues papers—further evidence of the widespread demand for better information on riparian management. The papers are available on the Internet at <www.rivers.gov.au>.

These guidelines are a follow-up to the issues papers. They provide additional information of a technical nature and have been designed to provide professional land managers, advisers, State and Territory agency staff and local government staff, with the information they need to assist non-technical people operating at the farm or catchment level to design and implement best-practice riparian management. The guidelines augment and complement other sources of information on riparian management. They provide sufficient technical information so that readers can understand important principles underlying riparian issues and adapt them, as required, to their particular objectives, climate, farming enterprise or other circumstance.

The focus of the document is on agricultural catchments where riparian land has been degraded in the past and where rehabilitation is required. While the guidelines do not refer specifically to forest management (where there are specific codes of practice relating to riparian land) the principles are the same and the guidelines are likely to be of use to foresters. Similarly, particular issues of urban settings are not addressed, but many of the same principles apply.

Because one of the major purposes of riparian management is to maintain healthy in-stream ecosystems, some of the material contained in these guidelines addresses the functioning of aquatic ecosystems.

The guidelines are divided into two volumes.

Volume 1, Part A provides the technical information on which management recommendations are based. The information is provided to remind, update or prompt the professional land manager, adviser or government officer about the technical issues that need to be considered. Part B provides a review of legislation relating to riparian management in each State and Territory.

Volume 2 contains the management strategies themselves. Each guideline can be used on its own by practitioners interested in particular objectives, but readers are encouraged to look at all the guidelines to see if additional objectives can be achieved.

Three qualifications

1. These guidelines are intended to have a national scope, but Australia has a huge diversity of environments. Thus it is not possible to be prescriptive about what to do in every particular region. What is provided, is a review of crucial factors for riparian management that need to be considered in each situation, with suggestions about how to vary management in line with local conditions. The aim is provide the technical framework which will empower those with local knowledge to make appropriate local decisions.
2. Some issues are beyond the scope of these guidelines. Issues not covered specifically, include the use of riparian land to reduce the level of pesticides and herbicides in streams; riparian management in non-agricultural areas; some causes of problems in streams (such as point sources of pollution and sand and gravel extraction); and 'non-vegetative' forms of management such as structural works.
3. There has been a large amount of research conducted overseas on the functions and management of riparian lands, but scant attention has been given to the subject in Australia. The overseas research cannot be simply transposed because of the distinctive characteristics of Australian environments—for example, native vegetation is largely evergreen and soils are old and poor in nutrients. In the absence of local research, these guidelines combine our knowledge of Australian catchments and the physical laws controlling in-stream ecosystems with overseas riparian research. Results of current research will improve our understanding over the next few years.

The intention is to revise these guidelines as knowledge of key processes improves. Your feedback is vital to this process—we welcome any comments or suggestions for improvement and any relevant examples and case studies of riparian management issues in Australia. If you would like to provide input, please contact

CHAPTER 1

The significance and status of riparian land

Wendy Tubman, Phil Price

Summary

- For the purposes of these guidelines, riparian land is defined as 'any land which adjoins, directly influences, or is influenced by a body of water'. However, there is no rule of nature which defines the 'width' of riparian land: the width of interest or concern is largely determined by the 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.
- Since European settlement, riparian land in Australia has been subjected to considerable degradation, much of which is associated with clearing of vegetation in the catchment.
- Fortunately, the importance of managing riparian land well is increasingly being recognised, and remedial work is being undertaken at the local, regional, State and Territory and national levels.

CHAPTER 1

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 is sometimes 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 takes little heed of 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

~ the land immediately alongside small creeks and rivers, including the river bank itself;
~ gullies and dips which sometimes run with surface water;
~ areas surrounding lakes;
~ 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 these are largely management decisions. For example, the width required to trap sediment may be a fraction of that required to provide wildlife habitat, yet both are legitimate objectives for riparian management. One of the aims of this manual is to help people make informed choices about the riparian and buffer widths appropriate to their particular management objective.

Because of the complex interactions between land and water in riparian areas, these guidelines deal 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 usually the most fertile and productive part of the landscape, in terms of both primary production and ecosystems. It often has better quality soils than the surrounding hill slopes and, because of its position lower in the landscape, often retains moisture over a longer period.

Riparian land often supports a higher diversity of plants and animals than does non-riparian land. This is a result of its wide range of habitats and food types, its proximity to water, its 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.

From an aquatic perspective, vegetation on riparian land regulates in-stream primary production through shading; 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 woody debris.

In addition to being productive, riparian land is often a vulnerable part of the landscape—being at risk of damage from cultivation and from natural events such as floods.

The combination of productivity and vulnerability means that careful management of riparian lands is a vital for conservation of both Australia's unique biodiversity and economic 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 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 interaction of land and water is depicted in Figure 1.1.

The use and management of riparian land

For some time, the important linkages between land and water in riparian areas were not well recognised by Australian land users. 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

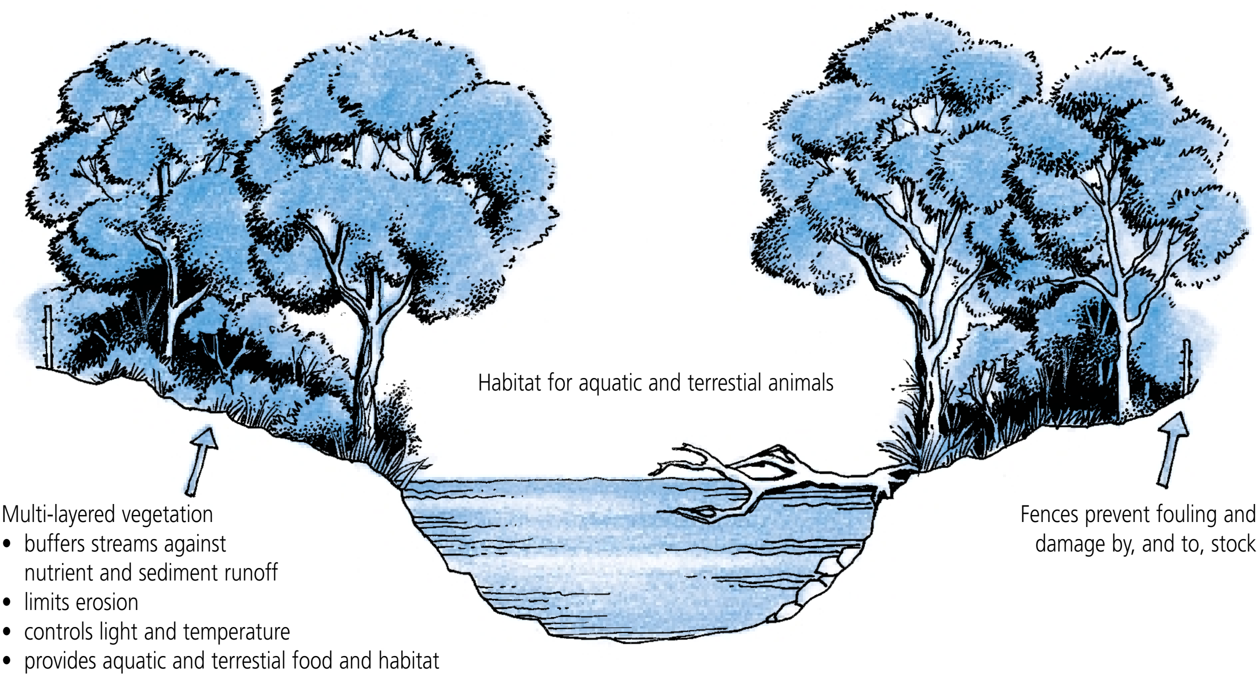

Figure 1.1 Interaction of land and water in the riparian zone

Undisturbed river system, Macquarie River, Tasmania. Photo by Michael Askey-Doran.

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.

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

~ trap sediment, nutrients and other contaminants before they reach the waterways;
~ reduce rates of bank erosion and loss of valuable land;
~ control nuisance aquatic plants;
~ 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;
~ help to maintain agricultural productivity;
~ provide recreation and deliver aesthetically pleasing landscapes.

Many of these benefits can be achieved through careful riparian management.

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 surrounding vegetation.

However, human impact since European settlement has resulted in widespread and large-scale degradation of these vulnerable areas. In southern Australia this degradation has resulted largely from the wide-scale removal of riparian vegetation, whereas in northern Australia the cane and beef industries and feral animals and plants have 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. The major impacts of this are summarised below.

~ Removal of riparian trees increases the amount of light and heat reaching waterways. This favours the growth of nuisance algae and weeds.
~ Under natural conditions, trees would occasionally fall into the river, creating woody debris—an important habitat for aquatic organisms. Removal of this debris and of the source of large branches and trunks disrupts aquatic ecosystems.
~ Continuation of agriculture to the top of stream banks 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

Unfenced Blackman River in Tasmania showing stock ramp pugging. Photo by Michael Askey-Doran.

growth. Increased nutrient load also affects estuarine and marine life beyond the river mouth.

~ Removal of 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.

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

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

However, removal of vegetation is not the only human land use that adversely affects riparian land.

~ Alteration of water regimes (through the imposition of dams, weirs and pumps) can severely affect aquatic populations and the capacity of the waterways to carry flow.

~ Sand and gravel removal and channel straightening can result in channel incision and head cutting, which in turn can influence bank height and shape and lead to increased erosion rates.

~ Uncontrolled access of stock can lead to grazing and trampling of vegetation, breakdown of soil structure and contamination of the water with nutrient-rich urine and faeces.

~ Altered 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 actually exacerbate each other. For example, clearing riparian vegetation from upland streams multiplies, many times, the impact of increased nutrients. This is because clearing also provides the light and higher temperature conditions needed to enable nuisance weeds and algae to flourish and dominate the aquatic ecosystem.

The extent of the problem

The following statistics, from the 1996 state of the environment (SoE) report (State of the Environment Advisory Council 1996) give some indication of the magnitude of the land and water degradation problem in Australia. As riparian land is the 'last line of defence', problems arising elsewhere in a region or catchment eventually affect riparian land.

Since European settlement it is estimated that

~ about 40% of all native tree cover (an area over one and a half times the size of Tasmania) has been completely removed;

~ a further 35% of all native tree cover has been subjected to harvesting;

~ all 22 coastal drainages between Fraser Island in Queensland and Lakes Entrance in Victoria have been impounded;

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

In 1991 the Darling River recorded the world's largest toxic blue–green algal bloom, the bloom covering a 1000 km stretch of the river.

The SoE report provides numerous examples of research which has shown the extent of degradation of Australia's waterways. It notes, for example, that

~ 38% of New South Wales lakes 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 land use are demonstrated in the following statistics.

~ Soil and water degradation costs Australia more than $1.4 billion each year.
~ Around 14 billion tonnes of Australian soil are moved by sheet and rill erosion each year—representing about 19% of global soil movement.
~ By 2010 an estimated 16%, or 2.9 million hectares, of the cleared land in Western Australia will be salinised.
~ Control of insect pests in Australia costs in the order of $1 billion every year.
~ Of 1900 plants introduced since European settlement, 220 are now declared noxious weeds and weed control costs about $3.3 billion annually.
~ About $450 million is spent each year in treating water for human consumption.

The nature and perceived extent of the problem for inland waterways are summarised in the extract from the SoE report reproduced in Table 1.1.

Table 1.1 Inland waters: key threats to sustainability

Issue	Detail	Comment
Dryland salinity	This is increasing in south-west Western Australia and eastern uplands; stream salinity is rising and will continue to worsen.	Much damage has already been done and the situation is deteriorating.
Wetlands	Deterioration of wetlands has been caused by drainage, changes to water regimes and increase in sediment run-off and nutrient input.	Wetlands continue to be under threat and large numbers are already destroyed. The situation is very poor.
Over-allocation of water to consumption	'Droughtproofing' by damming has starved rivers of water and drastically altered seasonal flow regimes in the most developed areas. Groundwater is being 'mined'.	Particularly severe in the south-east of the country. Deteriorating.
Irrigation	The greatest use of water and the cause of much over-allocation irrigation, causes waterlogging, salinisation and nutrient and pesticide pollution.	A major pressure on inland waters. Infrastructure is ageing and will need replacement. Some land may need to be retired from existing uses. The situation is deteriorating.
Endangered species	Pollution, over-allocation of water, changed flow regimes and exotic and displaced species are all affecting native species.	Many species of aquatic animals are endangered, in decline or extinct. Deteriorating.
Nutrients	Catchment erosion and point-source discharges have contaminated many water bodies so they now produce blue–green algae.	Effects are greatest in the south-east of the country. Trends are unclear but current situation is poor.
Water weeds	Several vigorous weed species are spreading, particularly *Mimosa pigra* and alligator weed.	Weeds affect the entire country and the situation is generally deteriorating.
Sediments	Although decreasing in some areas, sediments continue to have impacts on biota and water-treatment costs; trends differ between regions.	The outlook is improving in the south-east of the country but is deteriorating elsewhere.

Source: State of the Environment Advisory Council (1996).

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 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 medium and long term.

As a result, increasing attention is now being paid by individuals, community groups, 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. Under best-practice standards, techniques which mimic nature and are suited to the vulnerable and unique Australian environment are replacing the largely northern hemisphere techniques that have been practised over the last 200 years or so.

For example, revegetation is now widely accepted as a 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 km long.

It is important to recognise that 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

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 or because the health and productivity of animals grazed there is improved. 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 high cost of durable fencing.

For information contact your local Department of Agriculture or Natural Resources.

Stock access to small tributaries is a common problem.
Photo by Ian Bell.

lands will not overcome management practices elsewhere that lead to excessive soil erosion, loss of nutrients or contamination.

These guidelines are intended to help practitioners manage riparian land well. Although not exhaustive, they bring together a wide range of information and research results, as well as recommendations relating to riparian processes in Australia.

The following chapters in this volume concentrate on specific natural processes which dictate how riparian areas 'work' and which need to be taken into account if management decisions are to be informed and responsible. Guidelines for action are presented in Volume 2.

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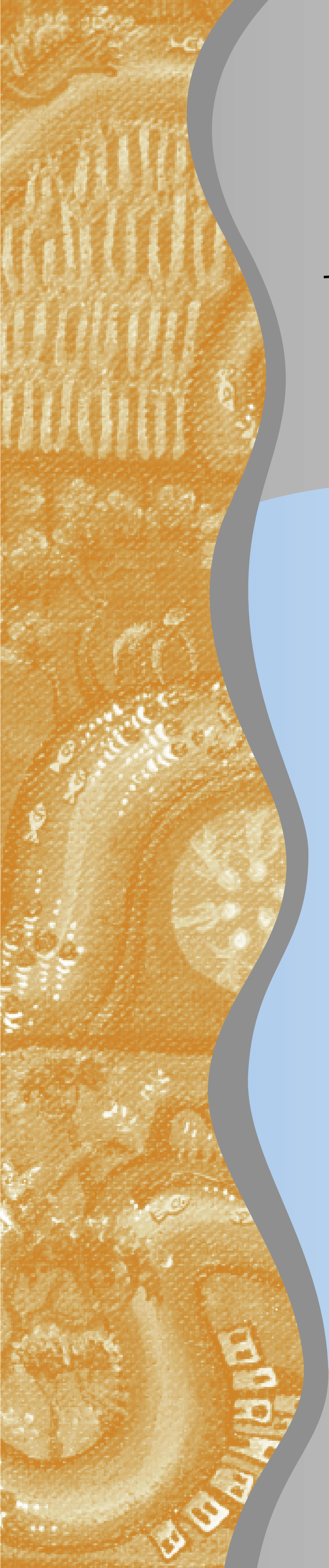


CHAPTER 2

The influence of space and time

Ian Prosser, Ralph Ogden, Stuart Bunn

Summary

- The nature of streams and rivers varies according to their size and position in the catchment, and this variation has implications for management.
- Many 'problems' start, and therefore management action is likely to be most effective, in and around first and second order streams.
- Human and natural impacts can quickly change the nature of streams; in contrast, reversing such changes often takes a very long time.
- Australian streams are naturally variable; the aim of management should be to slow the rate of major change to 'acceptable (but flexible) levels', rather than to stop change completely.
- The time spans under which stream managers operate are often much shorter than the time spans under which streams operate.

2.1 Spatial factors: stream size and position in the catchment

Stream order: a classification for examining variation within catchments

The classification of streams according to whether they are 'small' or 'large' allows differences to be easily visualised. However, these terms are imprecise. Classifying streams according to their position in the channel network helps overcome this imprecision.

Strahler's stream order classification system assigns a numerical 'order' to each stream segment. Under the system, a 'first order' stream has no tributaries. When two streams of equal order join, the section downstream of the junction increases in order (see Figure 2.1). Hence, the junction of two first order streams creates a second order stream, the junction of two fifth order rivers creates a sixth order river and so on. It is important to note that the section downstream of the junction of a first order and a second order stream is still a second order stream, since the junction does not involve two streams of equal order.

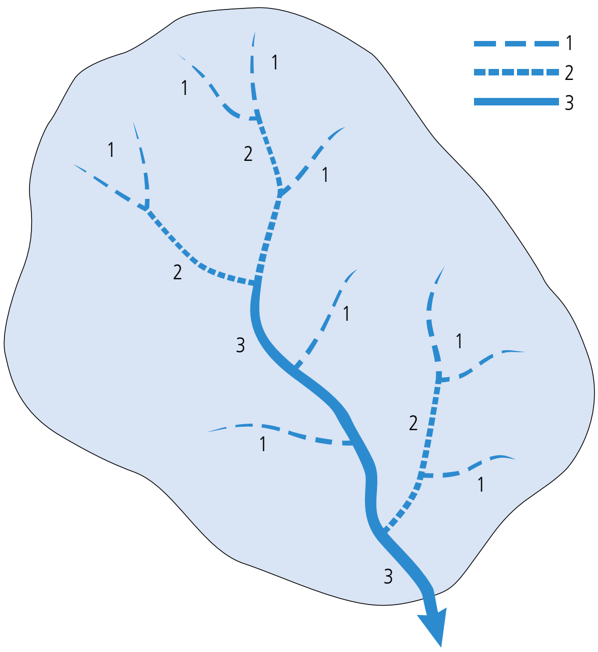


Figure 2.1 Relationship between stream order, variation and position in landscape

First order streams are small. Streams become larger as their order rises and an increasing number of segments contribute to the flow. First order streams may occur anywhere in the catchment, but large streams and rivers (fourth and fifth order and above) are only found lower down in catchments. The largest rivers rarely get beyond eighth order. The Snowy River at Mt Kosciuzko is an example of a first order stream, while the Murrumbidgee River at Wagga Wagga is an example of an eighth order stream.

The implications of stream order

Riparian functions and the influence of the surrounding catchment vary with stream size. As a result of this diversity, optimal management techniques are those that take account of the particular characteristics of the stream concerned.

Stream order and sources of nutrients and pollutants

Collectively, the many small source streams which contribute to a river are longer than the main stem (or trunk) of the river. Because of this, more of the total catchment area drains directly into small streams than into the trunk stream. (Figure 2.2 shows the proportion of the total stream length and catchment area draining over the stream banks for each order stream in a fifth order basin.) Most of the water carried by a source stream comes from local catchment runoff and from shallow groundwater discharging as baseflow into the stream. In contrast, most of the water carried by the trunk stream is fed into the river many kilometres upstream. Consequently, the sources of food, nutrients and pollutants differ between source and trunk streams.

Stream order and in-stream food production

As streams deepen and widen, the influence of stream-side vegetation changes. Along small streams, dense riparian tree and shrub cover can shade the entire stream bed. This lowers temperatures and limits

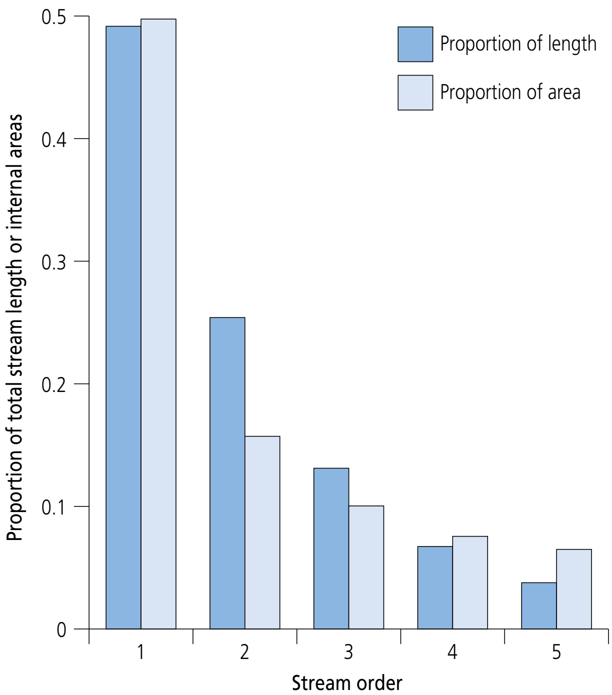


Figure 2.2 Length and area by stream order

aquatic plant growth. In these conditions the primary source of organic matter for stream food webs (leaf litter from either the riparian vegetation or from upstream) is *outside* the stream. As streams widen downstream, more of the stream bed is sunlit. Water temperatures rise and in-stream plant growth is promoted. In these conditions more of the organic matter for stream food webs originates from *in-stream* sources. The vegetative cover of riparian land thus has a greater effect on the water temperatures and food webs of small streams than of rivers.

Stream order and ecosystem function

The downstream flow of water not only influences the movement of aquatic plants and animals but also has a great influence on stream ecosystem function. Streams and rivers are referred to as 'open' ecosystems—nutrients are not cycled in the same manner as they are in lakes and other standing bodies of water, but are spiralled along the river length. As a result, processing of carbon energy and nutrients in headwater streams can influence ecosystem processes downstream. Similarly, contaminants (for example, nutrients, sediment and pesticides) entering headwater streams may affect downstream aquatic communities. Protection of 'receiving' rivers depends, therefore, to a large extent on protection of tributary streams.

Stream order and in-stream vegetation

Flow is more persistent in rivers than in small streams. As a result, vegetation is less able to encroach into river channels than it is into stream channels. The smallest ephemeral streams often have vegetation growing in the bed, whereas in large rivers permanent flow can prevent vegetation from establishing on the toe of the bank, the focal point for erosion.

Stream order and bed material

As the gradient of a stream declines the bed materials become finer. Thus, source streams located in a hilly upper catchment have gravel and cobble beds, while at the mouth of the river mobile beds of silt and sand predominate.

Stream order and bank stability

Streams are often deeper (and banks higher) downstream, with bank depths ranging from less than the rooting depth of trees along small streams to many metres along large rivers. The depth of banks influences their stability. Low banks, associated with small streams, are incapable of mass failure, regardless of vegetation cover. The intermediate-height banks of medium-sized streams can be effectively stabilised by trees. However, the banks of large rivers are often higher than the rooting depth of vegetation. In this case, vegetation can only assist bank stability if it continues down the bank.

Stream order and deposition

Hillsides often drop straight down to small streams. As streams get larger there is more likely to be a small footslope or alluvial fan of deposited soil and an alluvial flat or terrace next to the stream. In large rivers a floodplain forms, and the channel meanders across this. Runoff entering streams with only limited floodplains passes through a fringe of riparian vegetation, which can act as a trap for sediments and nutrients. As alluvial sediments deepen, a substantial portion of runoff passes underneath riparian vegetation and enters the stream as shallow groundwater flow. Floodplains and alluvial flats are depositional landforms, so sediment eroded from hill slopes is less likely to reach the stream. Floodplains and alluvial flats have the effect of distancing the hill slope from direct contact with the stream and have quite distinctive ecosystems.

These variations in the characteristics of streams of different sizes are generalisations and do not apply to all rivers. Significant exceptions are inland-draining rivers, which often become small and ephemeral as they enter the arid zone because flow is lost by evaporation and by seepage into the bed and banks. Some of these systems even split into several *dis*tributaries. Other exceptions are rivers with floodplains which enter a gorge where both the gradient and the size of bed material increase. Here, alluvial deposits disappear and slopes plunge straight into the channel.

The management implications of the differences between streams of different order are summarised in Table 2.1.

Table 2.1 The management implications of stream order

Variable	High in catchment (low order streams)	Low in catchment (high order streams [rivers])	Implications
Source of water	Local catchment runoff and shallow groundwater discharging as baseflow into the stream.	Higher order streams upstream.	The condition of high order streams is partly dependent on that of the low order streams which feed them.
Influence of stream-side vegetation	Vegetation able to influence the shallow, narrow streams.	Vegetation has less influence on deep, wide streams.	Vegetation in the upper reaches of the catchment is more effective in lowering temperatures and limiting growth of nuisance aquatic plants.
Cyclying of nutrients	Nutrients carried downstream, rather than being cycled in situ.	Nutrients and contaminants more likely to be cycled in situ.	The condition of high order streams and aquatic ecosystems is strongly influenced by the input of energy, nutrients and contaminants from upstream.
Flow persistence	May be ephemeral.	Likely to be persistent.	Vegetation less likely to encroach into river channels than into stream channels.
Stabilising impact of vegetation	Vegetation able to stabilise low banks of high order streams.	Stabilisation by vegetation may be limited because banks are higher than the rooting depth of the vegetation.	Stream-bank stablising effect of vegetation decreases downstream.
Deposition	Limited or no footslopes allowing deposition. Sediment and nutrients in runoff trapped only by vegetation.	Floodplains and alluvial fans enable deposition of sediment.	High order streams more protected from deposition of sediment (and associated nutrients and contaminants) by floodplains and alluvial fans; low order streams more protected by vegetation.

2.2 Temporal factors: changes to streams in time

Changes since European settlement

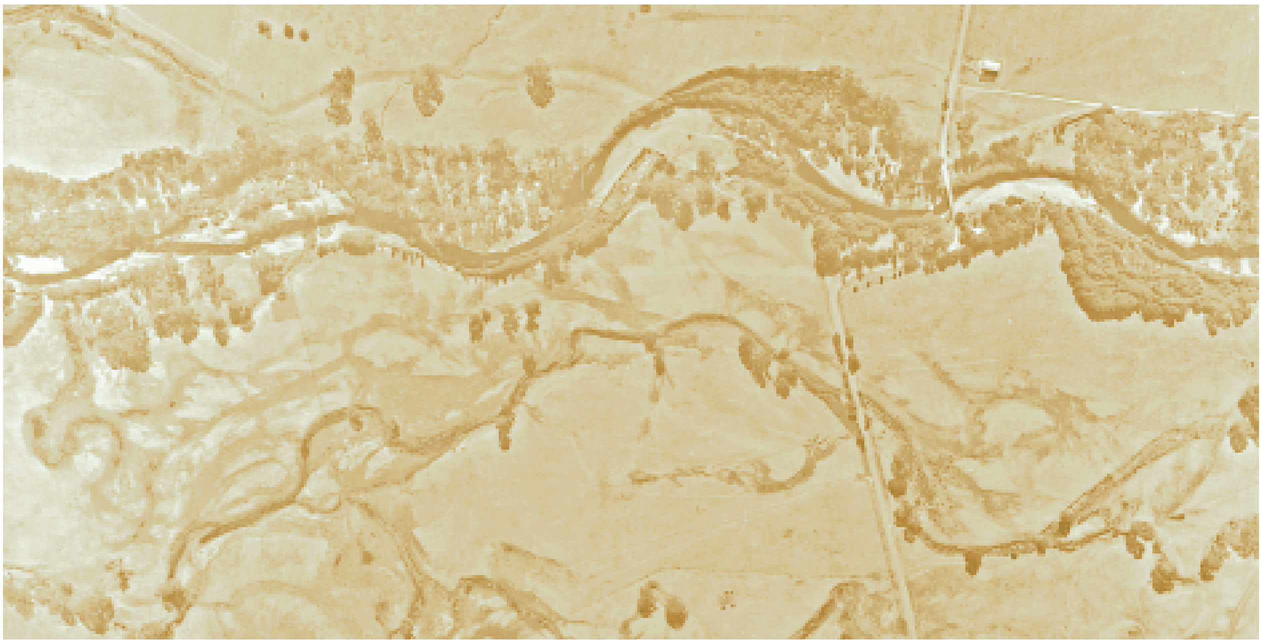
The Australian landscape has changed markedly since the introduction of European land-use practices. The change has dramatically affected stream ecosystems.

In some cases deforestation, clearing for agriculture, grazing and some other management practices have increased the amount of runoff from catchments, leading to larger and flashier flood flows. It should, however, be noted that in many cases this impact is relatively small and flow variation is similar to the natural variation between runs of dry and wet years.

In contrast, rates of erosion and of sediment delivery to streams have increased many times over.

~ Rates of erosion in the Southern Tablelands of New South Wales are now 10 to 20 times greater than they were before European settlement, mainly as a result of increases in gully erosion.
~ Rates of sheet erosion have also increased by an order of magnitude.
~ Rill erosion, now common, was largely absent before the introduction of cropping.
~ Much of the coarser sediment (such as sand) delivered to streams as a result of erosion has choked some streams, while fine-grained sediments have increased turbidity.
~ Removal of floodplain and bank vegetation has caused floodplain scour and massive channel widening on high-energy coastal streams. In many circumstances it has doubled channel width. Many valleys that had small channels with occasional deep pools, or were swampy with no continuous channel at all, now have deeply incised streams. These changes have contributed vast amounts of sediment to streams, destroying aquatic habitat.

Along with sediment loads, the nutrient loads of streams have increased as a result of greater erosion, application of agricultural fertilisers, unlimited stock access to streams, and sewage entering streams. For example, some of the nutrient added as fertiliser leaches through the soil and is transported to streams in shallow groundwater. This process can take several decades, so the full impact of increased rates of fertiliser application will not be seen for many years. Recent research is showing that phosphorus and dissolved organic carbon, as well as nitrogen, can move through some soil profiles without being absorbed. Thus they can completely bypass riparian buffer strips that target surface flow paths and be delivered to streams in groundwater flow. Phosphorus and organic carbon can drive excessive primary production, such as algal blooms, in the same way as nitrogen. Agricultural practices can influence how much phosphorus and dissolved organic carbon enters the groundwater and moves into streams via baseflow. For this reason, agricultural practices need to be carefully considered.



Abandoned old channels on the King River floodplain (north-east Victoria) showing that the channel eroded before the vegetation was cleared. Photo by Ian Rutherfurd.

In the Glenelg River catchment of Victoria extensive gully erosion, and to a lesser extent sheet erosion, has occurred, although it is now on the wane. Notwithstanding, it will take centuries for the eroded sand to clear the channel (Rutherfurd 1996). This is perhaps close to the 'worst case' scenario for management, but it shows that expectations about the success of management projects should incorporate the impact of time lags in the system (see, for example, Vought et al. 1994).

Reversing the impact of these sorts of changes takes much longer than the changes took to occur. It will be many decades before sediments deposited upstream leave the system by way of export from the river mouth, even though the land-use practices that caused the erosion may have ceased some time ago. Gullies can form and rivers can widen in individual storms, but it can take thousands of years for a gully to fill with sediment and decades for a river to contract by way of deposition along its banks.

The geological pick marks a layer of 'slaked' sediments in a gully in the Avoca catchment, western Victoria. Photo by Ian Rutherfurd.

For example, most of the phosphorus entering the Peel–Harvey system in south-western Australia comes from heavily fertilised coastal sandplain soils. Approximately 30% of phosphorus applied each year in fertiliser is lost directly via drainage (McComb & Humphries 1992).

Temporal variability of stream processes

Australia is famed as a land of droughts and flooding rains and, indeed, Australian streams do have very variable flow regimes. In many rivers the 100-year flood is 10 to 20 times greater than the mean annual flood. In comparison, the world average is for the 100-year flood to be only two to four times greater than the annual flood. (The 100-year flood is the largest flood you would expect to experience in a 100-year period; the mean annual flood is the mean of the largest flood you get in a year of record.)

Some rivers, such as those in northern Australia, which are strongly dominated by summer floods, have a strong seasonal regime. Others have highly erratic flows, with runs of several years of drought, during which even large rivers can shrink to a series of stagnant pools. This variability is quite natural and will always continue, but it has several important implications for riparian management.

First, the erosive power of a flow increases disproportionately with its discharge, so 100-year floods or runoff events are extremely powerful agents that help form landscapes. Such floods and runoff events carry the largest quantities of sediment and nutrients. In the past, natural vegetation cover provided a high level of resistance to flows. However, the clearing of vegetation cover has now made streams very sensitive to floods; as a result, a 10-year or similar-sized flood causes catastrophic erosion.

Second, in managing rivers the aim is to 'stabilise' them, or at least slow the rate of major change, by reducing their sensitivity and strengthening them against most flows. The level of protection required is a matter of judgment. For example, the cost and practicality of leaving or creating 'buffer' strips between human activity and streams and rivers will need to be weighed against the potential amount of sediment entering the stream. It is also important to remember that channel erosion is a natural process and rivers cannot be protected against the largest flows.

Management time scales

Stream processes that concern managers occur in time spans ranging from a matter of seconds to centuries. Long-term processes are particularly difficult to manage because human perceptions (and many management activities) are often relatively short-term phenomena. This creates several problems for stream managers.

As discussed, there are significant lags between the release of pollutants and their entry into streams, and the delivery of sediment to streams and its export from the river. Because of this, it may take several years for management solutions that are implemented today to reduce the supply of sediment and nutrients to streams. In some cases, the cause of the problems seen today may no longer exist to any great extent, but the symptoms remain. In other situations, increased problems can be expected in the future as current practices have not yet had their full impact. The slow movement of nitrogen to streams (see Chapter 5) is a pertinent example.

The aim of management is not to reproduce pristine conditions or to prevent any future variability in streams, but to reinstate some stability and sustainability into streams so that they are less sensitive to small floods and capable of recovering from them.

This chapter discusses how streams can be classified according to their size and position in the catchment and the impact of time on Australian streams. Both spatial and temporal factors have implications for stream management. Chapter 3 continues this exploration of stream processes by investigating the relationship between riparian vegetation and temperature and light.

Current research

Patterns of sediment delivery, riparian topography and stream order

This work is designed to describe how patterns of sediment delivery and riparian topography vary with stream order, so that places in the landscape in greatest need of buffer strips can be identified.

Researchers: Ian Prosser and Chris Moran, CSIRO Division of Land and Water

The relationships between bank stability, bank geometry and optimal placement of trees to prevent bank failure

This research will help identify the points along a river where bank strengthening by trees will have the greatest ability to prevent bank failure.

Researchers: Bruce Abernethy and Ian Rutherfurd, Monash University

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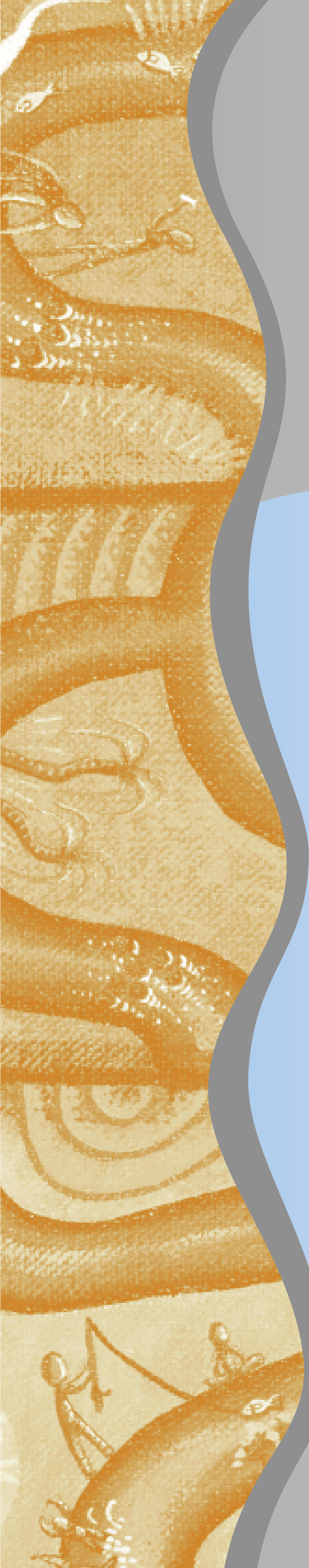


CHAPTER 3

Temperature and light

Stuart Bunn, Thorsten Mosisch, Peter M. Davies

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 channel because the growth of most aquatic plants is limited by light availability.
- Stream temperature can directly influence the growth and development of aquatic plants and animals.
- Increases in light and temperature resulting from changes to riparian shading can lead to dramatic changes in the distribution and abundance of aquatic organisms and in-stream productivity, and can result in an overall decline in stream health.
- 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.

3.1 Water temperature

Riparian vegetation is very effective in moderating stream temperatures. For example, research in the wet tropics of Australia has found that cleared stream sites were 3–5°C warmer than nearby forested stream sites and the daily fluctuation in temperature was three times greater (Bunn & Davies, unpublished data). In Tasmania, water temperatures of streams in logged sites were found to be higher than those of streams in adjacent forest sites, particularly where riparian vegetation buffer strips were less than 30 m wide (Davies & Nelson 1994). (For a more detailed description of the relationship between riparian shading and stream temperatures, see Collier et al. [1995b].) Similarly, summer daily maxima for streams in New Zealand were found to be 4–10°C higher in small open streams than they were in forested streams (see Figure 3.1).

Temperature can influence the structure and dynamics of aquatic plant and animal communities.

~ The growth and development of most aquatic organisms (such as algae, invertebrates, fish, reptiles and amphibians) are, in part, temperature dependent.
~ Egg hatching, larval development and other components of animal life cycles are often triggered by temperature.
~ Some aquatic plants and animals have specific temperature requirements.
~ Dissolved oxygen concentrations decrease as temperature increases; such decreases may limit plant and animal life.

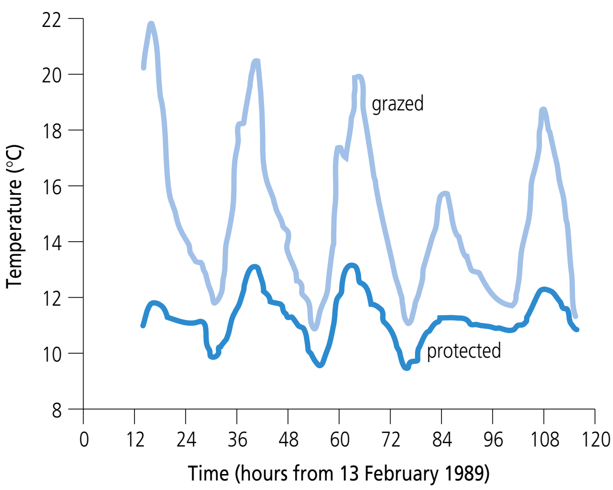


Figure 3.1 Temperature of cleared vs uncleared streams

Diurnal temperature variations in a riparian protected reach of a small southland stream (catchment are 3.3 km^2) and a more open, riparian grazed and channelised reach 2.4 km downstream.

Source: Quinn et al. (1992).

- Increased water temperatures elevate rates of bacterial breakdown of organic matter and increase oxygen consumption, further reducing dissolved oxygen levels.
- In the case of aquatic algae, temperature sets the maximum potential for primary production in streams, when other factors such as light and nutrients do not limit primary production (DeNicola 1996).

Most stream-dwelling animals are cold-blooded and their basic metabolic processes increase with increasing temperature. For aquatic insects, which dominate the fauna of most streams, increased water temperatures can

- accelerate larval development (Vannote & Sweeney 1980);
- influence egg development, timing of hatching, and emergence of adults (Hynes 1970);
- result in premature emergence of adults, perhaps at times when climatic conditions in the terrestrial environment are unsuitable for adult survival or when few mates from adjacent forested sites are present;
- lead to a reduction in fecundity because larvae mature at smaller sizes in warmer water and smaller insects produce fewer eggs (Vannote & Sweeney 1980).

The effect of temperature on the life-cycles of other aquatic invertebrates is also important. 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).

The rate at which 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). Water temperatures also trigger migration, spawning, egg development and hatching of many fish species (Sloane 1984, Cadwallader & Lawrence 1990, Gehrke 1994).

Temperature is also thought to influence the broad taxonomic composition of aquatic algal assemblages (that is, what type of algae will occur and in what proportions), although each species may have its own optimum and range. Diatoms (for example, the benthic forms in our 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. 1995a). However, little similar information is available for Australia. Nevertheless, it is known that larval lampreys (ammocoetes) will die at or above 28.3°C. This accounts for their distribution being restricted to Australia's southernmost streams (Macey & Potter 1978). Despite the lack of specific data, it is known that when water temperature varies more than normal the composition of the ecosystem is altered.

The solubility of oxygen in water decreases as temperature increases. For example, the dissolved oxygen concentration of freshwater (at sea level) at 15°C is 10.1 mg/l but only 8.3 mg/l at 25°C. Raised water temperatures can lead to further reductions in dissolved oxygen because at higher temperatures the metabolic rates (and thus the oxygen consumption) of organisms increase. The consequences of these processes are sometimes compounded in disturbed streams by the high respiration of aquatic plants. The combined effect may be the death of fish and other fully aquatic animals (Hynes 1970, Bunn & Davies 1992, Townsend et al. 1992).

These findings demonstrate that water temperature is a key determinant of water quality and aquatic habitat condition and, thus, is an important consideration in riparian management.

3.2 Light

Aquatic plants need sunlight in order to photosynthesise. During photosynthesis, inorganic carbon (CO_2) is transformed into carbohydrates, in a reaction described by the 'photosynthetic equation', by which (in highly simplified form)

$$6CO_2 + 6H_2O \underset{}{\overset{\text{Light}}{\rightleftharpoons}} C_6H_{12}O_6 + 6O_2$$

carbon dioxide + water ⇌ sugars + oxygen

primary production →

← respiration

Primary production is the rate at which light energy is converted to organic carbon. Respiration is the opposite process. 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. Obviously, light plays an essential role in the process of photosynthesis. As such, it is another factor which needs to be considered in riparian management decisions.

The distribution and production of aquatic plants in stream systems can be affected by a number of factors, but light availability is clearly one of 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 of macrophytes (Canfield Jr & Hoyer 1988).

Light requirements vary for different plant groups and there is evidence that light intensity is a major factor determining the composition of stream algal assemblages (Hill 1996)—see Table 3.1. For example, it has been established that chlorophytes (green algae) require higher light intensities than do diatoms (Langdon 1988). In a review of published minimum and maximum growth irradiances of phytoplankton groups, it was concluded that cyanobacteria and diatoms were able to tolerate lower light intensities than were chlorophytes (Richardson et al. 1983). The filamentous chlorophyte *Spirogyra* requires 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*) were found to be 'unusually common' in clear-cut forest streams (Lyford & Gregory 1975, Shortreed & Stockner 1983). It is thought that under conditions of high irradiance, filamentous chlorophytes play an important part in the productivity of stream systems.

From the point of view of stream function, micro-algae such as diatoms are more readily eaten by organisms higher up the food chain than are larger plants such as filamentous algae and macrophytes. Lower light (caused by shade or turbidity) and lower water temperatures enhance the production of palatable food material (see Chapter 4). 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.

Research has found that algal communities in non-shaded stream channels can have chlorophyll and biomass values four to five times higher than those at fully shaded sites (Lowe et al. 1986, Hill & Knight 1988). Shading of the stream channel is also a significant factor controlling the distribution and abundance of water plants. For example, standing crops of macrophytes increase significantly at sites where the forest canopy coverage is less than 50% (Canfield & Hoyer 1988). Shading alone was found to control highly invasive macrophytes which had choked the channels of open streams in the tropical canelands of far north Queensland (Bunn et al. 1998).

Table 3.1 Irradiance levels for different algal groups and taxa

Group/taxon	Irradiance ($\mu mol\ m^{-2}\ s^{-1}$)	
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]	1 100	
Spirogyra[c]	1 500	
Mougeotia[c]	330–2 330	

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

It is worth noting here that riparian shading may not be the only factor limiting light availability in some streams and rivers. Turbidity may be another. 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 feature. Recent work on 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*) (Bunn & Davies 1998). The vertical distribution of this layer is clearly light-limited in the highly turbid water.

The foregoing discussion demonstrates that variations in productivity and composition of aquatic plant groups, which are partly caused by light availability, can lead to dramatic changes in the 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. The implications of these changes in aquatic plant communities are considered in Chapter 4 and in Guideline B, 'Managing snags and large woody debris'.

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, latitude and season.

Research has shown that 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). Stream algae and macrophytes can be significantly restricted by a dense canopy of overhanging riparian vegetation.

Perhaps the most obvious factor determining the effectiveness of riparian shading is stream channel size. Moving through the stream hierarchy (see Chapter 2), the shading effect of riparian vegetation decreases as the stream channel widens. This effect is obvious in the relationship between stream channel width and canopy cover, using a uniform tree height and width (see Figures 3.2 and 3.3).

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 path of the sun (see Figure 3.4). In addition to seasonal (or long-term) variations in incident sunlight, benthic stream communities can

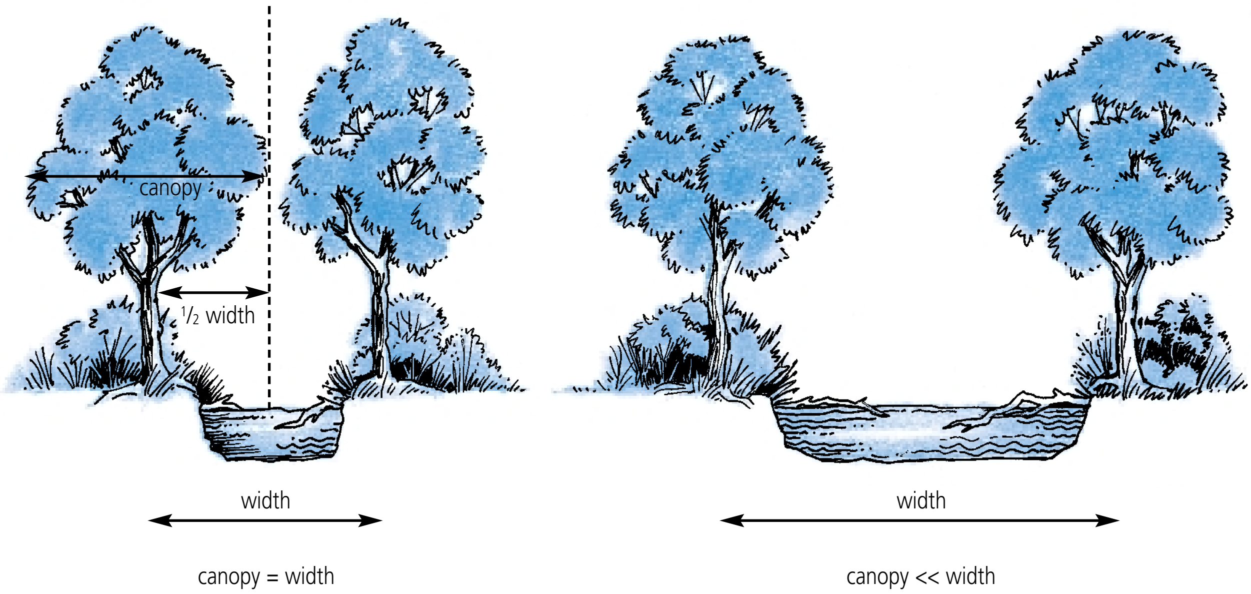


Figure 3.2 Influence of channel width on cover

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).

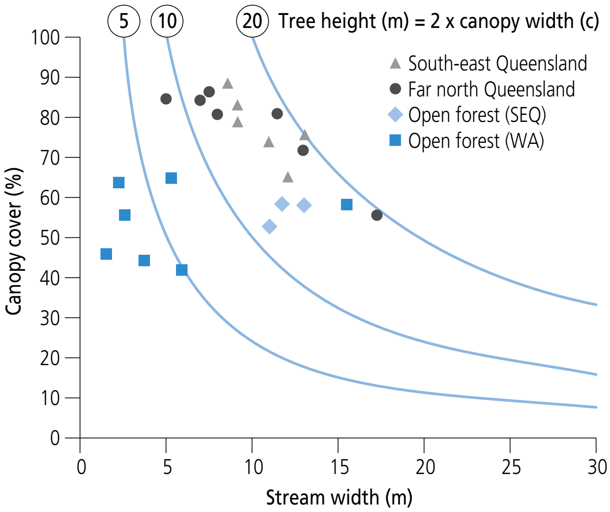


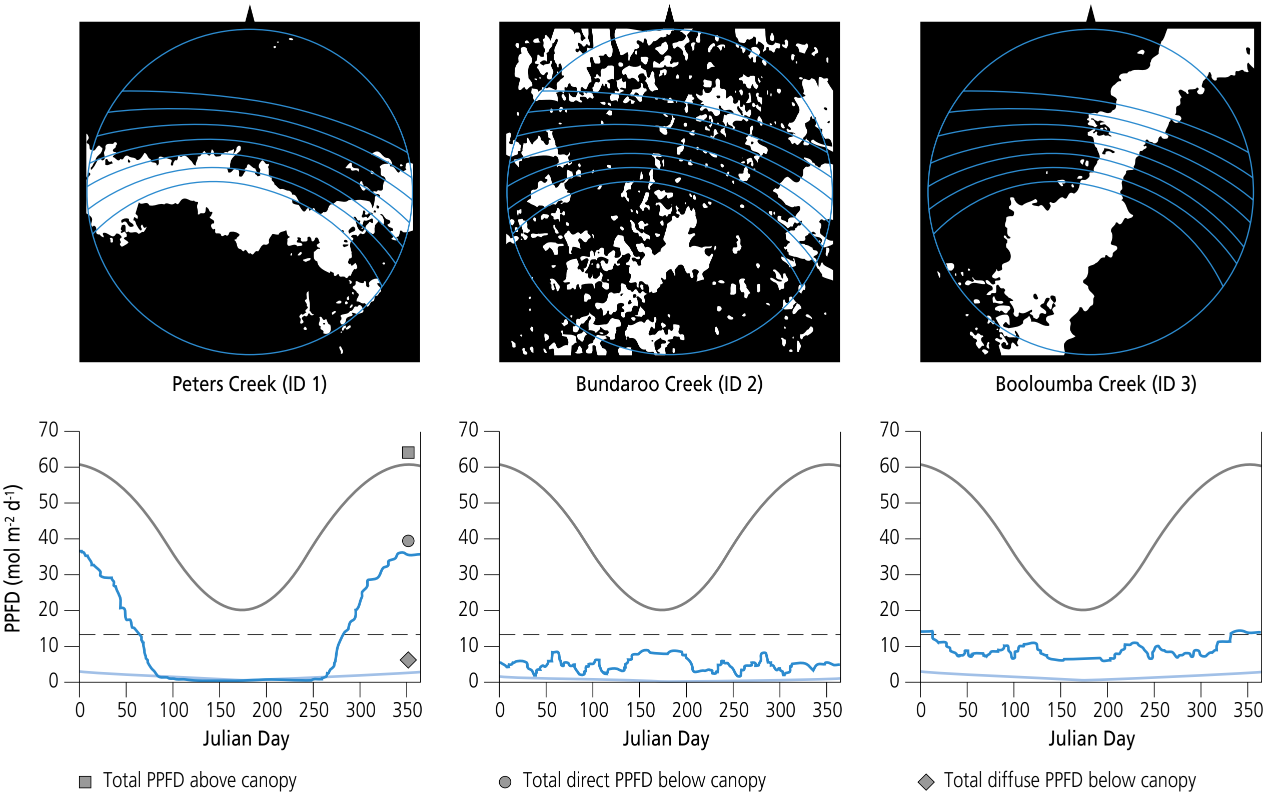
Figure 3.3 Influence of tree height on cover

Effectiveness of riparian vegetation as a function of stream width for different heights of riparian cover is shown in the graph. The three lines assume that tree height is twice that of the canopy width and that 100% cover is possible when the canopies are closed (that is, with dense foliage and no gaps).

The solid circles and triangles are actual canopy cover measurements for undisturbed forest streams in tropical and subtropical rainforest, respectively. Other symbols are for open woodland sites in south-east Queensland and south-western Australia. (Note that even the smallest of these streams is not heavily shaded by riparian vegetation.)

It can be seen that even in small, densely-forested streams canopy cover rarely reaches 100% because of gaps in the canopy. In dry sclerophyll forest streams, such as those in the northern jarrah forest in south-western Australia, the canopy cover is considerably less than it is in rainforests.

Source: Unpublished data, T. Mosisch (1997).



Canopy cover: 75%
Catchment area: 13.95 km^2
Channel width: 13 m

Canopy cover: 73%
Catchment area: 5.45 km^2
Channel width: 11 m

Canopy cover: 74%
Catchment area: 10.89 km^2
Channel width: 13 m

Figure 3.4 Canopy photos and light intensities of forest streams showing effect of orientation in south-east Queensland (Mary River)

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. It is worth noting that below-canopy light levels during this time are well below the know threshold levels for filamentous green algae of PPFD = 12.8 mol m^{-2} d^{-1} (indicated by the broken line in Figure 3.3). 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).

also be subjected to short-term variations in irradiance; for example, through sun-flecks in a stream channel shaded by dense riparian vegetation (Hill 1996).

Even though factors such as orientation can have a local effect, canopy cover alone explains most of the variation in below-canopy light regime (Bunn et al. 1999). In south-east Queensland, 75% canopy cover would be required to reduce below-canopy light intensities to below the thresholds required for 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 a greater filtering effect in the infra-red/red end of the solar spectrum, which is responsible for most of the heating of surface water.

Even in situations where the main part of a wide stream channel does not receive any shade at all, 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 at least part of the day (Hill 1996). In this way, riparian vegetation may still 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 approximately 8–10 m wide or less. This translates to sub-catchments of approximately 8–10 km^2 or less. Note that these relationships will vary with latitude and riparian vegetation density. At higher latitudes (for example, southern Victoria and Tasmania) the canopy cover required to prevent excessive growths of filamentous algae would be less than this because of the lower intensity of incoming solar radiation.

In more open forest, effective shading (75% cover) may be achieved only in smaller streams. While effective shading can only be achieved in these smaller streams, it is worth remembering that most of the catchment area is associated with such streams rather than with big rivers.

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 is therefore an important consideration in the management of riparian areas.

Current research

Predictive relationships between riparian cover and in-stream primary productivity

These are being developed for small streams in south-east Queensland, south-western Australia and the wet tropics in order to provide information on how best to manage riparian vegetation for the purposes of controlling the nature and extent of primary production in streams. Preliminary data for the Mary River in south-east Queensland confirm that canopy cover and, to a lesser extent, percentage of the catchment cleared explain much of the variation in ecosystem function among streams.

Researchers: Stuart Bunn, Peter M. Davies, Thorsten Mosisch

The relative importance of shade and nutrients for the growth of stream algae

This research, which is being conducted via field studies in south-east Queensland and in artificial stream channels in Tasmania, aims to provide managers with further information about the extent to which shade and nutrients influence stream algae.

Researchers: Stuart Bunn, Peter M. Davies, Thorsten Mosisch, Peter E. Davies

The relationship between riparian shading and stream temperatures

Models developed for New Zealand streams are to be tested in several focus catchments in Australia to determine the applicability of the New Zealand models to local conditions.

Researchers: Stuart Bunn, Peter M. Davies, Thorsten Mosisch

The role of riparian shading in influencing the distribution, composition and production of aquatic algae in turbid rivers

The role of riparian shading is currently being studied in highly turbid rivers of the channel country of western Queensland because, in these uniquely Australian environments, natural turbidity may be as important as, or more important, than shading in controlling light.

Researchers: Stuart Bunn, Peter M. Davies, Thorsten Mosisch

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CHAPTER 4

Aquatic food webs

Stuart Bunn, Peter M. Davies, Peter Negus, Simon Treadwell

Summary

- Organic matter from aquatic and terrestrial sources supplies the carbon energy which 'drives' aquatic food webs.
- Most forest streams are heterotrophic—that is, they rely on external sources of carbon energy to contribute to food webs. The reliance of larger rivers on external sources of carbon energy is less clear. However, only a small proportion of total carbon present in streams 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 large woody debris, although other sources such as coarse-particulate organic matter, fine-particulate organic matter and dissolved organic matter are more likely to directly enter aquatic food webs.
- Benthic micro-algae can play an important role in aquatic food webs in some forest streams, whereas macrophytes in larger rivers appear to contribute very little.
- Large woody debris is an important substrate for algal colonisation.
- Riparian fruits and arthropods may be an important food source for fish and other vertebrates in some forest streams.
- Riparian vegetation regulates in-stream primary production and supplies energy and nutrients; its removal can radically change the quality and quantity of energy in food webs and the function of aquatic ecosystems.

CHAPTER 4

Carbon is the principal building block of all living tissue and the fundamental element that drives ecological systems. Understanding the flux of organic carbon (that is, the input to and movement of energy) in streams and rivers is, thus, essential to the sustainable management of riverine environments as healthy and natural ecosystems. This is especially important because human activities result in considerable changes to the global carbon cycle.

4.1 Sources of organic carbon for aquatic food webs

Aquatic and terrestrial organic matter supply the carbon energy needed to drive aquatic food webs, especially in smaller, shaded streams where in-stream productivity is low. Aquatic insects, as well as non-insect species, are the major consumers of organic matter and represent much of the biodiversity, abundance and biomass of animals in streams and rivers (Bunn 1992). In turn, these smaller animals are essential elements of the food web which supports predatory invertebrates, fish and other aquatic vertebrates and terrestrial and semi-aquatic consumers in the riparian zone (see Chapter 9).

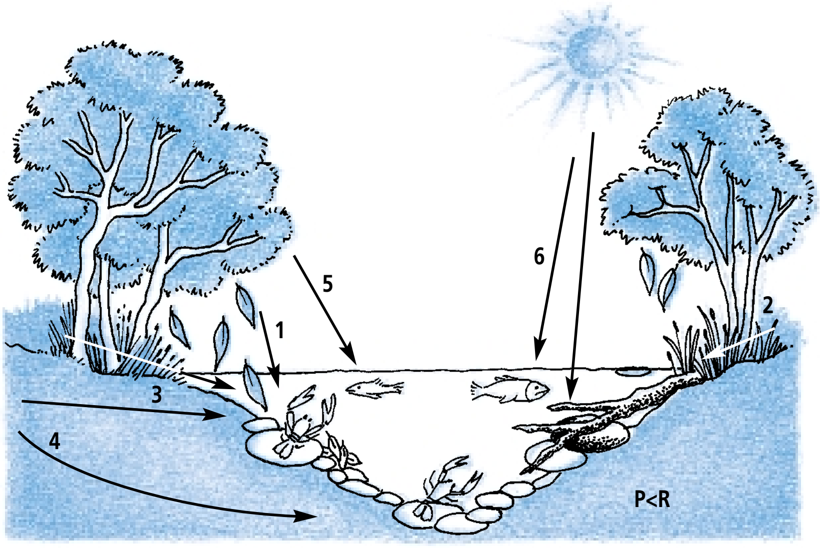
Knowing the sources and fate of organic matter in streams and rivers is central to understanding how riverine environments function as natural ecosystems (see, for example, Arthington et al. 1996, Robertson et al. 1996). Such information is required by managers if ecological processes and the biodiversity of stream and river ecosystems are to be sustained and enhanced.

Sources in small streams

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

- logs, branches and other large woody debris (LWD) or snags, primarily as direct inputs from riparian vegetation;
- litter (leaves, bark, and so on) and coarse-particulate organic matter (CPOM), as direct inputs from riparian vegetation or washed or blown in from elsewhere in the catchment;
- fine-particulate organic matter (FPOM);
- dissolved organic matter (DOM).

Leaves usually make up the greatest proportion of litter, although bark, branches and fruits may contribute significantly in some forest types (Briggs & Maher 1983, Campbell et al. 1992, Lake 1995). Other



1. Inputs of leaf litter (CPOM) from riparian vegetation
2. Inputs of logs and branches (important habitat role)
3. Leaves and fine particles of organic matter (FPOM) washed in from surrounding catchment
4. Dissolved organic matter (DOM) in sub-surface flow and groundwater
5. Terrestrial invertebrates falling from riparian vegetation
6. Microalgae (for example, diatoms) and other aquatic plants (for example, emergent and submerged macrophytes, filamentous algae) stimulated by sunlight. Primary production is low compared with respiration (P<R).

Figure 4.1 Sources of carbon and energy inputs to streams
Source: S. Bunn (1998).

riparian inputs, such as insects and fruits, can also be important sources of carbon for in-stream consumers.

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. Nevertheless, litter fall in the dry eucalypt forests is less than that in the wetter forests (Pressland 1982, Lake 1995, Benfield 1997).

A large proportion of the total carbon pool in many streams and rivers is in the form of large woody debris. This is because LWD usually moves and decomposes slowly compared with other carbon sources and so remains in situ for longer. In aquatic ecosystems, decomposition of woody material contributes significantly to the supplies of DOM (Cummins et al. 1983) and FPOM (Ward & Aumen 1986). These are readily transported in the water column and provide food for many aquatic organisms. The supply of DOM and FPOM from decaying snags in the stream may be one of the most significant sources of organic matter in large rivers which have been isolated from organic matter inputs by river regulation or floodplain clearing. Given the longevity of LWD, particularly of species such as river red gum, LWD's role as a sustained source of DOM and FPOM cannot be discounted and removal of snags from these rivers may have significant long-term negative impacts on the supply of organic carbon.

FPOM in streams is derived from a number of sources, including the processing of CPOM and LWD, riparian soil particles, flocculated DOM, and algal production (Ward 1986). The relative contributions of these sources to the FPOM pool is 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). 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 (see, for example, Trotter 1990 and Chapter 5).

Autotrophic and heterotrophic aquatic systems

Input of carbon from land sources (that is, allochthonous carbon) is often greater in amount than inputs of carbon produced from aquatic plants within the stream channel. Thus, it represents a major source of energy for invertebrates and other stream animals (Bunn 1986, 1993; Cummins 1993).

Where more organic carbon is consumed and respired than is produced by aquatic plants, forest stream ecosystems are described as heterotrophic—that is, they are dependent on external sources of carbon energy (much of which comes from riparian land). In simple terms, this occurs when respiration (R) exceeds gross primary production (P) and P:R ratios are less than one. In this regard, forest streams function in a very different way from many other aquatic ecosystems such as lakes and oceans, which are autotrophic (that is, where P:R ratios are greater than one).

Whether primary production is seen as a 'good' or a 'bad' thing depends on the type of production. In general, diatoms and some cyanobacteria are significant contributors to the food chain, whereas the larger plants, such as macrophytes and filamentous algae, contribute less.

Most of the small forest streams studied to date in Australia appear to be heterotrophic. 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 quite low by world standards (Lamberti & Steinman 1997) and it is likely that the poor nutrient status of soils across much of the Australian continent is also a contributing factor.

Terrestrial (land-sourced) inputs can also be an important source of carbon in streams in arid or sparsely wooded catchments (Boulton 1988). However, here the more open riparian canopy diminishes the controlling influence on in-stream primary production (shade) and the contributions of in-stream sources of carbon are likely to be greater than in similar-sized streams in forested catchments (Minshall 1978, 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). Similar high values would be expected for some arid zone streams where algal production is not limited by turbidity. Desert streams in other continents clearly have much higher values of gross primary production and higher P:R ratios than their forest stream counterparts (Lamberti & Steinman 1997).

Sources in large rivers

The sources of carbon and their quality and quantity change according to the position in the stream hierarchy (see Chapter 2). This is partly because with movement downstream the direct (lateral) contributions of carbon from riparian vegetation decrease relative to inputs from upstream processes, and partly because downstream the increased channel dimensions reduce the extent to which vegetation regulates instream primary production (see Figure 4.2).

Models of large river ecosystems

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 inputs to larger rivers is less well known. Three major models have been proposed to describe the function of these larger, 'receiving' rivers.

The River Continuum Concept (RCC) (Vannote et al. 1980) emphasises the importance to the lower river reaches of carbon and nutrients 'leaking' from upstream processes. In this model the 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 insignificant in larger river reaches, where in-stream primary production may also be limited by turbidity and depth.

More recent studies have emphasised the importance of flood-driven pulses of organic matter from riparian sources (other than those derived from up-stream processes) to the function of some large (floodplain) rivers (Junk et al. 1989). This Flood Pulse Concept (FPC) model emphasises the important river–floodplain interactions and suggests that riverine food webs are driven by production within the floodplain rather than by downstream transport. Inundation of floodplains also promotes microbial activity and decomposition of litter on the forest floor (Malanson 1993, Molles et al. 1995).

A further theory for carbon fluxes in some large rivers is the Riverine Productivity Model (Thorp & Delong 1994). This model emphasises the importance of local autochthonous production (phytoplankton, benthic algae and other aquatic plants) and of direct inputs (CPOM, FPOM and DOM) from adjacent riparian land. It has been argued that the RCC and FPC models have underestimated the role of local sources and have overemphasised the transport of organic matter from headwater streams (RCC) or floodplains (FPC) (Thorp & Delong 1994).

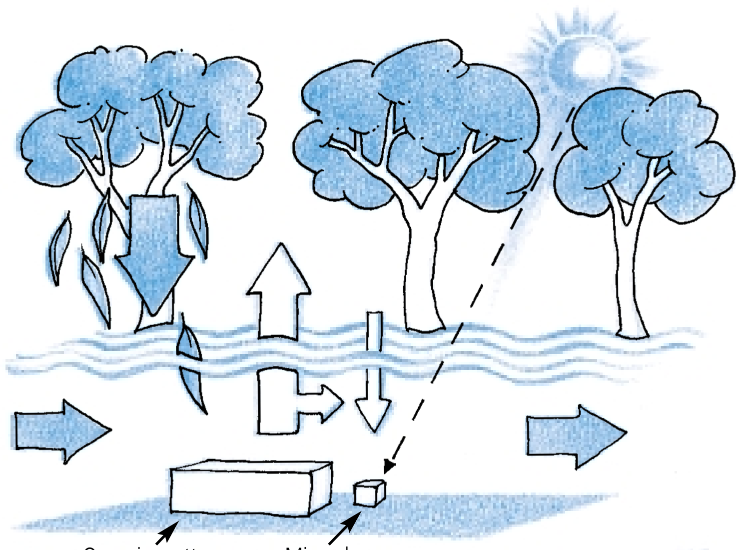


Figure 4.2(a) Food webs in an undisturbed stream

The large 'box' represents inputs of terrestrial organic matter (from direct litter fall or upstream—as per arrows); the small box represents a small pool of available (but highly nutritious) microalgae (such as diatoms). Terrestrial organic matter and microalgae are the major sources of organic carbon that drive food webs in forest streams. The size of the boxes indicates that there is a lot of terrestrial organic matter available in the system, compared with microalgae. However, microalgae can play a disproportionately important role in the food web.

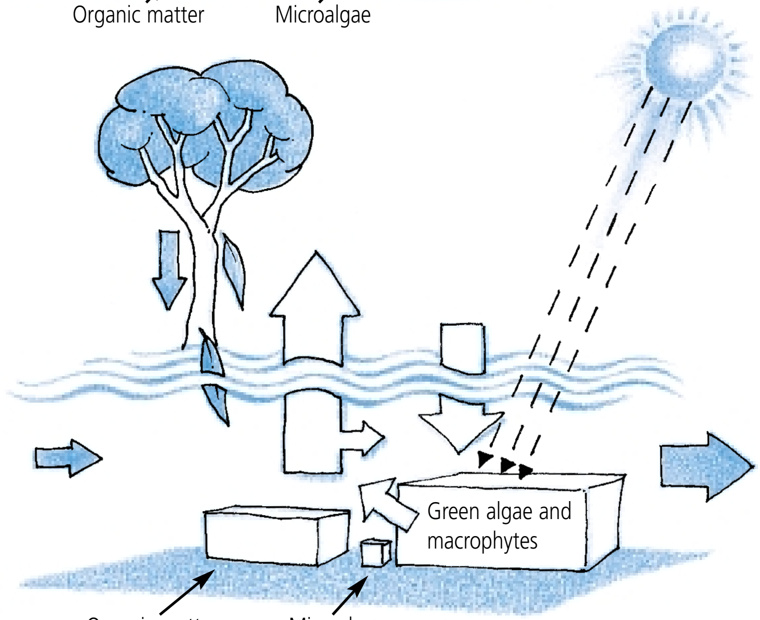


Figure 4.2(b) Food webs in a stream disturbed by riparian clearing

In the absence of riparian shading (and increased nutrients) there are lower inputs of terrestrial organic matter but, more importantly, the in-stream production is shifted to larger (less palatable) plants such as filamentous green algae and macrophytes.

These three models of how large river ecosystems function differ considerably in their emphasis of the strength of direct riparian linkages and much work is needed to identify which one (or combination) best describes key processes in large rivers (see Bunn et al. 1998). Without this understanding, it will not be possible to predict the consequences of changes to lateral and longitudinal exchanges of energy and nutrients resulting, for example, from river regulation or changes in land use. Nor will it be possible to identify an appropriate strategy for restoration.

Availability and quality of carbon

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 nature 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 chain. 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.

It is apparent that understanding stream and river food webs requires identification of the sources of organic carbon that are assimilated by metazoan consumers and so contribute to the food chain. This difficult task has been made simpler with the advent of stable-isotope tracing techniques (Rounick & Winterbourn 1982, Peterson & Fry 1987). Multiple stable–isotope analysis in particular offers a powerful alternative approach to the traditional methods of assessing food resources used by consumers.

4.2 Food webs

Food webs in small streams

There is considerable evidence that food webs in small 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, Lake 1995). However, it is often not clear which of the major components of terrestrial carbon (CPOM, FPOM or DOM) is most important.

Woody debris forms a substrate and carbon source for aquatic bacteria, fungi and some specialised invertebrates, all of which contribute to the decomposition of LWD in streams. Although fungal biomass on LWD can be high (Sinsabaugh et al. 1991), bacteria and actinomycetes are probably the major decomposers of LWD 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 entering stream food webs in the northern hemisphere (Cummins 1974). However, shredders seem to be poorly represented in 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

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, Rounick & Winterbourn 1986, Peterson & Fry 1987, Rosenfeld & Roff 1992, Boon & Bunn 1994).

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).

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). Preliminary 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 Oppossum 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 (Bunn, unpublished data).

Few comparable data are available for food webs in semi-arid or woodland streams, where the riparian canopy is naturally open.

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, the fact that there is very little evidence of assimilation of terrestrial carbon in coastal food webs (Haines & Montague 1979, Peterson et al. 1985) suggests that much of the particulate organic matter carried by larger rivers is of poor quality for aquatic consumers. Presumably, primary consumers in these large rivers also feed on sources of carbon (such as benthic or plankton microalgae) which are more palatable than the refractile (low nutrient value) riparian particles carried many kilometres from their headwater source.

Stable isotope analysis of the food web in permanent waterholes on the Cooper Creek system in central Queensland suggests that many of the larger consumers, including freshwater prawns (*Macrobrachium*), crayfish (*Cherax*) and fish (for example, *Macquaria ambigua*—yellowbelly) are ultimately dependent on a narrow littoral band of highly productive benthic cyanobacteria (Bunn et al. 1999). Although the wide channels have little direct riparian cover, this is a surprising result as the algae are clearly limited by high water turbidity and the highly anastomosing channel system and extensive floodplain offer considerable potential for riparian inputs of organic matter. Further work is currently in progress on riparian–stream linkages in these unusual floodplain river systems.

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 debris 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 snags 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). Snags also reduce shear stress due to high current velocities, resulting in increased primary production rates (Davies 1994).

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). 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 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).

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 are overhanging vegetation and numerous bank eddies. Similar conditions can be found at the margins of larger streams where overhanging vegetation and large woody debris cause eddies (Cloe III & 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

Ficus racemosa or Cluster Fig, whose fruit may be eaten by turtles and fish. Photo by Simon O'Donnell.

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 III & Garman 1996) and riparian vegetation type (Cadwallader et al. 1980, Mason & MacDonald 1982).

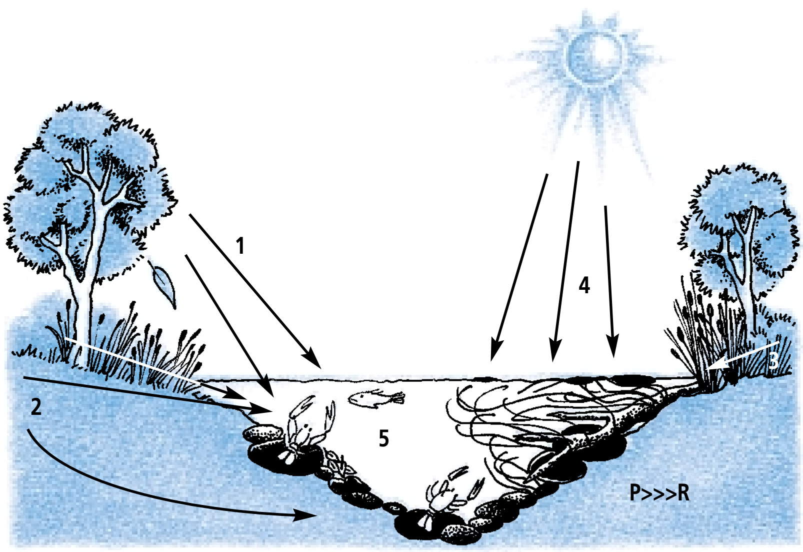
4.3 Consequences of riparian clearing for stream ecosystem function

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. 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 3.1) and are most likely to proliferate in the absence of riparian shade.

The large vascular plants and filamentous algae which 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).

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 4.3 and Chapter 7).

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 'unconsumable' plant biomass (carbon) that ultimately leads to water quality problems, loss of habitat, and major declines in stream ecosystem health and biodiversity.



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.

Figure 4.3 Effect of removal of riparian cover
Source: S. Bunn (1998).

Current research

Sources of organic carbon in aquatic food webs

Multiple stable–isotope analysis is being used to identify which sources of organic carbon are important for aquatic food webs across a range of different stream and river systems. Once these are identified work will focus on the environmental factors (for example, light and nutrients) that influence the distribution and abundance (availability) of important sources. This information will assist in the management of streams.

Researchers: Stuart Bunn, Peter M. Davies, Michelle Winning, Thorsten Mosisch

Identification of important ecosystem processes in larger rivers and arid zones

While much of the previous work has focused on small coastal forest streams, research currently under way aims at identifying these important ecosystem processes in larger rivers and particularly streams and rivers in more arid regions. This research will lead to an understanding of how strongly these systems are linked to their riparian zones.

Researchers: Stuart Bunn, Peter M. Davies, Michelle Winning, James Udy

What tropical fish eat

A detailed study of the diets of tropical fish in streams with different riparian land use is currently under way. This aims to determine the importance of riparian inputs of arthropods and fruits to fish diets.

Researchers: Peter Negus, Stuart Bunn, Brad Pusey

Riparian revegetation and ecosystem function

Monitoring of aquatic food webs and ecosystem function in disturbed streams in the wet tropics is currently under way to determine the rate of recovery following riparian revegetation.

Researchers: Peter Davies, Stuart Bunn, James Udy, Thorsten Mosisch

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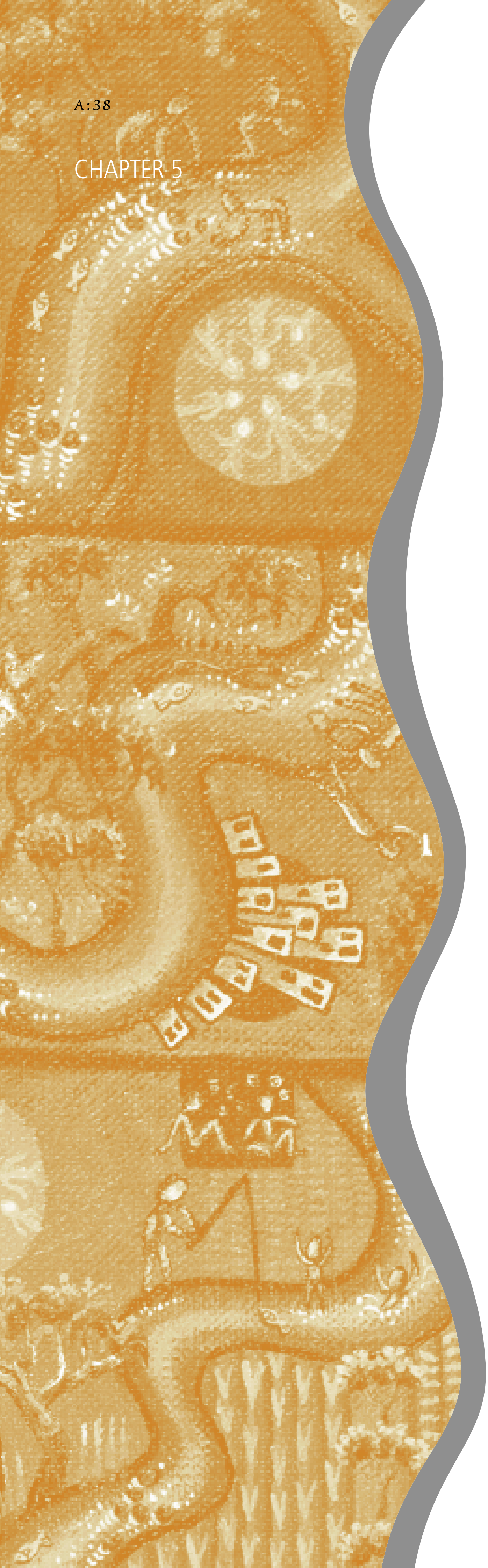
CHAPTER 5

The delivery of sediment and nutrients to streams

Ian Prosser, Stuart Bunn, Thorsten Mosisch, Ralph Ogden, Linda Karssies

Summary

- ~ The supply of sediment and nutrients to Australian streams has increased since European settlement, largely as a result of land-use practices, particularly the clearing of native vegetation.
- ~ Increased sediment and nutrients in streams can lead to loss of habitat, smothering of stream life, scouring, turbidity, and changes to the composition of aquatic flora and fauna communities.
- ~ The main sources of sediment and nutrients are hillslope erosion, stream-bank and gully erosion, and groundwater. The most significant nutrients are phosphorus and nitrogen.
- ~ Riparian land and vegetation protect streams from influxes of sediment and nutrients carried in runoff from the catchment. They do this by storing runoff, trapping sediment and transforming nutrients.



5.1 Sediment, nutrients and riparian land

Sediment and nutrients are transported from hillslopes to streams by way of runoff. Riparian land protects streams from the influxes of such sediment and nutrients. In this way riparian land contributes to water quality. The protection mechanism arises for three reasons.

~ Riparian land generally has lower gradients, which reduce the velocity of runoff, limit its ability to carry sediment eroded from upslope, and cause this sediment to be deposited.

~ The dense vegetation cover associated with riparian land reduces the velocity of runoff, promoting its infiltration into the soil and, again, causing sediment to be deposited.

~ Moist, organic riparian soils and vigorous vegetation transform and absorb nutrients dissolved in shallow groundwaters.

As a result, riparian land stores sediment and nutrients delivered from upslope (see Figure 5.1). Without such storage, all transported sediment and nutrient would enter streams.

Sediment and nutrient delivery are inseparable because much of the nutrient delivered to streams is attached to sediment particles, particularly clay particles. The main nutrients of concern in stream water are phosphorus and nitrogen. All organisms require these nutrients for growth. However, in excess

Several factors have increased the supply of sediment and nutrients to streams in many agricultural catchments. These include

~ clearing of native vegetation within catchments followed by intensive cropping and grazing, which has led to dramatically increased erosion rates;

~ leaching and eroding of some of the nutrients applied in fertiliser from the soil;

~ clearing of riparian vegetation, which has reduced the sediment-trapping efficiency of riparian land, destabilised stream banks and led to accelerated channel erosion;

~ continuation of cropping up to the stream bank and unlimited stock access, both of which have brought bare soil and higher nutrient loads into close proximity with streams and rivers.

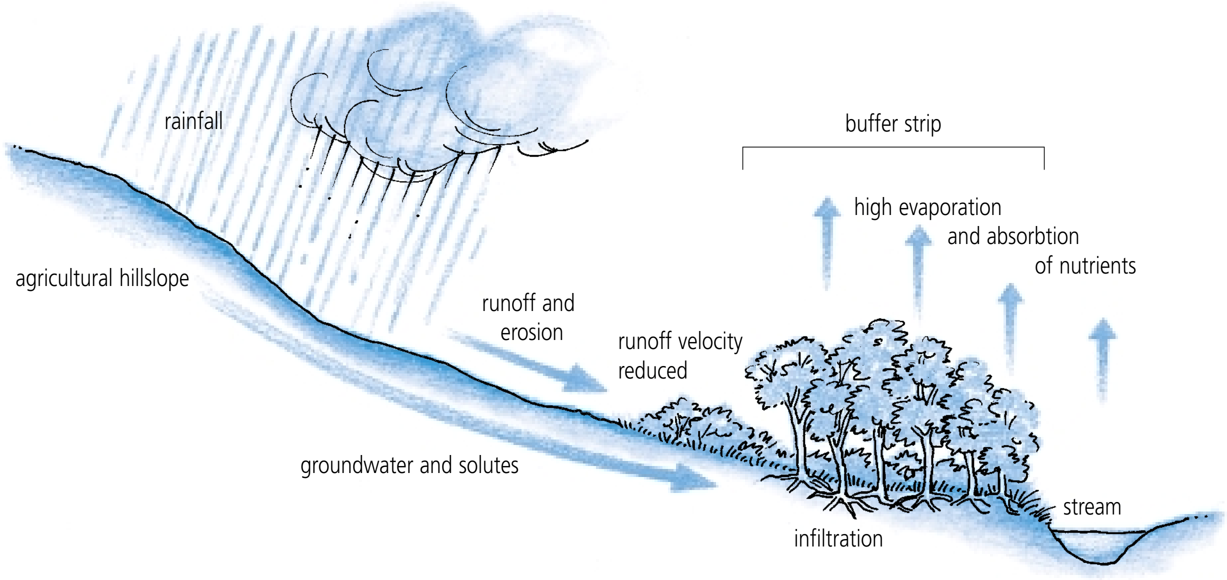


Figure 5.1 Overall concept of the functions of a riparian buffer zone

quantities they can lead to the occurrence of some organisms (such as algae and macrophytes) reaching nuisance levels. Excess delivery of sediment to streams also has a direct impact on aquatic ecosystems in that it increases turbidity and smothers benthic habitat.

The combination of these factors means that more sediment and nutrient passes from hillslopes to riparian land and streams than is the case under natural conditions. In many circumstances, riparian land is now a source of sediment and nutrient, rather than a store of such material. However, it is important to note that erosion of agricultural land is only one source of sediment and nutrients in streams. In many cases, erosion of unstable stream banks themselves delivers more sediment and nutrient to streams than does erosion of hillslopes. In other cases, nutrients are transported primarily as dissolved ions (solutes) carried by shallow groundwater into streams.

Effective riparian management can restore and improve the capacity of riparian land to trap sediment and nutrients and thus improve water quality. Riparian management can also help reduce the delivery of sediment and nutrients from channel erosion and groundwater flow. Nevertheless, the design of riparian management strategies will differ markedly from strategies for managing overland flow, reflecting the particular hydrological processes and the many functions of vegetation.

Before considering the sources of sediment and nutrients, the effect sediment and nutrients can have on in-stream ecosystems and how these vary with the form of nutrient is examined.

5.2 Ecological impacts of sediment and nutrients

Ecological impacts of sediment

Increased sediment can adversely affect aquatic fauna in a number of ways. In Australia, stream sedimentation is considered a major river health problem (Campbell & Doeg 1989). In the United States, it is considered the largest single pollutant (by weight) of rivers.

Gross loss of habitat

Sedimentation of streams reduces the complexity of benthic habitat at macro and micro scales. As waterholes and pools become filled with sediment, deeper refuges for fish and other vertebrates are lost. At a finer scale, sediment fills in the spaces between particles in the stream bed that are used by benthic invertebrates and fish (Bresven & Prather 1974, Ryan 1991). Substrates blanketed with fine sediment can become anoxic (Lemly 1982, McClelland & Bresven 1980, Findlay 1995). This leads to the release of heavy metals and nutrients, with related water quality problems (Bourg & Loch 1995, Forstner 1995).

An extreme example of the gross effects of accumulated sediment occurs in some lowland streams in the canelands of far north Queensland. It has been estimated that approximately 20 000 tonnes of inorganic sediment had accumulated per kilometre of stream channel in Bamboo Creek, near Innisfail. Oxygen penetration was limited to a depth of a few millimetres and few benthic invertebrates were recorded.


Sediment accumulation and consequent smothering of Bamboo Creek, near Innisfail (Queensland). Invasion of an introduced ponded pasture grass (*Brachiaria mutica*) has led to accumulation of organic rich sediments (up to 2 m deep). Photographs show experiments designed to assess the impact of shade on riparian vegetation. Photos by Ian Prosser.

Smothering of stream life

Accumulated sediment also reduces the hatching success of eggs and the survival of larvae of some fish species. For example, salmon populations on the United States west coast have plummeted during recent years, due predominantly to sedimentation caused by logging activities (Mestel 1993). This sediment smothers spawning grounds and eggs and prevents the emergence of hatched fry (Palfrey & Bradley 1991). Studies conducted in the area have revealed that a 2 mm layer of sediment was sufficient to kill all white perch eggs, while a 0.5–1 mm layer killed more than 50%.

Smothering of leaf litter and of other benthic organic matter by sediment may also have a deleterious impact on detritivores (Cummins et al. 1980, Webster & Waide 1982, Bunn 1988) because the high respiration rates of buried organic matter can reduce the level of dissolved oxygen in the stream (for example, Bunn et al. 1997). Reduction in dissolved oxygen levels can also occur in open water beyond the stream if suspended sediment particles are transported along with organic materials (Guy & Ferguson 1970). This demonstrates that the problem is not localised.

Suspended sediment also clogs the fine respiratory membranes of fish gills and the delicate filaments of invertebrate gills, causing cellular damage and interfering with normal gaseous exchange (Ryan 1991). Some species of fish and invertebrates may be killed by silt clogging their gills (Berkman & Rabeni 1987, Ryan 1991).

Scouring effects of stream sediments

The high-velocity movement of coarse sediment particles in suspension can dislodge benthic animals and reduce the biomass of algal food resources for invertebrate consumers (Cordone & Kelley 1961; Lewis 1973a, 1973b; Nuttall 1972). Passive filter feeders, such as blackfly larvae and net-spinning caddis larvae, can be killed as their guts fill with indigestible silt.

Turbidity

Suspended sediment interferes with light penetration and thus directly affects processes such as photosynthesis and the feeding efficiency of visual predators such as fish and waterbirds. High turbidity also prevents the establishment, survival and growth of periphyton (Cordone & Kelley 1961, Nuttall 1972) and can inhibit fish growth and reproduction (Palfrey & Bradley 1991).

It is worth noting, however, that some Australian streams and rivers are naturally turbid (see Section 3.2).

Ecological impacts of nutrients

Essential plant nutrients

The growth, abundance, distribution and composition of algal assemblages (and other aquatic plant communities) are influenced by many biological and physical factors. These factors include nutrient availability, light, flow regime, grazer abundance, water pH and water temperature (see Chapters 3 and 4). A change in any of these factors can affect primary production of algal communities and can also lead to changes in the species composition of algal assemblages. However, shade and nutrients appear to be the most important factors that limit algal growth in streams (see, for example, Hill & Knight 1988).

Nutrient limitation significantly controls the growth and composition of periphyton assemblages in streams (Hill & Knight 1988, Keithan et al. 1988, Winterbourn 1990) because the growth of algae (and

The most important nutrients affecting primary production and determining algal assemblage composition and algal distribution are nitrogen and phosphorus. Nitrogen plays a significant role in protein synthesis and photosynthesis and is sourced mainly in the form of nitrates. Ammonium salts and organic nitrogenous compounds are further sources of nitrogen, as is the fixation of free nitrogen by some members of the Cyanophyta (blue–green algae). Phosphorus is important in general algal metabolism and nutrition.

thus other elements of the ecosystem) depends on the availability of macronutrients (carbon, nitrogen, phosphorus, sulphur, potassium and magnesium) and of micronutrients and trace elements (calcium, iron, manganese, zinc, copper, molybdenum, silica, cobalt and sodium).

The uptake of inorganic nutrients is a critical factor in the growth and reproduction of aquatic algae, with either nitrogen or phosphorus often the limiting element (Boyle 1984). Consequently, these two elements are the nutrients which have been most frequently researched (Borchardt 1996). Nutrient uptake and growth rates of algae are affected by light availability and temperature. Algae often require an increased supply of nutrients when light and temperature conditions are not at favourable levels (Borchardt 1996). The capacity of algae to store particular nutrients is also important. For example, algal cells have little storage capacity for carbon, whereas their storage capacity for phosphorus is great (Borchardt 1996).

As water moves, the rates at which periphyton take up nitrogen and phosphorus increase (see Borchardt 1996). Exposure of algae to heavy metals (such as lead, zinc, copper and cadmium) may stimulate the uptake of phosphorus (Boyle 1984). However, during extended periods of low stream flow, de-nitrification can reduce the nitrogen supply in the water and nitrogen limitation may occur (Lohman et al. 1991).

‘Available’ and ‘unavailable’ nitrogen and phosphorus

In addition to their respective chemical forms, two broad fractions of nitrogen and phosphorus are recognised. The first is that portion of a nitrogen (or phosphorus) compound that can be absorbed and incorporated into plant or bacteria. This portion is deemed ‘bioavailable’. The second is that portion which cannot be utilised *directly* by the biota. This portion is deemed biologically unavailable. The bioavailability of nutrients is usually determined by reference to their availability to algae. The portion of phosphorus that is thought to be bioavailable is often termed ‘reactive phosphorus’.

The bioavailability of a nutrient compound depends on the biota and the time frame considered. Bacteria can use a broad range of different nutrient compounds; algae and higher plants can use a narrower range. Animals obtain their nutrients by eating plants or bacteria.

Tests for nutrient bioavailability apply more to fast-flowing streams than to lakes, dams or lowland river floodplains. In fast-flowing streams the residence time of nutrients that are not immediately bioavailable is short, so non-bioavailable nutrients have little chance of being made bioavailable by release from sediment storage, by microbial activity or by chemical transformation. This is especially so in large (but still relatively frequent) flow events, when most nutrient load is transported. As the flow of water slows, the residence time of unavailable nutrient fractions increases and the possibility that they will be converted to available forms of nutrients increases.

Phosphorus is present in streams as

~ dissolved phosphate (PO_4^{3-}, HPO_4^{2-} and $H_2PO_4^-$; all also termed orthophosphate);
~ dissolved polyphosphate (found in detergents);
~ phosphorus in dissolved and particulate organic compounds;
~ phosphate adsorbed to silts, clays, organic matter, and iron compounds in suspension or in bottom sediments (Cooke 1988).

It is important to recognise the difference between nutrient loading and nutrient concentration. Nutrient loading has units of gN or P/m²/day and is therefore a measure of the rate of supply of a nutrient. Nutrient concentration is merely the amount of nutrient in the water at any particular time. Although loading and concentration are often correlated, nutrients may be in low concentrations because of rapid biological uptake rather than because of a low rate of supply.

Use of phosphorus and nitrogen by aquatic plants

Aquatic plants preferentially use orthophosphate, although this is usually in low concentrations because it is strongly adsorbed to sediments. (Streams with fine sediments store phosphorus in quantities which far exceed the amount required by organisms.) When dissolved orthophosphate is absorbed by plants, phosphorus attached to sediment at the sediment–water surface can dissolve into the water column, restoring the chemical equilibrium between the phosphorus in water and that attached to sediment. The dissolution of phosphorus into the water column increases under anaerobic conditions, such as those that occur at the base of stagnant water bodies. It is possible that this mechanism of phosphorus release is important for algal blooms, which occur during low-flow periods. Phosphorus delivered to streams in a dissolved form, from detergents, sewage or groundwater, is quickly bound to sediment in streams that are turbid or have clayey banks and beds. Some aquatic organisms are able to produce compounds that effectively unlock bound phosphorus, making it bioavailable.

As a result of these mechanisms, the proportion of total phosphorus in streams that is bioavailable is quite variable. For example, it was estimated that at different times in the upper Murray and Ovens Rivers between 20% and 90% of total phosphorus was bioavailable. In addition, 5–80% of the phosphorus adsorbed to particles, even though particle-adsorbed phosphorus is at times thought not to be available (Oliver et al. 1993).

In terrestrial and aquatic ecosystems nitrogen is most commonly present as nitrate (NO_3^-), as ammonia (NH_3, which in water becomes ammonium, NH_4^+) and as $-NH_2$ molecules incorporated in organic matter (see Table 5.1).

Ammonia is the preferred form of nitrogen for aquatic plants (Golterman 1997). Ammonia may be present in appreciable amounts in aquatic zones low in oxygen. However, in well oxygenated water it is oxidised to nitrate. Nitrate is the dominant form of dissolved inorganic nitrogen in rivers and is the second most preferred form of nitrogen for biota after ammonia (Golterman 1997). Organic nitrogen is not bioavailable unless it is decomposed and the nitrogen released as ammonia or nitrate. Particulate organic nitrogen makes up, on average, over 50% of the total nitrogen transported in rivers (see Table 5.1).

Generally, a low ambient nitrogen:phosphorous ratio (less than 10:1) indicates that the system is nitrogen limited, while a high N:P ratio (over 20:1) indicates phosphorus limitation (Schanz & Juon 1983, Pringle et al. 1986). In the case of ratios between 10:1 and 20:1, either of the two elements could be limiting (Schanz & Juon 1983).

Geography appears to play a role in determining whether nitrogen or phosphorus is limiting algal growth in streams and rivers. For example, in the United States streams in the east which drain forested watersheds have been found to be phosphorus limited, while those in the Pacific north-west are predominantly nitrogen limited. Phosphorus limitation of periphyton growth has also been reported from the mid-west, northern Canada and arctic Alaska (Pringle et al. 1986). In a New Zealand stream periphyton assemblages were both nitrogen and phosphorus limited (Winterbourn 1990). Experimental evidence from a nutrient enrichment and shading experiment in a headwater pasture stream in the Mary River catchment, south-east Queensland, suggests that periphyton growth in this stream may be limited by nitrogen and not phosphorus (Mosisch & Bunn, unpublished data). Similar reports of nitrogen limitation have been made for the freshwater sections of the lower Brisbane River (W. Dennison, University of Queensland, pers. comm.).

Algal growth can be controlled not only by the limiting nutrient but also by physical factors. For example, algae are broken up in turbulent flow; the impoundment of rivers has produced large areas of still water which are very suitable for algal growth.

5.3 Consequences of nutrient enrichment

The overall nutrient status of catchments is a major determinant of in-stream primary production. Given the low nutrient status of many Australian catchments, primary production in undisturbed streams would be expected to be low. This appears to be the case in subtropical and tropical rainforest streams in eastern Australia (Bunn et al. 1999). It is also most apparent in the dry sclerophyll forest streams of south-western Australia, which have some of the lowest levels of net primary production recorded for any stream (Bunn & Davies 1990, Davies 1994). This history of low nutrient status and associated poor representation of truly herbivorous fish may be why nutrient enrichment of Australian streams leads to such prolific growths of filamentous algae, macrophytes and/or blue–green algae (Bunn & Davies, in preparation).

Table 5.1 Typical concentrations of nutrients in streams and rivers and fractions of nitrogen measured by various common assays

	Natural streams: temperate	Natural streams: tropical	Natural rivers: temperate	Natural rivers: tropical	Rivers draining cities and agricultural regions
Concentration of P (mg/l)					
Orthophosphate (PO_4^{3-})	0.0007–0.015	0.005–0.019	0.007–0.011	0.002–0.024	0.004–2.475
Total dissolved P	0.0040–0.069		0.015–0.055	0.008–0.060	0.044–1.860
Particulate P, as % of total, for a variety of rivers					
Organic	–	–	38	–	–
Total			95		
Concentration of N (mg/l):					
Dissolved N:					
Nitrate (NO_3^-)	0.003–0.44	0.098–0.150	0.060–0.212	0.025–0.240	0.082–10.10
Nitrite (NO_2^-)	0.002	0.001–0.003		0.001–0.003	0.005–0.20
Ammonium (NH_4^-)	0.011–0.14	0.060		0.007–0.040	<0.010–8.40
Organic N (R-NH_2):	0.056–0.16				0.416–1.49
Particulate organic N (PON), as % of dissolved and PON, for a variety of rivers					
	–	–	59	–	–

Measurement of nitrogen	
Fraction	*Term*
Dissolved organic DON and NH_4^-	Kjeldahl N
NO_2^-, NO_3^-, NH_4^-	dissolved inorganic N (DIN)
NO_2^-, NO_3^-, NH_4^-, DON	total dissolved N

The number of streams and rivers used to derive values of concentration varies considerably between compounds and classes. Total particulate nitrogen has not been estimated, so the % contribution of this fraction cannot be evaluated. However, particulate organic N (PON) is thought to predominate over NH_4 and organic N adsorbed to suspended sediments in river waters, so PON should not underestimate total particulate nitrogen by much.

Source: Prosser & Hairsine (1995).

Nutrient enrichment in streams results from a number of different activities, including runoff from dairies and feedlots, nutrient inputs through other agricultural activities (for example, fertiliser runoff and irrigation drainages), deforestation, cattle access to streams, and removal or degradation of riparian vegetation.

If there is insufficient light, nutrient enrichment will have little effect on algal growth (Hill & Knight 1988, Winterbourn 1990). However, in unshaded or lightly shaded streams, low nutrient availability (particularly of nitrogen, phosphorus, carbon and/or micronutrients) plays a significant role in limiting primary production (Peterson et al. 1983, Pringle et al. 1986, Winterbourn 1990).

The species composition of an algal assemblage can alter as a result of changes in the nutrient availability. For example, as a stream becomes enriched with nitrogen and phosphorus, growth rates of blue–green algae are likely to increase; indeed, these algae are likely to become the dominant algal group under these conditions. Shifts in dominant algal groups (for example, from Chlorophyta to Cyanophyta) can result from changes in the nutrient-uptake ability of various algal species.

High rates of nitrogen fixation by blue–green algae and the algae's consequent growth frequently result in degraded water quality (Boyle 1984). High levels of nitrogen and phosphorus combined with sufficient sunlight frequently lead to abundant growth of filamentous green algae such as *Cladophora glomerata* and *Stigeoclonium tenue* (Borchardt 1996). While the effect of phosphorus enrichment on the composition of benthic stream algal communities is less predictable, an increase in phosphorus levels will frequently lead to a phytoplankton community in which nitrogen-fixing blue–green algae dominate (Borchardt 1996).

5.4 Sources of sediment and nutrients

Hillslope (or surface wash) erosion has traditionally been regarded as the dominant source of sediment and nutrients entering streams. However, evidence is now emerging that in many Australian environments the contribution from either stream-bank erosion or inputs from groundwater is greater.

In isolated circumstances, concentrated point sources (such as unsealed roads, feedlots and sewage treatment works) may also be significant sources of sediment and nutrients in streams.

The circumstances that determine which source dominates are a matter of debate, but some of the conditions that lead to high delivery of sediment and nutrients by each process are known and are discussed below. Importantly, quite different pathways exist for phosphorus and nitrogen.

Hillslope erosion

Overland flow erodes sediment from hillslopes as diffuse surface wash erosion and when flow is more concentrated as rill erosion. Rills are small, often ephemeral channels that form in cropland and on unsealed roads after intense rains. The significance of rill and surface wash erosion to in-stream water quality is controlled by two factors:

~ the intensity of erosion;
~ how much of the eroded sediment actually reaches streams as opposed to being deposited downslope before reaching them.

The intensity of hillslope erosion on agricultural land is determined by the intensity of rainfall, the rate of overland flow, and the availability of sediment to be transported by those flows. This last factor is influenced by, for example, soil type, ground cover and intensity of soil disturbance.

Sediment is loosened from the soil primarily by the impact of raindrops on the surface. The bigger the raindrops and the greater the rainfall intensity, the more sediment is removed. Thus the summer storms and rainfall characteristics of northern Australia are much more erosive than the winter rainfall or the relatively gentle rains of southern Australia.

Much of the impact of raindrops is absorbed by ground-cover vegetation. Once ground cover exceeds 70%, the impact of raindrops is relatively insignificant (see Figure 5.2).

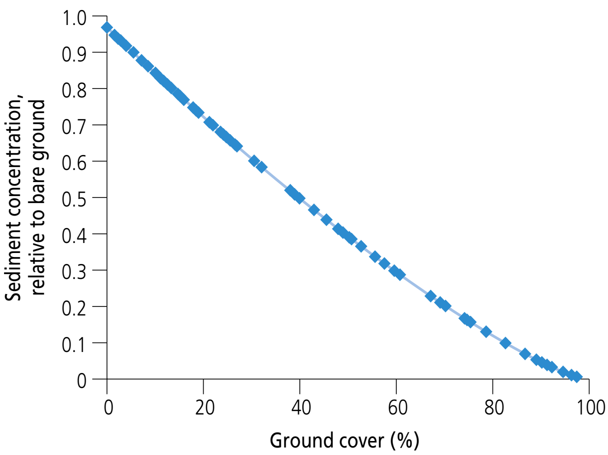
A 70% ground cover is provided by native ground cover vegetation, good pasture or dense cereal crops. The greatest amounts of sediment are generated from bare, freshly tilled soils. Trees are less effective in reducing raindrop impact because drops falling from the high canopies of trees are often as erosive as direct rainfall. The impact of raindrops also causes surface sealing. This sealing increases both the amount of runoff and the removal of entrained sediment.

Traditional tillage leads to the greatest intensity of hillslope erosion because the soil structure is broken down by machinery. Minimum tillage practices greatly reduce soil loss by improving soil structure and retaining a protective cover of stubble on the surface.

Erosion rates increase with hillslope gradient because the velocity of overland flow is greater and because there is a greater tendency for the flow to coalesce into a few streamlines. Soils which are dispersable or weakly aggregated are most prone to erosion because they are readily broken into small particles and because their surfaces seal easily when bare.

Figure 5.3 shows the rates of soil loss from hillslopes in a range of environments. It shows that rates of erosion are highest on bare soil and lowest on pastures. Indeed, the rate of erosion can approach zero on well-maintained pastures.

Figure 5.2 Relationship between ground vegetation cover and sediment concentration



Source: Prosser & Hairsine (1995).

Flume studies have shown that when slope decreases flow velocity decreases and the capacity of the flow to transport sediment falls. Thus deposition occurs in places where there is a change of slope—for example, where a footslope meets a floodplain or on the lower part of a concave slope (Lu et al. 1989, Govers 1990).

Sediment and nutrients generated by overland flow will be delivered to streams only if the overland flow continues all the way to streams. Runoff often commences in agricultural paddocks because the disturbed soils have low infiltration rates. This runoff may flow downslope onto a footslope, an alluvial fan or an alluvial valley flat. These areas tend to have low gradients, high infiltration rates, and thick soils capable of storing large volumes of runoff. As runoff is often generated by short, intense storms it is possible for all of this runoff to be absorbed by the alluvial flat or footslope. If all the runoff is absorbed no sediment or nutrients reach the stream.

A reduction in runoff volume will lead to shallower and slower overland flow and a reduced capacity for the flow to transport sediment. In such cases at least the coarse fraction of sediment will be deposited. Absorption of runoff is high when the rate of runoff generation is low. The rate of runoff generation can be slowed by good on-farm management techniques (such as minimum tillage) and by natural spurs, ridges and alluvial fans, where flow naturally spreads out.

In the case of large rivers, the river channel itself is often separated from the surrounding hillslopes by extensive floodplains, alluvial fans and terraces. Diffuse overland flow will not reach these rivers unless the river is in full flood across the floodplain, and even then the velocity of flood waters is usually low enough for deposition to occur. These factors explain why floodplains build up and why they have very fertile soils.

Overland flow has little chance of being absorbed in areas where runoff naturally converges, such as hillslope hollows and small depressions. This is especially so where water tables are relatively high and where there is rapid lateral throughflow of water in the soil. Under these circumstances, the water table will rise to the surface during a storm, saturate the soil and generate more runoff than occurs on agricultural areas upslope. Sediment and nutrient delivery in these areas is reduced by the lower velocity of flows rather than by the lower amounts of runoff.

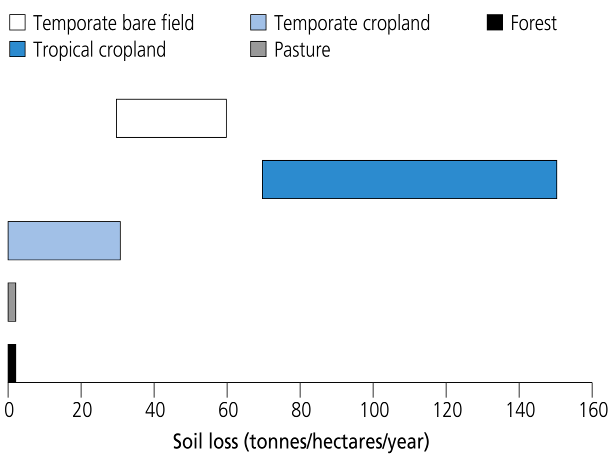
Erosion and trapping of nutrients

So far, this chapter has discussed the transport of sediment by overland flow, and it has been implied that the sediment has nutrients attached to it, so that sediment trapping automatically results in nutrient trapping. The relationship between nutrient erosion and trapping, however, is complex.

Phosphorus is preferentially adsorbed to clay particles because, although these are small particles, they have a high surface area capable of adsorbing a high amount of nutrient per mass. Sand particles have a relatively low surface area and little electrostatic charge, so will not adsorb phosphorus unless the sand is coated in oxides or organic matter (Sharpley 1980) (see Figure 5.4).

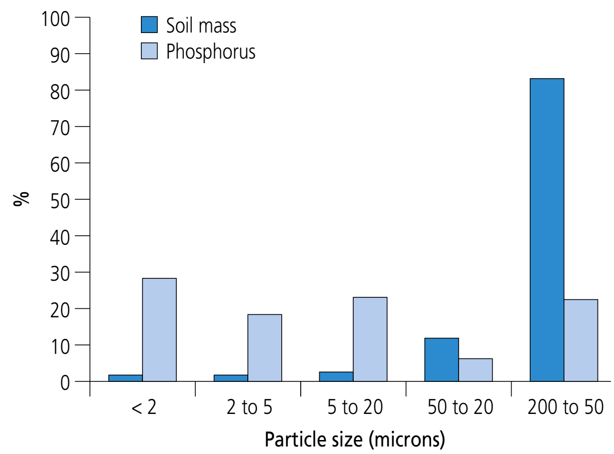
The situation is similar for nitrogen. However, nitrogen is not strongly adsorbed to mineral sediment and, when associated with sediment, is predominantly

Figure 5.3 Rate of soil loss under different landuses



Source: Prosser & Winchester (1996).

Figure 5.4 Soil mass and phosphorous distribution with particle size



Source: Sharpley (1980).

found as a constituent of soil organic matter. Organic colloids are similar to clay particles in that they are small, low-density particles that can be transported very easily by overland flow (Rose & Dalal 1988).

It is this preferential association of nutrients with clays and organic matter that makes nutrients harder to trap than sediment.

Runoff will preferentially transport clays and organic matter because they are easily eroded. As a result, these elements are more easily transported than coarser particles and so much of this fine sediment is not trapped but continues to make its way to the stream. The preferential transport of fine particles is facilitated by the tendency of clays and organic matter to aggregate into large particles, often the size of sand grains or larger but with lower density. If the aggregates are stable under the impact of rainfall and if they are saturated, considerable runoff will be required to transport these particles and they will be deposited more easily when flow velocities fall. Because of these factors, nutrient delivery rates to streams can be similar to sediment delivery rates. However, if clays and organic matter are poorly aggregated, nutrients are more easily transported and are very difficult to trap.

Stream-bank and gully erosion

Prior to European settlement, the larger rivers in Australia were often fringed with dense vegetation and the channel itself was thick with woody debris. This vegetation has now been cleared and the woody debris removed, leaving bare banks prone to slumping and scour. The introduction of agriculture resulted in the dramatic expansion of channel networks (Eyles 1977). At the time of European settlement many valleys in temperate areas were poorly drained, contained swampy vegetation and had no continuous channel—or, at most, a narrow, shallow, tightly meandering channel that was very inefficient at transporting sediment. These same places now contain deeply incised gullies, some over 10 m deep and 30 m wide. The gullies and incised channels have steep bare banks that in many cases continue to erode.

The change in the size of the gullies alone indicates the amount of sediment that has been delivered downstream from this erosion. On the Southern Tablelands of New South Wales, the volume of material removed is equivalent to 100 tonnes/hectare/year. Much of it is removed early in gully formation (Prosser & Winchester 1996)—see Table 5.2. Such rates are much greater than rates of hillslope erosion in the

Table 5.2 Sediment yields from gullies in south-eastern Australia

Location	Date of initiation	Sediment volume (m^3)	Period	Number of years	Drainage	Sediment yield ($m^3km^{-2}y^{-1}$)
Bombala	1988	560	1988–93	5	0.035	3 200[a]
Bombala	1988	740	1988–93	5	0.057	2 600[a]
Bathurst			1983–86	3	1.2	705[b]
Wellington	1920s		1982–84	2	2.9	221[b]
Canberra			1966–87	21	0.08–4.3	11–555[b]
Jerrabomberra Creek, ACT	1823–45		1960–87	27	80	118[b]
Fernances Creek, Hunter Valley	1831–67	190 000	1867–1983	116	14	116[a]
Bango Creek, Yass	<1900	16 000	1915–61	46	3.87	90[a]
Wangrah Creek, Cooma	1842–1900	330 000	1842–1944	102	45	72[a]
Gilgandra			1949–61	12	0.45	47[b]
Gilgandra			1972–84	12	0.45	19[b]
Gilgandra			1978–83	5	0.45	9.4[b]

Source: Prosser & Winchester (1996).

a. Calculated as sediment volume/number of years/drainage.

b. Calculated by direct measurement.

Map of locations in Table 5.2

pastures of this landscape—see Figure 5.3. Much of the sediment eroded from hillslopes in this region does not reach streams because it is trapped in the broad valley flats and alluvial fans.

The bulk of gully formation occurred in the first few decades after settlement and most gully expansion is now complete in south-east Australia (Prosser & Winchester 1996). However, in many places gullies continue to degrade water quality because their steep, bare banks often expose highly erodible soil. Indeed, one of the major concerns now being faced by managers is the fact that gullies contribute sediment and nutrients to creeks and rivers downstream.

Four main factors make gullies a more intense source of sediment and nutrient than hillslopes.

~ Gullies occur where flow converges and they are prone to much more erosive flows than the diffuse flows which occur on hillslopes.
~ Gully walls are steep and bare and susceptible to seepage and other processes that generate large quantities of loose sediment.
~ Gullies expose the subsoil material, which is generally more erodible than topsoil materials. This is a particular problem in areas of sodic soils where the subsoil is dispersive and the transport of disassociated clay particles generates turbid waters.
~ Importantly, gullies deliver water downstream as concentrated channel flow. Unless the channel bed is densely vegetated with wetland species, there are very few opportunities for much of the sediment to be deposited once the flow is channelised. Only where gullies occur high on the hills and are not connected with the creeks and rivers is there going to be significant deposition before reaching the stream. However, as most gullies occur lower in the landscape and are connected to waterways, nearly all sediment eroded from gullies reaches the stream network.

Little is known about what controls the sediment yield from gullies but, by the above reasoning, it can be surmised that bare gully walls are an important factor. Deeper gullies have a greater surface area of bare soil than shallow gullies, and the steeper pastoral areas tend to have gullies up to 10 m deep. The greatest problems occur where the exposed material is highly weathered and dispersive.

The importance of gully erosion as a source of sediment is shown by isotopic signatures of sediment (Olley et al. 1993). Low amounts of radioactive isotopes that fall from the atmosphere attach to surface soil particles and make their way into stream sediment when the soil is eroded by overland flow. Tracing of this sediment in a small gullied catchment on the Southern Tablelands of New South Wales has shown that 90% of the sediment emerging from the catchment has come from erosion of the gully walls. Sediment budgets, which compare erosion rates by overland flow with erosion rates from gullies, confirm this result. In areas of intense gully erosion and low-intensity land use gully erosion far exceeds overland-flow erosion. This probably applies to the more intensely gullied croplands and to much of the inland grazing areas.

The subsoils eroded by gully erosion contain small amounts of naturally occurring phosphorus. Because gully erosion as a source of sediment dominates hillslope erosion, these low concentrations of phosphorus can outweigh the contributions coming from the slopes. Thus, gully erosion can be just as important a process for phosphorus transport as it is for sediment.

Little nitrogen is likely to come from the erosion of gullies and stream banks. As noted, nitrogen is transported in organic forms with sediment and the amount of organic subsoil eroded by gullies is low. Nitrogen delivery is more likely to arise from the seepage of shallow groundwater containing dissolved nitrogen through the stream banks. This process is described below.

Groundwater

Water that infiltrates the soil either is taken up by plants or contributes to groundwater. The steady baseflow of streams between storm events is maintained by the seepage of groundwater. In this publication, 'groundwater' is defined in its broadest sense as all sub-surface waters. This includes permanent aquifers tens of metres deep that flow through fractured bedrock, seasonal water tables that saturate the subsoil, and sub-surface stormflows that flow for brief periods, often perched above the deeper water table, through permeable upper horizons of the soil. All of these waters can flow into streams and thus contribute nutrients and other solutes to those streams. Unlike organic nitrogen from hillslope runoff, nitrate in groundwater is immediately available to stream biota (see Figure 5.5.).

Groundwater delivers only a small amount of sediment to streams. This is because the friction between the water and the surrounding material slows the flow and because the water flows through pores in soil and rock which are too small to allow the transport of particles other than the finest clay and organic colloids. Only when shallow, sub-surface flow erodes pipes or where there are large connected pores of more than 1 cm in diameter is there any potential for groundwater to deliver significant quantities of sediment to streams.

Groundwater is a more significant process for the transport of phosphorus and nitrogen than it is for the transport of sand. These nutrients are transported predominantly as dissolved constituents (solutes) in groundwater, although some phosphorus may be transported in fine colloidal material where clays are dispersive.

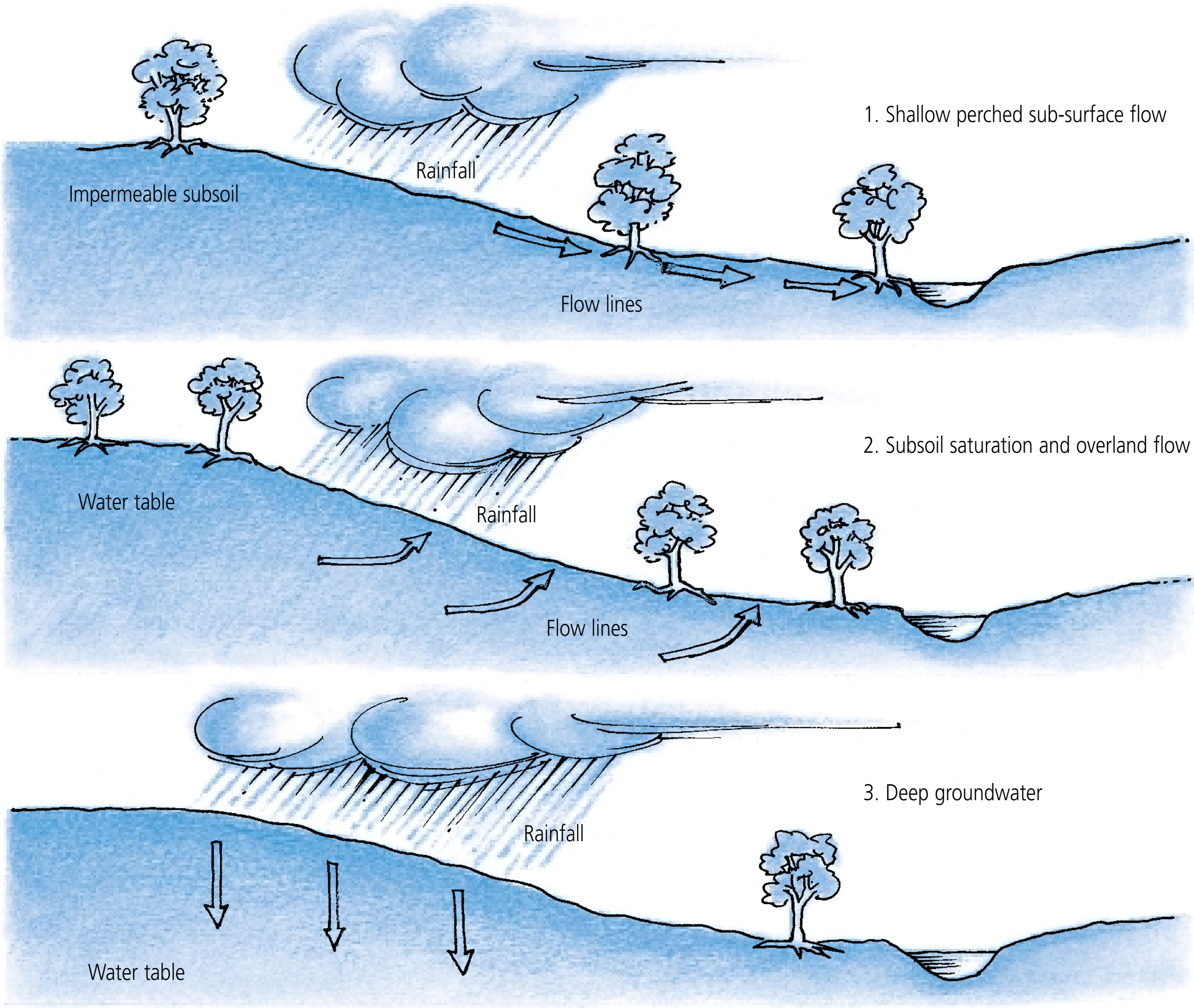


Figure 5.5 Types of groundwater flow

The combination of high infiltration rates, significant leaching and low phosphorus absorption makes groundwater an important pathway for phosphorus transport (Sharpley et al. 1993). Sand absorbs little phosphorus and in areas of sandy soil where fertiliser has been added for several decades the soil may have reached its full potential to absorb phosphorus. Any excess will be lost from the profile by leaching in the soluble form (Kirkby et al. 1997).

Phosphorus leaching has also been detected in soils with clayey subsoils where the clays are cracked and fractured. This is typical of stony red podsolic soils in the previously forested landscapes of much of southern Australia. In this case, high hydraulic conductivities promote rapid groundwater flow (Leaney et al. 1993). When this flow moves rapidly through soil macropores there is little opportunity for absorption of phosphorus onto clay surfaces. Rapid flow of groundwater through cracked subsoils saturates the soil downslope, returning water to the surface as saturation overland flow. This is often observed on footslopes and hollows late in winter. The returning groundwater can be high in dissolved phosphorus and, as long as there is adequate ground cover, it will not entrain any sediment or attached nutrients. Gully erosion can exacerbate the problem of laterally flowing groundwater by creating a deeper channel that taps directly into lower level groundwaters.

Groundwater flow as a source of dissolved phosphorus is a significant problem in the highly permeable sandy soils of Western Australia (Weaver et al. 1996), in the red podsolics of South Australia (Kirkby et al. 1997) and, possibly, in other areas of similar soils and hydrology.

Groundwater flow is becoming an ever-increasing pathway by which nitrogen moves into streams. This is because large quantities of nitrogen are transported as nitrate (NO_3^-), which has a low capacity for absorption into soils and which is transported as a solute. Excess nitrogen in the soil, often a result of fertilisers, is 'lost' into streams as water is leached beyond the root zone of plants. This is a particular problem early in the growing season, when plant uptake of both water and nutrients is relatively low and when large storms can leach nitrate from the soil.

Nitrate leaching is an important problem for on-farm management because it results in net acidification of the soil. This has an adverse impact on crop yields and pasture growth in much of the lower rainfall areas. The lost nitrogen also has an impact downstream when groundwaters enter streams. However, concentrations of nitrate in groundwaters which emerge into the stream are often lower than concentrations in leachate from soils. This may be because riparian soils effectively remove nitrogen from the water passing through them or it may be because of the slow flow rate of groundwater.

Groundwaters, particularly the deeper ones, move slowly and it may take several decades for leached water to emerge at the stream. The water emerging today may come from a time of lower nitrate leaching under less intense agriculture. Groundwater with higher nitrate concentration may be gradually working its way to the stream. Thus, the impact of the current rates of nitrate leaching from soils may not be seen for several years to come.

5.5 The impact of riparian filters on the movement of sediment and nutrients

Riparian filters remove sediment and nutrient from agricultural runoff before it reaches the stream in two ways.

~ Water with dissolved nutrients and sediment infiltrates the soil in the filter.
~ Sediment with attached nutrients is deposited in the filter.

Infiltration in forest filter strips removes dissolved nutrients mainly by means of biological transformation and absorption; deposition is mainly related to the physical trapping of sediment in vegetated filter strips.

Infiltration

Infiltration is the main trapping mechanism for soluble nutrients and clay particles. Once the water has infiltrated, nearly all the sediments and phosphorus, as well as part of the nitrogen, are trapped in the soil profile. Infiltration is relatively easy to measure and many filter strips have been designed so that all runoff infiltrates the strip. However, such designs ignore other removal mechanisms and usually involve very wide filter strips (Vanderholm & Dickey 1980).

For example, 50% of rainfall may be converted to runoff on a typical 200 m long hillslope which receives an intense burst of rain of, say, 50 mm over one hour. This will produce 5000 litres of runoff at the base of the hillslope for each metre width of slope. A 2 m deep riparian soil with 30% available pore space could store 300 litres of runoff for each square metre of riparian land. To store the 5000 litres of runoff would require a 16.5 m wide filter at the bottom of the slope. Studies have confirmed that filters generally need to be greater than 10 m wide to store runoff (Herron & Hairsine, in press).

Converting runoff to infiltrated water will work only on spurs and straight hillslopes where flow spreads out as it moves downslope—or at least does not converge into a small area. In hollows and valleys the soil is usually close to saturation because of the convergence in the valley of soil water from a large contributing area. Saturated soils are not able to infiltrate or store any overland flow from upslope. Saturation is likely to be prevented only when the hollows contain coarse-grained alluvial fills.

The extent to which water can infiltrate partly determines the storage capacity of the soil. Because riparian lands often support dense vegetation they have permeable soils that allow infiltration. Vegetation also protects the soil from the sealing impact of raindrops and increases porosity by producing high amounts of organic matter and sustaining a varied soil. These factors enable water to infiltrate. The total water-storage capacity of a soil is also determined by the soil depth. A history of deposition on the floodplain results in soil usually being deeper than on a hillslope. Once water containing sediment and nutrients has infiltrated it becomes part of the sub-surface water. The removal of nutrients from groundwater is dealt with later in this chapter.

When water flowing downslope hits a vegetated filter, a small ponded area can occur just upslope of the filter (see Figure 5.6). This phenomenon, called a backwater, can act as a true pond, in which low flow velocities allow deposition. In a backwater sand particles will settle quickly, silt particles more slowly, and clay particles only when the backwater conditions allow (Dabney et al. 1995). The backwater effect is mainly important behind stands of stiff, dense grass. These stands act as a dam. The lower the gradient of the land, the more effective is the pond because of its larger size.

Most filter strips are made up of dense grass, which decreases flow velocity and instigates deposition of sediment. Sediment-bound nutrients are deposited with the sediment.

Transport capacity is influenced by the slope and the friction, usually caused by vegetation, that the flow has to overcome. An increase in slope increases the transport capacity; an increase in friction, caused by vegetation, microtopography, or litter or stones, decreases transport capacity. A clear decrease in slope in the direction of the flow can have a similar effect to vegetation. In practice, it is difficult to determine whether vegetation, microtopography or slope has the greatest effect on determining transport capacity. Dense vegetated strips have been found to trap sediment efficiently, as long as the flow does not submerge the grass stems (Barfield et al. 1979). Filter strips best trap sediment where slopes are low, vegetation is dense, and flow is shallow.

Deposition

When water carrying sediment encounters a filter strip of dense vegetation, deposition of sediment occurs because the flow is slowed down. This mechanism is effective in trapping sediment, absorbed phosphorus and nitrogen.

Vegetation

As stated, both forest and grass filter strips can

~ improve surface water quality by instigating deposition of sediment on the soil surface and by removing bacteria and nutrients within the soil profile;

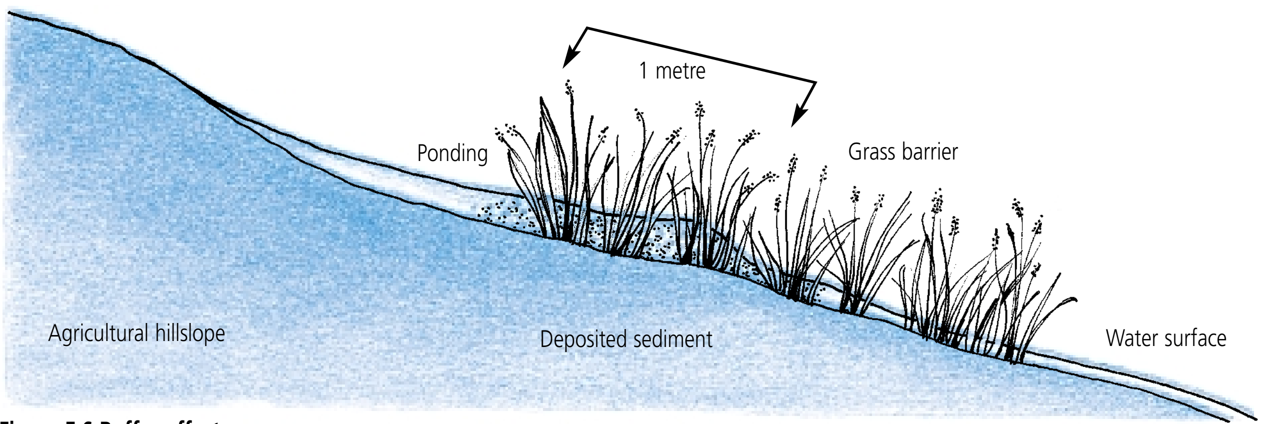


Figure 5.6 Buffer effects

- improve the storage capacity and infiltration rate of riparian soils, thus increasing trapping via the infiltration mechanism;
- slow down the velocity of the flow, so that sediment is deposited before it reaches the stream.

While little research has been done in Australia on this topic, overseas studies which support these findings are relevant because of the identical physical nature of the processes involved.

Different types of vegetation have different properties, but only ground cover is important for deposition purposes. Dense, relatively short grass is most effective in trapping sediment. Clumpy vegetation deflects the flow into sparsely vegetated depressions between the clumps, and this increases flow velocity and prevents deposition. On forest soils where the undergrowth is sparse, runoff flows quickly along preferred pathways around tree trunks and roots. A grass filter strip results in slower, more uniform overland flow than that which occurs in a riparian native forest (Mackenzie & Hairsine 1996). The difference between the two increases with total overland flow. Furthermore, deposits in grass plots tend to be short and fan-shaped, while forested plots tend to be covered in a layer of sediment over their entire length. Thus, a forested filter needs to be wider to have the same trapping efficiency as a grass filter.

The height of the grass is an important consideration, because this determines the surface roughness and the likelihood that the grass will bend over during a flow event. Research has indicated that heights of 10–15 cm are optimal for deposition purposes.

A minor filtering mechanism, which is not well understood at this stage, is the adsorption of pollutants to the surface area of the vegetation. To achieve this a dense vegetation stand with a large leaf area would be needed.

Type of sediment and nutrients filtered

The degree and stability of particle aggregation is a key factor in the effectiveness of filter strips. Filter strips are more effective at removing coarse sediment and aggregates than at removing clay-sized or fine organic particles. General agreement exists that, even under low-flow conditions, the clay-sized and fine organic particles move through a vegetation strip virtually unchecked because of their extremely low fall velocity (that is, they take a long time to fall to the bottom of a pond even in still water). Flocculation of clay particles, which is the chemical bonding of primary particles into larger and heavier aggregates, increases the chance of this type of sediment being trapped.

Unfortunately, the hard-to-trap fine particles are associated with the transport of adsorbed nutrients. Total phosphorus-trapping efficiencies were found to be greater than 50%, while total sediment-trapping efficiency was found to be greater than 90% (Hairsine 1996). Herbaceous filter strips are slightly less efficient in removing total phosphorus and nitrogen than they are at removing total sediment (Dillaha et al. 1989, Magette et al. 1989). Sixty-nine per cent of the total phosphorus and 63% of the total nitrogen were removed by a 4.6 m grass strip, where 93% of the phosphorus in the runoff was sediment-bound (Dillaha et al. 1989).

The proportions of adsorbed phosphorus, insoluble inorganic phosphorus and organic phosphorus (in plant or animal matter) in the runoff are controlled by the nature of the sediment and by kinetic factors such as turbulence and the flow rate. Most of the phosphorus trapped in filter strips is particulate, because that is the dominant fraction in overland flow and because filters are less able to trap dissolved phosphorus (see Table 5.3). Only 9% of the soluble phosphorus and none of the soluble nitrogen were removed with a 50 cm filter strip (Doyle et al. 1977). With a 4 m strip these percentages were 62% and 68% respectively.

Based on the research conducted thus far, it would appear that filter strips do not reliably remove soluble phosphorus and nitrogen from runoff. Nevertheless, even though filter strips are not always successful in reducing the flux of the (immediately) bioavailable portion of phosphorus, the efforts to trap sediment are still worthwhile. This is because the ‘non-bioavailable’ fraction of phosphorus in sediments may become bioavailable in the future, as suspended organic material is broken down (Paerl & Downes 1978) or as the sediments are exposed to stream water low in phosphorus. Another reason for attempting to trap sediment is that it is a major pollutant.

The intensity of the sediment source

Most filter strip field experiments have simulated extreme storm events, as it is these events that transport the majority of the sediments and pollutants. Under conditions of large amounts of water and sediment, grass filter strips have been found to trap sediment efficiently. For major runoff

Table 5.3 Examples of the effects of riparian filters on runoff quality

Source	Hillslope characteristics (slope; soil; use; runoff)	Type of filter	Type of runoff	Metres into filter	Trapping efficiency (% of inputs retained) or *improvement in water (% change in pollutant concentration)*					
					Total sediment	Total P	PO_4^{2-}	Total N	NO_3^-	NH_3
Chaubey et al. (1995)	3% slope; silty loam; poultry manure effluent; 1st runoff event only	Grass	Overland flow	3.1 9.2 21.4	37 17 48	40 74 91	39 71 90	39 67 81		47 78 98
Daniels & Gilliam (1996)	Mean slope 2.1–4.9%, max slope 10%; sandy to clay loam, and silty clay; crops; 2 years' runoff, including large storms	Grass	Overland flow	3 7	*50 (40)[a]* *60 (60)[a]*	*50* *65*	*25* *50*	*35[b]* *60[b]*	*90* *65*	*30* *45*
Daniels & Gilliam (1996)	Mean slope 2.1–4.9%, max slope 10%; sandy to clay loam, and silty clay; crops; 2 years' runoff, including large storms	Grass then tree	Overland flow	6 15	*20 (60)[a]* *30, 60 (80)[a]*	*40* *60*	*0, -50* *50, -225*	*10–40[b]* *40–50[b]*	*60* *65*	*-55[c]–5* *-30[c]–25*
Dillaha et al. (1989)	Slopes 5, 11, 16%; silty loam; crops; simulated rainfall (max. intensity 2–5 year recurrence) following fertilisation	Trimmed grass	Overland flow	4.6 9.1	53–86 70–98	49–85 65–93	-83–69 -31–48	43–82 56–91	2–72 22–78	9–74 42–89
Greenhill et al. (1983)	Slopes 9, 17, 25%; loams/high infiltration; crops; 1 in 2 year storm	Pasture	Overland flow	5 10 22	*70* *84* *86*	*61* *73* *75*				
Hairsine (1996)	Slope planar 16%; sandy clays over sandy loams; crops, tilled 4 weeks prior to study; 3 simulated rainfall intensities, applied progressively in order of increasing intensity, without delays	Grass	Overland flow	*Low flow:* 3 6 *Medium flow* 3 6 *High flow* 3 6	*(from graphs)* 98 98 98 99 99 99	*(raw data)* 31 59 28 32 33 10				

Table 5.3 continued

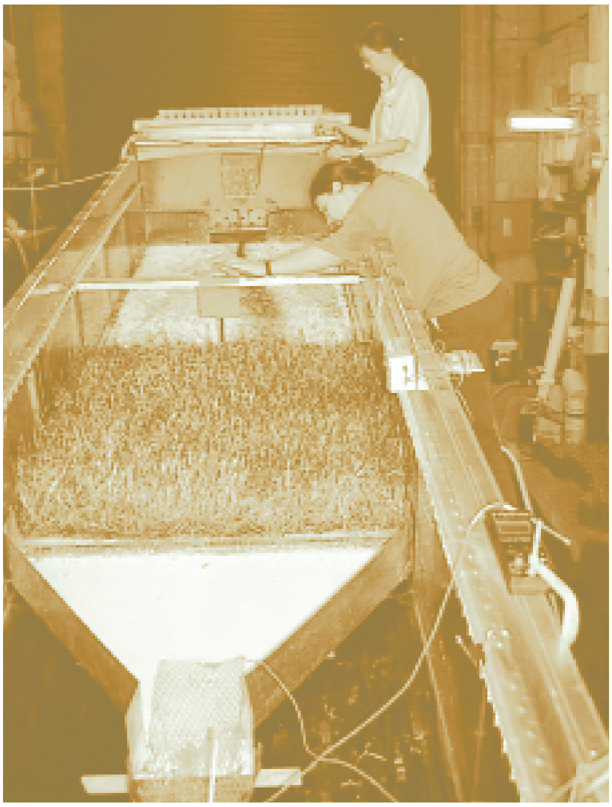
Source	Hillslope characteristics (slope; soil; use; runoff)	Type of filter	Type of runoff	Metres into filter	Trapping efficiency (% of inputs retained) or *improvement in water (% change in pollutant concentration)*					
					Total sediment	Total P	PO_4^{2-}	Total N	NO_3^-	NH_3
Hairsine (1996)	Slope planar 16%; sandy clays over sandy loams; crops, tilled 4 weeks prior to study; 3 simulated rainfall intensities, applied progressively in order of increasing intensity, without delays	Grass then forest	Overland flow	*Low flow:* 3 grass, 3 for. 6 forest *Medium flow:* 3 grass, 3 for. 6 forest *High flow:* 3 grass, 3 for. 6 forest	*(from graphs)* 93 96 94 96 95 94	*(raw data)* 70 53 -39 53 58 8	 30			
Hubbard & Lowrance (1996)	Duplex soils with a surface of fine loam to loamy sand; killed grass; 2.5 years of monitoring	Forest	Subsurface	2 7					low high	
Lowrance et al. (1983, 1984)	Duplex soils with high infiltration; crops; 26 runoff events over a year	Tree	Overland and subsurface flow	n.a. (filter area = 30% of catchment)	30		68			
Magette et al. (1989)	Slope 3–6%; fertilised sandy loam; fallow; simulated intense, frequent rainfall	Grass	Overland flow	4.6 9.2	52[g] 75[g]	6[g] 20[g]		-15[g] 35[g]		
Peterjohn & Correll (1984)	Slope 5%; fine sandy loam with an aquiclude at 2 m; crops; 1 year	Tree	Overland and subsurface flow	19 50	90 94	57 80	12 -12	 89[d]	 79[e], 94[f]	 ~70[e], -380[f]
Weston et al. (1985)	17% slope; clay loams with high infiltration; crops; simulated rainfall (3 sequential storms, intensity 2 year recurrence)	Pasture	Overland flow	5 10 22	98–99 ~100 ~100	96 97 97	n.a.			

a. Minus data from one large storm. b. Total Kjeldahl nitrogen. c. Storm runoff directly following application of nitrogen fertiliser.
d. Total runoff. e. Overland flow. f. Sub-surface runoff. g. Percentage improvement of runoff exiting from filter strips compared with runoff from bare plots.

events with an intense hillslope source of sediment, the sediment-trapping ability of grass filters, riparian forests and combined systems was found to be greater than 90% (Hairsine 1996). Trapping efficiencies decreased slightly with increases in flows. For situations where sediment concentration is low, trapping efficiencies are likely to be somewhat lower. This is because a smaller amount of coarse sediment will have eroded during the less intense, more frequent rainfall events, and filter strips are less efficient at trapping fine particles.

Slope

The slope of the ground affects the extent to which the downslope velocity of water is increased by gravity. Higher velocity flows have greater capacity to transport sediment and less capacity to trap sediment. Laboratory work on bare soils has shown that deposition can occur on low slopes even under high discharges (Beuselinck, pers. comm.), as well as downslope of rills where the gradient is less than 5%. Sediment transport capacity increases with slope angle, where dense vegetation is required to induce deposition. Field experiments on grass filter strips have found that slopes as high as 16% and 23% still trap approximately 90% of sediment generated from plough furrows upslope (Hairsine 1996).



Measurements of flow depth during a sediment trapping experiment. Photo by Ian Prosser.

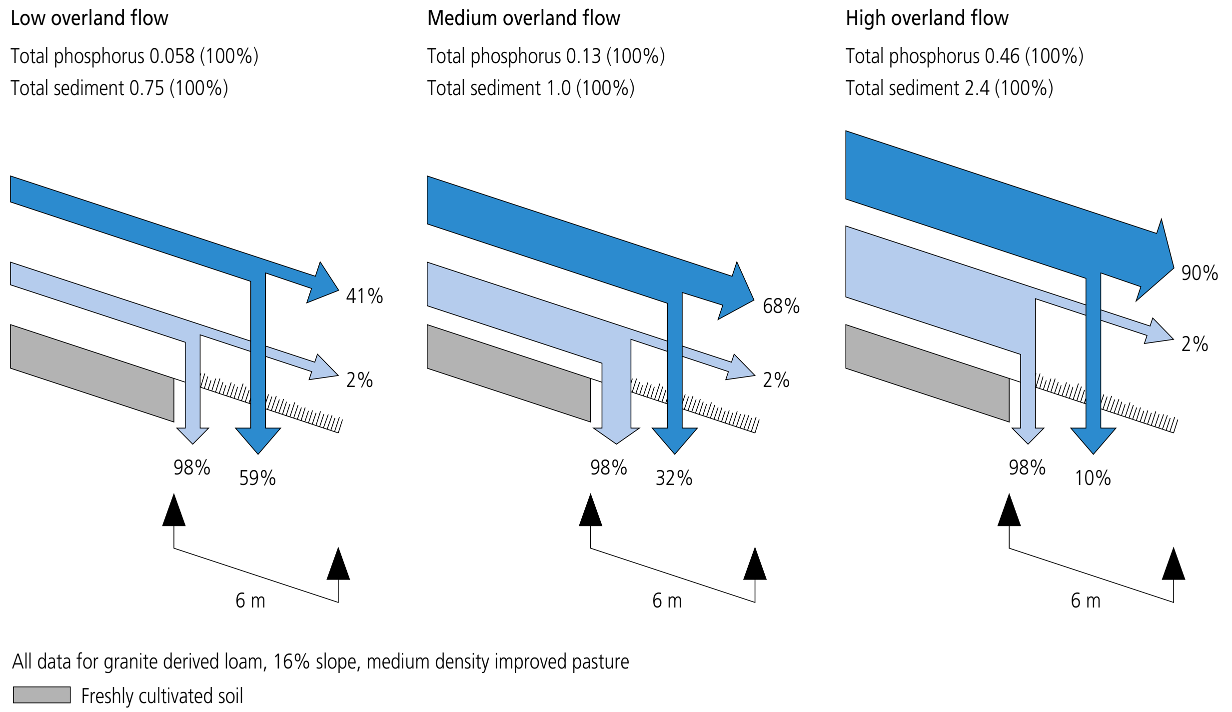
Just as slope angle is important, so is the sequence of slope angles, or the slope shape. Concave slopes decrease in slope in a downward direction. As a result, flow velocity and transport capacity decrease, and deposition occurs on the footslope. Convex slopes display the opposite effect and are unlikely to trap sediment.

Degree of channelisation

When runoff is channelled (by topography forcing the flow to converge in hollows or by large objects such as fallen trees), the greater depth of runoff will often inundate the vegetation. Filter strips existing under channelised flow have been found to be only 40% to 95% as effective at removing sediment as they are for non-channelised flow (Dillaha et al. 1989). Figure 5.7 shows the amount of phosphorus and sediment transported and deposited under varying levels of overland flow. It is important to interpret these figures in relation to your specific situation (for example, what is regarded as low, medium or high overland flow in your region).

Life expectancy of grass filter strips

Grass filter strips do not stay unchanged during their life. Starting as undisturbed strips, they transform into sediment depositional areas during rainfall events. A typical deposition wedge, 30–50 cm wide, forms just upslope of the filter strip and within the first metre of the filter. This continues until the upper portions of the filter are buried in sediment. Research has found that 91% of the incoming sediment load was deposited within the first 60 cm of the filter (Neibling & Alberts 1979). Interestingly, once the initial deposition zone fills up, the deposition front moves downslope into the filter at 50 cm intervals until the filter is completely full; at this stage the filter ceases to be effective. Filter strip effectiveness is thus a function of the proportion that is inundated with sediment (Magette et al. 1989, Dillaha et al. 1989). However, in some cases, the filter vegetation may completely grow back after inundation, thereby renewing the filter. The rate of inundation by sediment will depend on both the frequency of overland flow events and the growth rate of the vegetation. Grass has been observed to germinate and completely cover deposits within three months of deposition.



All data for granite derived loam, 16% slope, medium density improved pasture

Figure 5.7 Impact of flow
Source: Hairsine (1997).

Reduction of nutrients in groundwater flow

The main nutrient entering streams from sub-surface runoff is nitrate, which does not bind well to sediments and remains in solution. In contrast, dissolved phosphorus and ammonia bind well to soil material and will tend to get 'stripped' from sub-surface runoff as it percolates through the soil. (This is not the case with sandy soils, where the low capacity for phosphorus absorption may have already been reached; nor is it the case with soils where phosphorus travels through macropores with little interaction with the soil matrix.)

The nutrient load of groundwater entering a stream can be reduced by

~ riparian plants absorbing nitrogen;
~ reactions in organic riparian soil and stream-bed sediments which convert nitrate to gaseous forms that are then lost to the atmosphere in a process called de-nitrification;
~ soluble phosphorus being absorbed by plants or becoming adsorbed onto fine-grained riparian soils or stream-bed sediments.

The processes of nutrient removal require significant interaction of groundwater with riparian vegetation, or with fine-grained deposits in the stream bed. This means that the processes are most effective where groundwaters are shallow and where the groundwater flows slowly, maximising the time of interaction between soil and water. The implication of this for management is that some understanding of the local groundwater hydrology is required to assess the effectiveness of riparian lands in removing nutrients.

Uptake of nutrients for growth of riparian plants and microbes

Nitrate in sub-surface flow may be absorbed by plant roots. In certain situations rates of uptake of nitrate by trees for tissue growth exceed rates of nitrate input from sub-surface flow (Hill 1996). For example, it has been calculated that in riparian forest in Georgia in the United States, plants annually take up 51.8 kg/ha of nitrogen, even though annual groundwater nitrate supply was only 29 kg/ha (Lowrance et al. 1984). Clearly, these rapidly growing trees were accessing nitrogen stores in the soil (possibly associated with organic matter) as well as groundwater nitrate. Young trees are thought to be most effective at nutrient uptake because of their vigorous growth. Uptake of nitrogen by older trees appears to be balanced by nitrogen inputs from the breakdown of plant litter in riparian soils. Even in young stands of riparian trees, nitrogen uptake may be only seasonal in regions where plant growth is seasonal. Dense grass stands will also absorb nitrate, but the limited data available suggest that riparian forests absorb 10–15% more nitrogen (Hill 1996).

Phosphorus is also required for plant growth, and a portion of the soluble phosphorus that becomes adsorbed to sediments may eventually be taken up by plants.

De-nitrification in the riparian zone

Nitrate may also be removed from sub-surface water by being converted to gaseous forms of nitrogen which are then released to the atmosphere. This process, termed 'de-nitrification', is dependent on anaerobic conditions, a supply of organic carbon and, of course, nitrate supply (Vought et al. 1994, Hill 1996).

Riparian lands are favourable sites for de-nitrification for three reasons.

- They store water, allowing time for the de-nitrifying bacteria to convert the nitrate.
- They often provide the necessary anaerobic conditions and carbon supply. De-nitrification rates fall as the water table drops, reducing waterlogging and thus anaerobic conditions.
- The supply of organic carbon from litter and root exudates is high.

The rate of de-nitrification is often greater close to the upslope edge of riparian land than it is close to the stream, where de-nitrification is thought to be limited by nitrate supply. Rates of de-nitrification on riparian land are comparable with losses of nitrogen due to plant uptake in favourable conditions and result in 50–98% capture of nitrogen (Hill 1996, Lowrance et al. 1984, Nelson et al. 1995). However, rates of de-nitrification are temporally and spatially variable (Nelson et al. 1995). In particular, it is unlikely that de-nitrification is important where groundwaters are oxygenated (Bohlke & Denver 1995) or where they enter streams from below the root zone (where carbon supply is likely to be low). It is unknown whether this latter pathway is a major one for nitrogen loss in Australia, especially in regions where soil moisture is relatively low and where soils are oxygenated. In studies where de-nitrification has successfully balanced agricultural inputs of nitrate, the inputs have been relatively low (Hill 1996).

Dependence of nitrate removal on groundwater hydrology

The most effective rates of nitrate removal have been recorded in broad low-relief environments where there is an impermeable layer in the top 2 m of riparian soil. This forces groundwater to flow in the upper parts of soil, where there is significant interaction with vegetation and organic-rich soil. The low relief of the landscape reduces flow rates to a level where plant uptake and de-nitrification can keep pace with the rate of groundwater flow. Measurements of nitrate concentration in riparian lands show that over 90% of nitrate is removed from groundwater under such favourable conditions, which occur, for example, along the Atlantic coastal plains of the United States, in England and in New Zealand (Peterjohn & Correll 1984, Jordan et al. 1993, Lowrance et al. 1984, Haycock & Pinay 1993, Cooper 1990). In these areas, much of the reduction of concentration occurred in the outer 10–20 m of riparian land and input concentrations were of the order of 1–20 mg/l.

There is less information about nitrate removal from less favourable hydrological settings, such as deeper sandy aquifers that discharge beneath the root zone of riparian soil (Phillips et al. 1993, Bohlke & Denver 1995). In other circumstances groundwater emerges at the surface in springs immediately upslope of riparian land and then flows over the surface to the stream, again bypassing the riparian soil (Hill 1996). In both situations, with input concentrations similar to those cited above, reductions approached zero.

In-stream and stream-bed removal of nutrients

Riparian land is not the last opportunity to remove nutrients from flows, although it is probably the best opportunity. Stream flow interacts with the sediments on the stream bed and these sediments may absorb nutrients—although in some circumstances they are a source of increased nutrient supply. In large rivers there may be significant interaction between stream water and the underlying sediments, with stream flow entering floodplain aquifers and travelling for several kilometres from the surface flow. These sediments, known as 'hyporheic zone sediments', then become an area where surface flow and groundwater flow can mix (Hill 1997). If the sediments are anoxic and contain some organic matter de-nitrification can take place. This usually occurs in association with fine sediments. There are, however, just as many studies which show increased nitrate levels in bed sediments where ammonium is oxidised to form nitrate (Hill 1997).

Sediments on the bed of a stream can exchange nutrients with the stream flow but usually stream flow is too rapid for the exchange processes to occur. Furthermore, the highest nutrient loads occur at times of greatest flow. Baseflow nitrate concentrations can be reduced in slow-flowing streams by de-nitrification in the top centimetres of sediment, just below the boundary between oxic and anoxic sediment (Hill 1997). Rates of nitrate removal are higher in summer than in winter, and higher in the fine-grained sediments of slow-flowing streams. Nitrate concentrations can be reduced by plant growth in the stream. However, if these are nuisance plants, the nutrient is recycled back into the stream during decomposition.

There is substantial potential for exchange of phosphorus between the water column and the streambed or the suspended sediment. Reduction in stream-dissolved phosphorus, through plant uptake, can be balanced by phosphorus dissolving from the bed sediment. Under anaerobic conditions, levels of dissolved phosphorus can be increased markedly by phosphorus desorption from fine sediments.

It is clear from the material presented in this chapter that the delivery of sediment and nutrients to streams is an important issue for managers. This is because sediment and nutrients, and their relationship with riparian land, strongly influence water quality and habitat condition. Perhaps the most important message of this chapter, however, is that sediment and nutrient delivery to streams has been considerably altered as a result of relatively recent human activity. The challenge for managers, therefore, is to develop strategies that address environmental as well as economic requirements.

Current research

The efficiency of riparian lands at trapping sediment and nutrients, and their hydrology in the Kalgan River, Western Australia, and the Johnstone River, far north Queensland

This work involves monitoring and is being done to evaluate the effectiveness of riparian buffers in real catchment situations, as opposed to experimental situations. It is a collaborative project.

Researchers: Ian Prosser and Lucy McKergow, Cooperative Research Centre for Catchment Hydrology; David Weaver and Adrian Read, Agriculture Western Australia; and Dale Heiner and Heather Hunter, Queensland Department of Natural Resources

Processes of deposition

Rainfall simulation and flume studies are being used to better understand processes of deposition and help guide models of these processes. These studies will help to develop models and protocols for buffer strip design, including the impact of stock access to riparian lands.

Researchers: Peter Hairsine and Linda Karssies, Cooperative Research Centre for Catchment Hydrology

The potential of in-stream wetlands to improve water quality

This project, being undertaken at Jugiong Creek, New South Wales, evaluates the potential for in-stream wetlands to improve water quality in an environment where gully erosion is a significant process, reducing the effectiveness of traditional buffer strips.

Lead researchers: Christoph Zierholz and Peter Fogarty, New South Wales Department of Land and Water Conservation

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CHAPTER 6

Stream erosion

Ian Rutherfurd, Bruce Abernethy, Ian Prosser

Summary

- Erosion of stream beds and banks is an essential, natural and continuing process.
- Vegetation tends to reduce the rates of channel erosion, including catastrophic widening and gullying. Channels lined with trees also tend to be narrower and deeper than cleared streams.
- Vegetation will not stop all erosion, but the key to controlling erosion with vegetation is to closely match the vegetation characteristics to the erosion processes that are occurring. Both the erosion processes and the types of vegetation change along a stream's length.
- Erosion processes fall into three groups: sub-aerial erosion, scour and mass failure. Vegetation has a different effect on each process group.
- Scour of the bank toe is the most important process that maintains erosion rates and will often be the priority target for revegetation.
- The main impact of vegetation on mass failure is the root reinforcement of the soil. The weight of trees on banks (surcharge) usually reduces mass wasting or is irrelevant to it.
- Removing willows from streams, whilst desirable, can lead to erosion problems and needs to be planned and managed carefully.

CHAPTER 6

All streams erode. Stream erosion is a natural and essential process that has been accelerated by human impacts, often to unacceptable levels. Riparian and in-channel vegetation can reduce rates of stream erosion, but it is unrealistic to expect revegetation to eliminate all erosion. This chapter examines the role of vegetation—on the bank top and in the channel—in stream bank erosion. It begins by describing the general differences between a vegetated and an unvegetated channel, then goes on to describe the major erosion processes and how they can be influenced by vegetation. In particular, we emphasise that managers can match the type of vegetation to the type of erosion process in a stream, and that both vegetation and erosion processes change throughout a stream network.

6.1 General effects of vegetation on stream shape and stability

Two general points can be made about the effects of vegetation on stream shape and stability.

- ~ Stream channels carrying medium to large flows lined with dense vegetation are narrower, and sometimes deeper, than their equivalents with grassed banks.
- ~ Channels with substantial vegetation cover in the bed and on the banks erode at a slower rate than bare or grassed channels.

Channel shape and vegetation

It is difficult to isolate the effect that vegetation has upon channel shape and size because there are so many other variables that influence channel geometry. There have been a few studies that compare the morphology of vegetated and unvegetated streams, but none in Australia. Research has found (Andrews 1984) that in Colorado, gravel bed channels with dense bank vegetation were about the same depth, but flowed 25% faster and were 26% narrower than comparable unvegetated streams (for channels 0.1–2 m deep and 5–80 m wide). These findings were supported by similar work in the United Kingdom, which showed that unvegetated streams (1–3 m deep and 12–40 m wide) were up to 1.8 times wider than similar grassed streams (Hey & Thorne 1986). This effect of vegetation has been explained in terms of reduced critical boundary shear stresses at the channel edges, and increased shear stress in the channel centre (Ikeda & Izumi 1990).

On the other hand, some studies of small streams have suggested that replacing riparian forest with a dense sward of grass will encourage bank deposition and produce a channel that is up to half the size (Trimble 1997, Davies-Colley 1997, Zimmerman et al. 1967).

It is likely that there is a threshold channel size (and catchment area) above which vegetation is no longer the dominant control on channel morphology. The examples just cited, in which grassed channels are smaller than forested ones, occur only in catchment areas of less than tens of square kilometres (Zimmerman et al. 1967, Davies-Colley 1997). The relationships between vegetation and cross-section shape appear to hold even for channels that are up to 50 m wide, but it is unlikely that the morphology of rivers much larger than this is fundamentally controlled by vegetation. It has been suggested 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 (Masterman & Thorne 1992). 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 processes. In Australia, for example, the root zone seldom extends below 2 m in depth. Although some roots extend deeper than this, they tend to add little extra strength to the banks. This is discussed in more detail later in this chapter.

Gross effects of vegetation on erosion rates

In Australia the removal of vegetation has greatly contributed to the general instability of streams. The clearing of catchments and the removal of bank vegetation from some rivers in coastal New South Wales last century led to massive widening during large floods (Raine & Gardiner 1994, Brooks & Brierley 1997). While others argue that the key issue was not the vegetation, but the unprecedented magnitude of the floods (Erskine 1986, Nanson & Erskine 1988), in general there is little doubt that riparian vegetation plays an important role in reducing the magnitude of channel change during large floods.

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 (Odgaard 1987, Pizzuto & Mecklenburg 1989, Hickin 1984). Bends of streams in British Columbia (1–2 m deep and 20–30 m 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 1995).

Thus, there is strong evidence that vegetated stream channels can have a different shape and erosion rate than unvegetated streams. The remainder of this chapter explores the specific impacts of vegetation on erosion processes that occur in a stream.

6.2 Riparian forest structure and bank erosion: some definitions

Bank erosion is strongly influenced by the density and type of riparian vegetation cover. Riparian vegetation can be defined according to its size, its position on the bank, and its strength as overstorey, understorey, ground cover and macrophytes (see Figure 6.1).

Overstorey

The overstorey consists of emergent trees, which typically grow to a height anywhere between 5 and 20 m (depending on species composition and local conditions). Trees are often heavy (for example, a 20 m tall river red gum will weigh at least 10 tonnes) and, because of this, can affect bank stability.

The root systems of trees are as variable as the above-ground parts and are thus difficult to characterise. In most riparian species the density of roots declines rapidly away from the trunk and with depth. There is a central root ball, or root plate, of dense roots that can usually be considered as half a sphere below the surface; it has a diameter about five times the diameter of the trunk. The main body of roots extends to a depth of about two to three times the tree diameter. Root density declines beyond the root ball; there are usually few roots beyond the drip line of the tree (that is, the edge of the tree's canopy) and low root densities below 1 to 1.5 m in depth. The root ball grows parallel to the ground surface, so where a tree grows on a sloping stream bank the root ball will be at the same angle. Few tree species can maintain root networks below the summer water level in the stream, which means that root balls can be shallow where there are high water tables. They can also be shallow where there are heavy sediment strata they cannot penetrate.

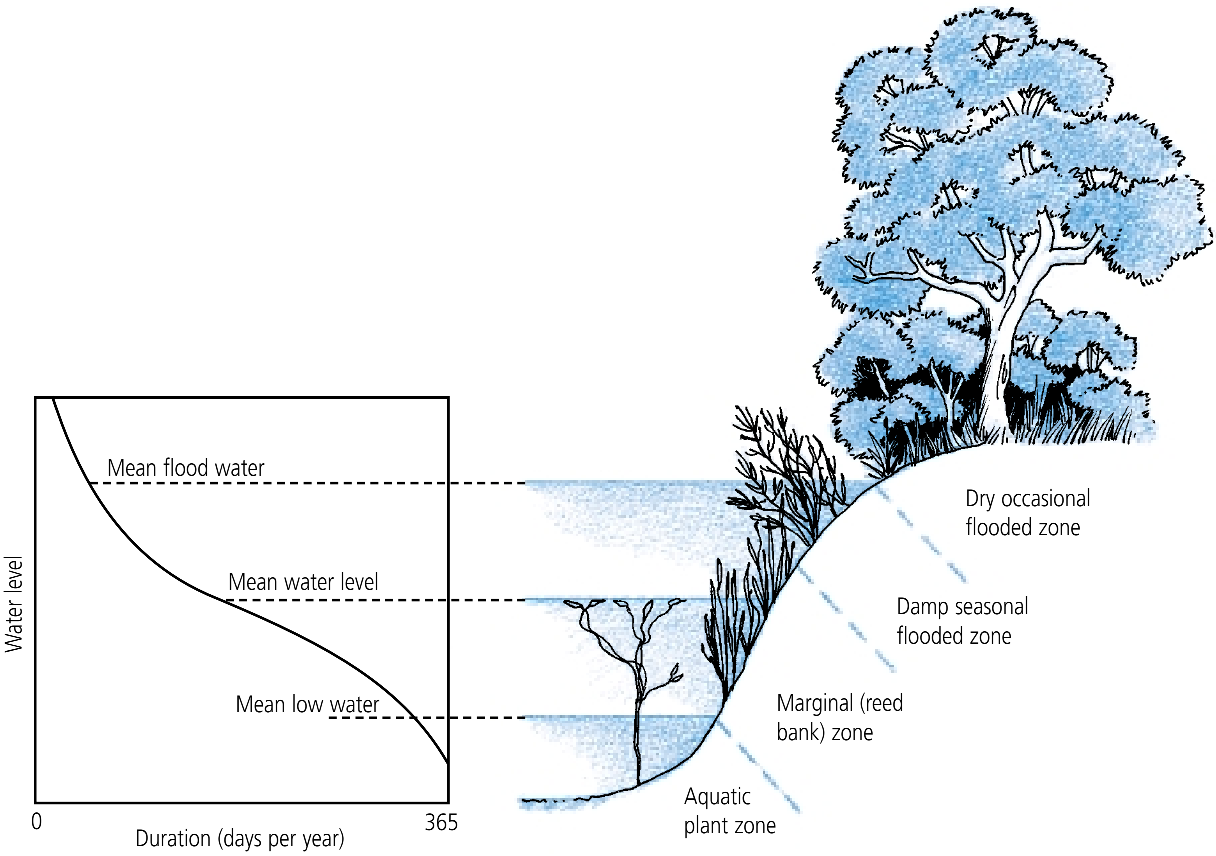


Figure 6.1 Figure of channel, type of vegetation, and associated mean water levels
Source: Adapted from Seibert (1968).

Understorey

The riparian understorey ranges from nothing, to a complex array of shrub species. For the purposes of bank stability, the shrubs of the understorey are simply little trees. Generally, the understorey grows to a height of between 1 and 5 m, with a rooting depth less than that of trees but still over a metre. As with trees, the lateral extent of the root mass is about that of the drip line, and the root density quickly diminishes with depth and distance from the trunk. Neither the weight nor the wind effects of understorey species is an issue for bank stability.

Ground cover

Riparian ground cover is typically less than 1 m high. It usually consists of native and introduced species and can include prostrate shrubs, grasses, sedges and forbs. It is usually quick to establish on a bank but susceptible to trampling and other grazing pressures. Although the roots of grasses can be seen at depths of over 1 m on exposed bank profiles, their reinforcement potential is negligible at depth. For the purposes of bank reinforcement, the maximum zone of influence of ground cover is probably constrained to about the top 0.3 m (although some North American studies have shown the root reinforcement of some grasses to be effective down to 0.75 m). Regardless of the exact depth, the effective rooting depth of grasses will be fairly shallow and may vary between species and between sites. The main advantages of ground cover are that it densely covers the bank surface (except for vertical banks) and has a dense (if shallow) root mat. A disadvantage of many ground covers is that they will not grow below the low-flow water line.

Emergent aquatic macrophytes

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

6.3 Bank erosion

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

- bank material (weight, texture and strength);
- bank geometry (height and angle);
- bank hydrology (groundwater level and bank permeability);
- stratigraphy;
- vegetation.

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

- sub-aerial erosion of bank material;
- direct scour of bank sediment;
- mass failure mechanisms.

All of these processes tend to act in concert along the entire length of rivers. However, 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.

Sub-aerial erosion

Stream banks that are exposed to air are subject to erosion from a variety of processes which are largely external to river processes. Such processes are collectively termed sub-aerial erosion. Some of these directly cause erosion, while others render banks more susceptible to erosion. Sub-aerial processes include

- windthrow of stream-side trees;
- damming by large woody debris (see Chapter 7);
- frost heave;
- desiccation leading to cracking and ped dislocation;
- rain splash and micro-rill development;
- slaking;
- stock trampling.

Windthrown trees directly deliver sediment into the flow when their rootballs detach from the bank. Furthermore, flow is often redirected against the bank by the resultant debris dams, with the scallops formed in the bank after the trees have fallen, ideal places for concentrated erosion by the flow. Shallow-rooted trees in swampy upper reaches are prone to windthrow. However, as bank height increases downstream, bank penetration by tree roots has the potential to increase, and the incidence of windthrow is reduced. Windthrow problems are exacerbated when trees occur in a single line along the bank top: a wide stand of trees is preferable in terms of their impact on bank stability (Thorne 1990). Wind loading is significant for trees only when the wind velocity exceeds 40 km/hr (Coppin & Richards 1990), which is fast enough for large branches to move.

Frost heave can be the dominant bank erosion mechanism in cold regions (Lawler 1986). It occurs where sufficient moisture supply, appropriate soil pore geometry, and limited vegetation combine with sub-freezing temperatures. Under these conditions, needle ice forms and lifts up soil particles. The fluffy sediments that result are easily removed by any flows in the stream. This erosion process is important in alpine streams in Tasmania and the Australian Alps.

The effect of frost heave increases with the number of freeze–thaw cycles (Bohn 1989). Vegetation dramatically reduces freeze–thaw erosion by shading the banks and limiting fluctuations in soil temperature—even sparse grass cover in upland environments protects banks from freeze–thaw cycles. It was found that the number of days where soil temperatures under grass crossed 0°C was around half that for bare soil (Bohn 1989).

Desiccation is the drying and cracking of bank material so that it is easier to erode. Indeed, desiccation sometimes has a greater influence on erodibility than does the composition of the bank material itself (Knighton 1973). Vegetation can reduce desiccation by binding bank material together, while shade from trees, grass and leaf litter reduces drying.

Bare stream banks are subject to the same erosion processes of rain splash and rill development as any soil slope. Well-established bank vegetation will reduce the rate of such surface erosion by one to two orders of magnitude. Indeed, overland flow on well-vegetated banks can be considered an insignificant contributor to bank stability (although this is not always the case in gullies).

Slaking occurs as a result of the rapid immersion of banks. Water entering a dry soil aggregate encloses air within the aggregate. The compressed air so trapped will shatter the aggregate if the aggregate's mechanical strength is sufficiently low. The resulting loss of structure renders the bank material susceptible to erosion by the flow in the channel. The roots of vegetation contribute to greater porosity, and the strength of aggregate is improved by root reinforcement. Note that slaking is possible only when water enters the aggregate from all sides at once: when aggregates are held in close contact with the bank by vegetation, air is displaced as the water enters from the channel side only and slaking does not occur.

Stock trampling reduces the resistance of the river bank to erosion by reducing the vegetation cover and exposing otherwise protected bank material. Trampling also directly breaks down banks and transfers large quantities of bank material straight into the flow.

These processes, and the way that vegetation might influence them are, described below and summarised in Table 6.2.

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

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, in turn, is a function of flow depth and slope. Scour is most pronounced at the outside of meander bends.

Flow resistance

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, 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 bank-full flow (Andrew Brookes, pers. comm.). This difference produces a fourfold decrease in shear stress.

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 (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;

Table 6.2 Summary of sub-aerial processes

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 dislodge bank material.	Vegetation insulates bank material reducing ice formation.
Rilling	Over-bank runoff erodes bank sediments.	Vegetation limits over-bank runoff by promoting infiltration and slowing velocity.
Rain splash	Rain splash 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 aggregates escapes as banks are rapidly submerged.	Vegetation maintains a more porous bank material structure and bonds aggregates together.
Trampling	Unrestricted stock access transfers sediment into the flow.	Vegetation cannot resist prolonged stock trampling.

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, which can often be seen around large river red gums on floodplains.

The density of the tree stand is also 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 reattachment 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 m wide can absorb about two-thirds of the wave energy generated by the wash from a 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. Reduced erosion rates at some sites on the Murray River near Albury–Wodonga have been ascribed to the presence of *Phragmites* spp. (Frankenberg et al. 1996).

Resistance to scour

Vegetation on the bank face also reduces the effects of scour by directly strengthening the banks. A dense root mat, as found on willows and several native species, such as she-oak (*Casuarina nana*), bottlebrushes (*Callistemon* spp.) and tea tree (*Leptospermum* spp.), 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.

Mass failure

Bank erosion can occur if whole blocks of material slide or topple into the water. Mass failure of river banks typically occurs in floodplain reaches, where the 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.

Types of mass failure

The way in which bank failure occurs depends on the geometry of the bank. There are four broad failure types:

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

The failure types are illustrated in Figure 6.2.

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 (see Figure 6.2c) (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 m or so wide) usually have a curved failure plane (Terzaghi & Peck 1948) and often have tension cracks.

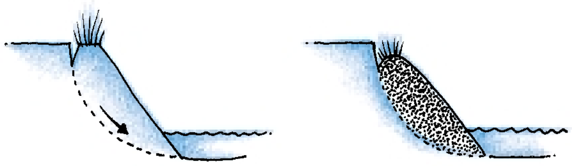
Cantilever failure. Figure 6.2 also shows the principal mechanisms of cantilever failure. These failures occur when undercutting leaves a block of unsupported material on the bank top, which then slides or falls into the stream. (For a more detailed discussion of cantilever failures see Thorne and Tovey [1981].)

Figure 6.2 Processes for broad failure

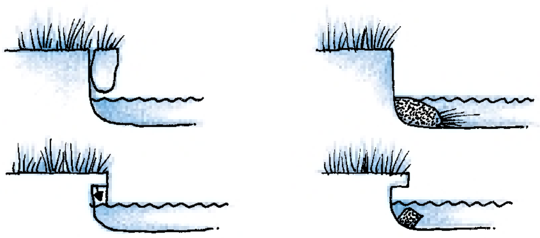
BEFORE AFTER

(a) Shallow planar-slide failure

(b) Slab failure
slide → topple



(c) Deep-seated rotational failure
slope failure → toe failure → base failure



(d) Cantilever failure
shear failure → beam along neutral axis → tensile failure

Broken lines indicate failure planes.
Source: Adapted from Hemphill & Bramley (1989).

Shallow slip failures on the Tarwin River, Victoria.
Photo by Ian Rutherfurd.

Slab failure in the Tarwin River, Victoria. Photo by Ian Rutherfurd.

Deep seated rotational failure, Latrobe River, Victoria.
Photo by Ian Rutherfurd.

Effects of vegetation on 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. Well-rooted and closely spaced trees that are growing low down on the face of a river bank can also provide an effective buttressing effect (see Figure 6.3). Buttressing by trees directly supports the upslope bank material and, as noted, may protect the toe against shear failure (Thorne 1990). 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 mm 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. Probably the most important are the root tensile strength, the roots' frictional resistance to movement

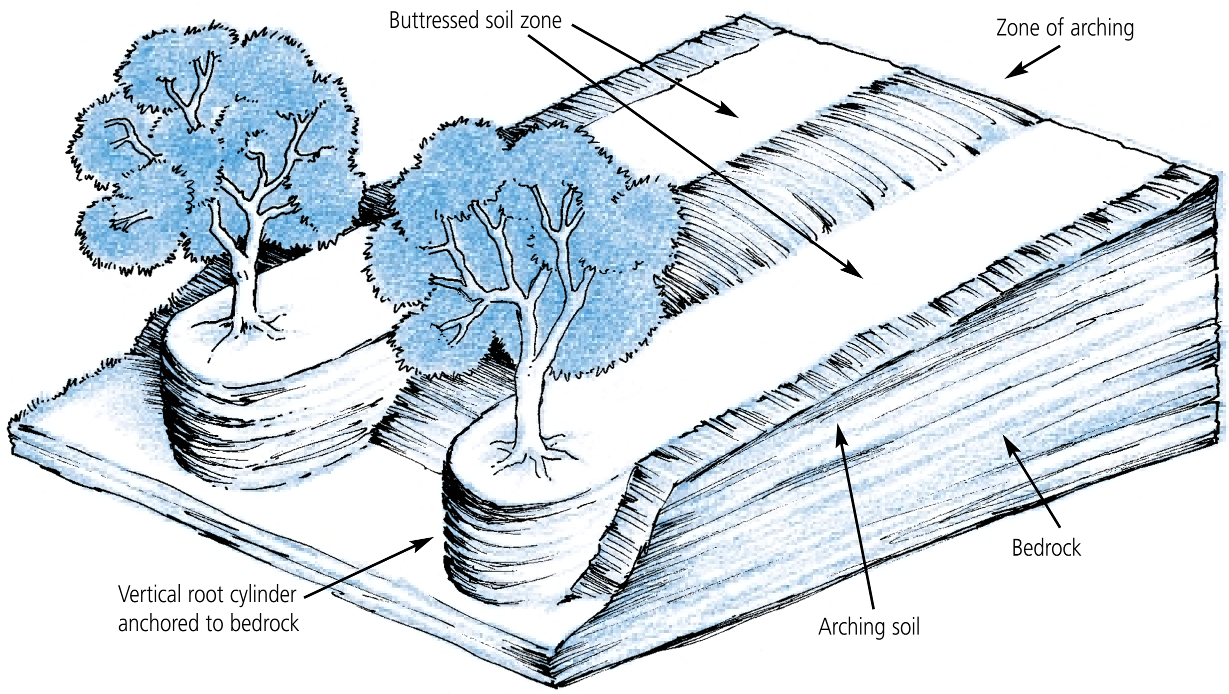


Figure 6.3 Schematic representation of soil buttressing and arching. Source: Coppin & Richards (1990).

A tree buttressing a column of soil on the Tarwin River, Victoria. Photo by Ian Rutherfurd.

within the soil, and root density. Generally, smaller roots are the main contributors to additional soil strength. Roots over about 20 mm 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). However, work overseas suggests that small roots of northern hemisphere species can increase cohesion by an average of 20%, although this can be up to 50% (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.

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 kilopascal increase in apparent bank cohesion from tree roots, applied throughout the profile, extends the stable height of a 90° bank by some 2 m (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 m higher than for its bare counterpart. The increase in cohesion from roots can be put into context by expressing the effect in terms of bank height. Experiments on the Latrobe River suggest that a 10 kilopascal increase in apparent cohesion from tree roots, applied throughout the profile, would mean that a 90° bank could be 2 m higher before it would fail (Abernethy & Rutherfurd 1998). At an angle of 45° the bank could be 4 m higher.

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.

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).

The surcharge weight of trees is usually not an important cause of bank failure. Photo by Ian Rutherfurd.

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.

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.

Basal endpoint control: limits to the application of vegetation

Basal endpoint control describes the competing tendencies of scour and accumulation of sediment in the basal area. The basal area is that part of the bed and lower bank that surrounds the toe of the bank. Removal or accumulation of bank debris from the basal area depends entirely on the capacity of the stream flow to break up and entrain bank debris and transport it downstream.

The notion of basal endpoint control argues that of the three groups of erosion processes (sub-aerial erosion, scour and mass failure), it is scour of the base of the bank that is the most important.

The reasoning is that both sub-aerial erosion and mass failure tend to reduce the slope of the bank, while basal scour tends to increase the bank slope. Slumped sediment from mass failure, for example, tends to accumulate at the toe of the bank, producing a lower, stable slope. However, basal scour removes the material deposited at the toe and increases the slope of the bank again, triggering further mass failure.

It is important to note that basal scour, often associated with the outer bank of meander bends, is the most difficult process to control with vegetation because it takes place below the point where vegetation can be established. When considering vegetation of banks to control erosion, the most effective priorities for planting are, in order,

1. the toe of the bank (including the sediment delivered to the toe of the bank by slumping), where it will both strengthen the bank against scour and reduce flow velocities. Vegetation hanging into the water has the same effect;
2. the bank face, where it will slow the rate of sub-aerial erosion and mass failure.

Certain types of plants are better suited than others for specific stabilisation objectives. Woody vegetation is stronger and deeper rooted than grasses and provides greater mechanical reinforcement at depth. It also provides buttressing benefits and beneficial surcharge. These features mean that woody plants are superior for mass stability. On the other hand, grasses provide a dense ground cover and are, therefore, more effective at reducing scour and sub-aerial processes. Most grasses are not adapted for the very wet habitat formed at the water's edge. Here, macrophytes can perform a role in stabilising the bank.

Managers confronted with eroding banks that they believe can be treated with riparian revegetation should consider the dominant erosion processes occurring at the site and their likely interactions with the various plant types. In this regard, position in the catchment and the scale of the channel should also be considered. The following section explores both these features.

6.4 Erosion of small and large channels

So far we have described the effect of vegetation on 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. This section describes some of the changes.

Upland creeks

Live and dead vegetation in the channel can have a huge influence on small streams. The low banks of these streams mean channel morphology is overwhelmed by the type of riparian plants growing on the banks and by the relatively large size of timber falling into the channel.

Sub-aerial mechanisms (see Section 6.3) tend to dominate the bank erosion processes in these upper reaches of the stream network. Because the banks are so low, the risk of mass failure is reduced, the strength of bank materials alone generally being enough to support the bank and withstand mass failure. The small catchment area also precludes highly erosive discharges and scour is limited. The main role of the flow is to transport bank material that is loosened in situ or delivered to the flow by sub-aerial processes. This situation changes dramatically, of course, if the small stream becomes incised. Gullies are discussed in Section 6.5.

Mid-basin streams

As catchment areas increase in size, so do discharge and channel dimensions. In mid-basin reaches, slope and discharge can combine to produce conditions where flow erosivity (scour) is maximised.

Sub-aerial erosion by desiccation, slaking and over-bank flow is likely to be increasing in these reaches due to the higher banks and greater variation in flood stage. Similarly, bank scour may undercut the bank to the point where cantilever failures occur. The dominant form of erosion in mid-basin reaches is scour of the bank as individual particles are removed by the flow and transported away. The other processes tend to merely supplement the bank loss associated with scour.

Vegetation can form an effective protection against high rates of erosion in these reaches, and any plant that comes into contact with the flow will exert an influence. Trees (and associated large woody debris) can slow flow velocities considerably and, where they are correctly positioned, direct flow away from the banks and into the centre of the channel. Grasses and shrubs are important for directly protecting the bank from high near-bank velocities, and their fibrous root systems provide valuable strength for retaining surface grains on the bank face.

Lowland rivers

On the broader floodplain, mass failure becomes more and more apparent. Here, the contributions of sub-aerial erosion and scour to the overall erosion rates are secondary to mass stability considerations. As the bank height increases, shallow-seated, relatively planar slips become more common. On steeper bank sections, toppling slab failures occur—often in association with tension cracking. On higher, less steep banks, deep-seated rotational failures are the common failure mechanism. In reality, all mass failure types may occur within a short reach of the stream, depending on channel form, bank geometry and riparian vegetation.

Erosion in lowland rivers is concentrated on the outside banks of meander bends, which are often quite steep. Meander migration commonly proceeds by mass failure followed by basal cleanout of the failed material by scour.

The steepness of the bank face often prevents the establishment of vegetation there, and the roots of trees at the tops of banks may not penetrate deeply enough to provide additional stability throughout the bank profile. In these cases, vegetation is able to control erosion processes.

In other parts of lowland rivers the angle of the bank enables vegetation to become established on the bank face. In this case the roots of shrubs and trees can easily cross the shear planes of shallow slips, while ground cover species and macrophytes can protect against basal scour and sub-aerial erosion.

Vegetation as a 'front-line' erosion control tool

Now that we have discussed the interaction between vegetation and erosion processes, we can discuss how much stability can be expected in a stream following revegetation. Vegetation will not solve all stream stability problems, neither will it stop all channel change. There are three important points to make in relation to the limitations of revegetation in stability.

1. Before European settlement of Australia, even with a full cover of native vegetation, streams eroded their banks and experienced major changes of channel form and position, admittedly at a slower rate than without vegetation. The evidence for such changes is manifest as old channels and features on our floodplains.
2. Clearing of vegetation and other European modifications have greatly increased the effective 'power' of our streams. That is, over the last 150 years many of our streams have deepened and enlarged so that they now carry a higher proportion of water in the channel than on the floodplain. This fundamental transformation of our streams cannot be simply reversed by returning the original vegetation to the stream. In many cases the forces now operating in our transformed channels are too great to be controlled by vegetation alone.
3. There are many situations where the assets threatened by erosion are too valuable to be protected by vegetation alone; that is, vegetation alone cannot provide enough certainty of protection. After many years of experience in using vegetation for stabilising slopes and streams, Gray and Sotir (1996) conclude that a prerequisite for success is having a stable base on which vegetation can grow. In most cases it is necessary to stabilise the toe of a bank with rock, gabions or some other engineering structure first. This point gets back to the basal endpoint control issue discussed above—it is the toe of the bank that is critical in erosion control.

It is also important to note that these engineers have reached this conclusion working with much stronger and more responsive vegetation than we can in Australia. Almost without exception, the bio-engineering designs used in the northern hemisphere use willow stakes as the central feature. The stakes are 'woven' into the engineering structure and then grow quickly, producing a true bio-engineered structure. As there are sound reasons for not using willows in most rehabilitation work in Australia (at least for the long term), we face an even harder job in incorporating vegetation in engineering designs than do our northern hemisphere colleagues. While techniques have recently been developed to grow Australian native plants found naturally along river banks (for example, *Casuarina* and *Callistemon* species with long stems suitable for planting into stream banks) it is not yet known whether these genera will grow quickly enough to be able to substitute for the willows and poplars used in the past to help secure eroding sites. There is also the ecological question of introducing these plants outside their natural range.

6.5 Some special issues of erosion and vegetation: gullies and willows

Gully erosion

The importance of gullies as contributors to an oversupply of sediment and nutrient to streams is discussed in Chapter 5. Gullies not only contribute to the oversupply of sediment and nutrients; they also dissect fertile valley flats, damage fences, buildings and roads, and present an eyesore in rural landscapes.

Gully initiation

The main phase of gully expansion occurred last century, but there are still areas where new gullies are forming and areas where gullies could form in the

An active gully in the Avoca catchment, western Victoria.
Photo by Ian Rutherfurd.

future. Gullies originate in steep valleys and towards the foot of long slopes where flows naturally accumulate (Prosser & Abernethy 1996). Flows can reach several centimetres in depth during large storms and can exert a powerful force on the soil surface. Because the binding action of roots increases the resistance of the soil to scour, a complete ground cover of grasses can prevent erosion. Grasses also absorb up to 90% of the force of the flow (Prosser et al. 1995). Much of the gully erosion we see today occurred because the vegetation cover on valley floors was degraded by stock, was ploughed, or was deliberately channelised and drained. In other words, in most cases it was the local degradation of vegetation, rather than increased runoff resulting from land use upslope, that was the primary cause of gully erosion (Prosser & Slade 1994). It is evident that much future gully erosion can be prevented by identifying areas of concentrated flow which are prone to gully erosion and keeping these areas protected with a good grass cover or by replacing grasses with trees. The highest priority areas will be steep hillslope hollows with upslope catchment areas of 1 hectare or more.

Gully widening and extension

Gullies erode rapidly in the first few decades after they are initiated as the headcut retreats upslope and the banks widen and decline in angle. Many of the gullies evident today are deep, long and devoid of vegetation. They look as if they are capable of considerable future erosion. However, if they are several decades old and are in pastoral or agricultural land they are probably approaching their limits of headward erosion, and structural works are rarely required to prevent further erosion of the gully head. Today, the main source of sediment from gullies is from erosion of the gully walls (Blong 1982). This erosion produces poor-quality, turbid water that is high in phosphorus (see Chapter 5). Vegetation can be used to both stabilise the banks and improve water quality.

Gully walls erode by much the same processes as do hillslopes (see Chapter 5 and Section 6.3). Rain splash and runoff over the banks entrain sediment; wetting and drying as well as frost heave loosen sediment; seepage in the gully banks pushes loose sediment into the gully; and flows down the gully scour the toes of the bank. The sediment entrained by these processes can be reduced by establishing a dense ground cover on the gully walls. This will only be possible once the bank is approaching stability (otherwise the grass itself will be eroded away) and where the banks are sloping rather than vertical. Trees planted at the top of the banks will have very little effect on bank erosion if grasses and sedges do not grow on the face of the banks themselves. Deeper gullies with steep banks are prone to mass failure (specifically, toppling and slumping) of their banks (see Section 6.3). Trees planted within 3 m of the edge of the bank can help prevent this process, but those planted further back will have little effect.

Revegetating gully floors

Over the past 10 000 years, many gullies formed naturally. However, within a few hundred years of the gullies being formed, sedges and grasses had colonised the gully floors (Prosser et al. 1995). This vegetation trapped sediment, promoted vegetation growth, and eventually led to complete filling of the gully. Unfortunately, because this process (from formation to re-filling) takes several thousand years, it is not by any means a quick solution to present gullies. However, the process of trapping sediment can be used to reduce the delivery of eroded sediment downstream. Vegetation planted in the gully

The floors of many of the older gullies are now being colonised by vegetation and, in bigger gullies, these can be considered as in-stream wetlands. A good example is the very extensive in-stream wetlands of the Jugiong Creek catchment in central-west New South Wales. These wetlands are vegetated with very dense stands of *Typha*, *Phragmites*, *Juncus* and members of the Cyperaceae family, which completely cover the channel floor for uninterrupted lengths of 1 to 15 km. The channels of the Jugiong Creek catchment are frequently incised and there are only small patches of floodplain, with the result that almost all stream flow is forced to pass through the wetlands. The wetlands have expanded in the last 10 years and have trapped an approximately 10 cm depth of fine mud, which would otherwise have been delivered downstream. Where stock have been excluded, the vegetation in the area is also stabilising the foot of the gully walls. About one-third of the gullies drain through at least 2 km of wetland before entering the Murrumbidgee River. Perhaps the most remarkable feature is that streams with catchment areas as large as 50 km^2 have well-developed and persistent wetlands. This natural spread of vegetation demonstrates the potential for revegetating gully floors and restoring swampy valleys to something like their natural condition.

Ian Prosser, Christoph Zierholz and Peter Fogarty in Jugiong Creek, New South Wales. Photo courtey Ian Prosser.

floor can deflect flow toward the walls of the gully. This can be avoided by planting densely on both sides of the gully and less densely in the centre of the gully floor.

6.6 Willows and erosion

Willows are a major stream-management issue in southern Australia. In much of the south-east they are the dominant riparian species. There is a strong trend to remove willows from streams because they choke and shade out channels, use a large amount of water (this is of particular concern in Tasmania), have low biological value, and are beginning to spread dramatically by seed. Balanced against the arguments for removing willows are two major concerns. The first is that many people like the look of willows (for example, there is resistance to removing weeping willows along the upper Murrumbidgee River because the willows are considered to be part of the 'cultural landscape'). The more substantial argument is that willows are very effective at stabilising stream channels. This was often the reason they were introduced in the first place.

Willows grow rapidly, right on stream banks, and vigorously resist erosion. Some native tree and reed species share some of these features, but few share them all. Banks planted out with willows are at least 80% more resistant to fluvial scour than grassed banks and perhaps 30% more resistant than a dense stand of native vegetation (see Table 6.3). A dense

Table 6.3 Tractive stress rating of various materials

Bank material	Tractive stress (Newtons/m²)
Bare banks	1 to 10
Grass (turf)	15
Dense native vegetation	about 50
Willow revetment	70
Rockfill bank protection (average diameter 0.4 m)	150

Source: Walter Hader, NSW Department of Land and Water Conservation, pers. comm.

stand of willows can increase the shear strength of soils by up to 100% (Waldron 1977). The result is that many unstable streams are now lined with willows, and in small streams there are many places where large erosion heads are caught in willow roots.

Despite their advantages in erosion control in many parts of south-east Australia, the disadvantages of willows are seen to outweigh the erosion benefits. As a result, there are several willow eradication programs being run across the country, with catchments in South Australia, Victoria and Tasmania undertaking work in this area. As this chapter demonstrates, it is important that managers consider the potential erosion problems when removing willows. Without such consideration, problems can increase rather than decrease. Potential solutions to problems associated with willows are provided in Guideline C.

Large woody debris is also an important factor in stream erosion; this is dealt with in Chapter 7.

Willows in the Torrens River, South Australia, divert flow around them and erode the banks. Photo by Ian Rutherfurd.

Current research

The role of trees in mass failure of stream banks

This research is investigating the strength and density of roots from Australian species, as well as their mechanical effects in stream banks, in order to provide information on suitable native species for stream-bank stabilisation.

Researchers: Bruce Abernethy and Ian Rutherfurd, Cooperative Research Centre for Catchment Hydrology at Monash University

The effect of vegetation on stream-bank scour, including the processes of undercutting and frost heave

This research is being conducted to determine the role of vegetation in preventing generation of turbid waters in small incised streams. It is a collaborative project being conducted in Tasmania.

Researchers: the Inland Fisheries Commission, the Hydro-Electric Commission and the Cooperative Research Centre for Catchment Hydrology at Monash University

Identification of native vegetation species that can effectively stabilise stream banks

The critical role of large woody debris and riparian vegetation in the geomorphology (stability and shape) of Australian streams

The effect of large woody debris on bed and bank erosion in streams

The effect of vegetation on hydraulic resistance in channels

These four projects are designed to help predict the height of floods at cross-sections with and without vegetation and to enable improved design of river restoration projects.

Researchers: Ian Rutherfurd and students from the Cooperative Research Centre for Catchment Hydrology at Monash University

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CHAPTER 7

Large woody debris and other aquatic habitat

Simon Treadwell, John Koehn, Stuart Bunn

Summary

- Although much large woody debris has been removed from Australian streams, what does remain provides important habitat for microbes, invertebrates, fish and other animals.
- In addition to directly controlling the way many streams and rivers function as ecosystems, riparian vegetation and large woody debris contribute to aquatic habitat and thus have a major influence on biodiversity.
- Riparian vegetation increases the variance in channel form, and this leads to a diversity of in-stream habitats, a major determinant of biodiversity.
- In-stream cover in the form of woody debris, rock ledges, overhanging vegetation and undercut banks is an important feature of stream habitats.
- The habitat features which provide fish with shade, shelter from predators, shelter from currents, and food and feeding areas are considered in this chapter.
- Riparian vegetation also protects aquatic habitats by reducing the inputs of inorganic sediment to streams, which chokes stream pools and smothers the interstitial habitats in coarse gravel beds.

7.1 Large woody debris

What is large woody debris?

Several interchangeable terms are used to describe woody debris, which is made up of the sticks, branches, trunks and whole trees that fall into rivers and streams. The scientific literature generally refers to woody debris as 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. The Australian term commonly used when referring to LWD is 'snag', although this typically refers to a complex structure that generally consists of very large, highly branched debris or more than one piece of LWD. In these guidelines, 'LWD' is used when referring specifically to wood as a substrate; 'snag' is used when referring to more complex LWD accumulations.

Large woody debris is a significant ecological component of streams, both in Australia (Lloyd et al. 1991, O'Connor 1991a, Gippel et al. 1996a) and elsewhere (Marzolf 1978, Bilby & Likens 1980, Benke et al. 1985). It is an important structural component of rivers, influences many ecological processes (see Chapter 4) and provides essential habitat for aquatic and terrestrial organisms. It also plays a role in stream morphology and stability.

Sources, amounts and longevity

Sources

Most LWD enters streams from adjacent and upstream riparian land. In the natural state, 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, this depends to a large extent on topography and forest age.

Large-scale disturbances (such as landslides and erosion of undercut stream banks) can increase the import of LWD to a stream. A further source of LWD to large streams is floods, which bring in LWD from tributaries and floodplains (Harmon et al. 1986). However, floods can also *remove* LWD from small streams and deposit it on the floodplain. Along Australian rivers, self-pruning of *Eucalyptus* species due to osmotic stress in hot weather is a major source of LWD (Lloyd et al. 1991).

Amounts

Records, mostly from the Murray–Darling River system, indicate that most large 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).

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

There is limited historical evidence of snag loadings from other river systems around Australia, although there is evidence 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).

Even though the ecological importance of woody debris in riverine environments is now well known, and many of the arguments for snag removal can be discounted, removal of snags continues in many rivers. De-snagging is continuing mostly as misdirected efforts to reduce flooding of agricultural land, reduce erosion and increase hydraulic capacity. However, the Murray–Darling Basin Commission has recognised the importance of snags, and a moratorium on their removal from the Murray River has been recommended (Lawrence 1991).

Available data on current LWD 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 US data are summarised in Table 7.1.

De-snagging and clearing of riparian land reduces the supply of wood to the adjacent river and results in a slow decline in the amount of LWD present. This is because the wood which decays is not replaced. However, natural LWD loadings of Australian streams (at least in temperate regions) are generally higher than those of streams in the northern

> With the realisation of the importance of LWD to stream ecosystems, researchers have started to quantify the amounts of LWD in streams. Large woody debris loadings can be measured in a number of ways, but this can make comparisons between different systems difficult. A simple measure of LWD is the number of wood pieces, or snags, 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 debris 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 snag surface compared with other benthic surfaces can also be estimated.

Table 7.1 Large woody debris loadings in Australian and some US rivers

Stream	Catchment size km² (stream order)	LWD loading kg.m⁻² (m³/m²)	Density items/100m (both banks)	Surface area m²/m² stream bed	Proportion of total habitat area available as snag surface	Land use	Riparian vegetation	Reference	Comments
Pranjip Ck (Vic)	787	0–5 (0–0.008)		0–0.2		Agriculture	Degraded	O'Connor (1992)	
"	>787	3.9–42.4 (0.005–0.055)		0.28–0.91	21–47%	Agriculture	Intact	O'Connor (1992)	
Keppel Ck (Vic)	14.3 (4)	4.3 (0.007)	490	0.31	21%	Forested	Intact	Treadwell et al. (1997), S. Treadwell & I. Campbell (unpub.)	
Wellington R (Vic)	122 (4)	(0.0057)		0.097		Forested	Intact	I. Campbell & M. Shirley (unpub.)	
Carey R (Vic)	244 (5)	(0.0004)		0.015		Forested	Intact	"	
Dolodrook R (Vic)	145 (5)	(0.0056)		0.048		Forested	Intact	"	
Murray R billabongs (NSW and Vic)					5–15%	Agriculture	Various	M. Shirely (unpub.)	
Murray R Yarrawonga (NSW)			14			Agriculture and forested	Various	J. Koehn (unpub.)	Mature red gum trees along banks
Murray R Barmah Forest (NSW)			9.5			Forested	Intact	Gippel et al. (1992)	Channel de-snagged in past
Murray R Overland Corner (SA)			2.7			Agricultural	Degraded	Lloyd et al. (1991)	Channel de-snagged in past
Goulburn R (Vic)	16 125		23.6			Agriculture and forested	Intact	Anderson & Morison (1988)	Logs and log jams
Thompson R (Vic)	3540	(0.0172)	12.1	0.1184		Agriculture	Intact	Gippel et al. (1996a)	

Table 7.1 continued

Stream	Catchment size km² (stream order)	LWD loading kg.m⁻² (m³/m²)	Density items/100m (both banks)	Surface area m²/m² stream bed	Proportion of total habitat area available as snag surface	Land use	Riparian vegetation	Reference	Comments
Johnstone R and Mulgrave R (north Qld)	(1)		9.2					B. Pusey, A. Arthington & M. Kennard (unpub.)	LWD only within 1 m of bank = > underestimate
"	(2)		22.4					"	"
"	(3)		14.4					"	"
"	(4)		3.8					"	"
"	(5)		4.8					"	"
"	(6)		0.2					"	"
Dandelup R (WA)	(4)				0.4%	Agriculture	Degraded	Beesley (1996)	Channel de-snagged in past
Serpentine R (WA)	(4)				1.8–2.4%	Agriculture	Intact	Beesley (1996)	
"	(4)				1.6–7.9%	Forest	Intact	"	
Willamette R (Oregon)	29 138		55: before de-snagging 0.3: after de-snagging				Extensive riparian forest now cleared for agriculture	Sedell & Froggatt (1984)	
Walton Ck (Colorado)	26.1 (2)	(0.001)	20				Degraded	Richmond & Fausch (1995)	
Ogeechee R (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

Table 7.1 continued

Stream	Catchment size km² (stream order)	LWD loading kg.m^{-2} (m^3/m^2)	Density items/100m (both banks)	Surface area m^2/m^2 stream bed	Proportion of total habitat area available as snag surface	Land use	Riparian vegetation	Reference	Comments
Satilla R (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 R (Oregon)	1024 (6)	0.5 (0.001)				Forest	Intact forest floodplain	Keller & Swanson (1979)	
Lookout Ck (Oregon)	60.5 (5)	11.6 (0.023)				Forest	Intact	Keller & Swanson (1979)	

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 other factors probably also contribute to higher natural LWD loads in temperate 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.

It has generally been considered that as stream size or stream order increases, the amount of LWD present 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 LWD 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 m wide stream than in a 25.6 m 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.

Longevity

The slow decay and high stability of LWD 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 LWD 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 debris 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).

Based on the age of some logs, some debris accumulations appear to have been stable for up to 2000 years (Nanson et al. 1995), indicating the ability of LWD to reduce stream power and stabilise channel beds and banks over long periods.

7.2 Direct use of LWD as habitat

Large woody debris provides habitat over a range of spatial scales for many aquatic organisms. It 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).

Snags 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 small sticks, twigs and other debris trapped against larger material 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 refered 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.

Although wood provides a significant stable substrate, and in some cases with surface areas equivalent to that of the stream bed (O'Connor 1992), algal development within this biofilm in Australian lowland rivers may be restricted. This is because algae can be smothered by fine sediment and rapid changes in river height (due to river regulation) prevent stable light environments. Where algal development is so restricted, fungi and bacteria are likely to constitute the greatest biomass in biofilm on snags, and heterotrophic respiration is likely to be the major process.

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 LWD in preference to other substrates. This highlights the importance of LWD in contributing to biodiversity. Most invertebrates that colonise LWD 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 LWD provides the only stable substrate for invertebrate colonisation, particularly during high-flow periods (Beesley 1996). In intermittent streams, LWD 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 contributing to surface complexity and promoting further colonisation (Flint 1996, McKie & Cranston 1988).

De-snagging, particularly in rivers where LWD is 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

Much of the in-stream habitat available for fish originates from riparian zone vegetation (Koehn & O'Connor 1990). In Australian lowland streams

Large woody debris are a vital component of in-stream habitat. Photo by John Koehn.

LWD is usually the major form of in-stream structural habitat used by many species.

Fish need complex snags to hide from predators and to avoid intense sunlight and high current velocities. Large woody debris provides protection from predation but 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 snags 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' snag (J. Koehn, unpublished data).

Snags 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. Snags 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 woody debris provides 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 snags, 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, LWD in anabranches and other channels provides 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.

Trout cod *Maccullochella macquariensis*.
Photo courtesy of Murray–Darling Basin Commission.

Table 7.2 Native freshwater fish species with a documented use of LWD 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)
Two-spined blackfish	*Gadopsis bispinosus*	Likely spawning site, preferred habitat	Robison & Beschta (1990), Koehn (1987)
Murray cod	*Maccullochella peelii peelii*	Spawning site, preferred habitat	Llewellyn & MacDonald (1980), Cadwallader & Backhouse (1983), J. Koehn (unpub.)
Trout cod	*Maccullochella macquariensis*	Spawning site, preferred habitat	Cadwallader (1978), J. Koehn (unpub.)
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), Merrick & Schmida (1984)
Spotted galaxias	*Galaxias truttaceus*	Preferred habitat includes woody debris	Williams (1975)
Tasmanian mudfish	*Galaxias cleaveri*	Preferred habitat includes woody debris	McDowall (1980)
Mountain galaxias	*Galaxias olidus*	Preferred habitat includes woody debris	Marshall (1989)
Catfish	*Tandanus tandanus*	Affected by de-snagging	Reynolds (1983)
Australian bass	*Macquaria novemaculeata*	Preferred habitat includes woody debris	Marshall (1979)
Estuary perch	*Macquaria colonorum*	Preferred habitat includes woody debris	Sanders (1973), McCarraher (1986)
Barramundi	*Lates calcarifer*	Preferred habitat includes woody debris	Merrick & Schmida (1984)
Australian smelt	*Retropinna semoni*	Preferred habitat includes woody debris	Cadwallader (1978)
Tupong	*Pseudaphritis urvilii*	Preferred habitat includes woody debris	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 woody debris	Merrick & Schmida (1984)
Empire gudgeon	*Hypseleotris compressa*	Spawning	Allen (1989)
Barnett River gudgeon	*Hypseleotris kimberleyensis*	Preferred habitat includes woody debris	Allen (1989)
Prince Regent gudgeon	*Hypseleotris regalis*	Preferred habitat includes woody debris	Allen (1989)
Midgeley's carp gudgeon	*Hypseleotris* sp. A	Preferred habitat includes woody debris	Allen (1989)

Table 7.2 continued

Common name	Species name	Reason for use	Reference
Northern trout gudgeon	*Mogurnda mogurnda*	Spawning	Allen (1989)
False-spotted gudgeon	*Mogurnda* sp.	Preferred habitat includes woody debris	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 woody debris	Allen (1989)
Flat-head gudgeon	*Philypnodon grandiceps*	Spawning	Allen (1989)
Dwarf flat-head gudgeon	*Philypnodon* sp.	Preferred habitat includes woody debris	Allen (1989)
Swan River goby	*Pseudagobius olorum*	Spawning	Allen (1989)
Lake Eacham rainbowfish	*Melanotaenia eachamensis*	Preferred habitat includes woody debris	Merrick & Schmida (1984)
Westralian pygmy perch	*Edelia vitata*	Preferred habitat includes woody debris	Merrick & Schmida (1984)

Golden perch *Macquaria ambigua*.
Photo courtesy of the Murray–Darling Basin Commission.

At least 34 native freshwater fish species from around Australia use LWD 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 LWD 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 woody debris 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.

Other animals

Snags provide habitat for other aquatic and terrestrial species. Birds, reptiles, amphibians and mammals use woody debris for resting and foraging and as lookout sites (Harmon et al. 1986). Birds commonly use the exposed branches of snags as perch sites, while turtles climb out of the water using snag surfaces. Partially submerged snags provide habitat for both terrestrial and aquatic organisms and also allow small terrestrial animals to approach the water surface to drink and bathe. Snags 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 does woody debris located on riparian land and on larger floodplains.

7.3 De-snagging and river improvement

De-snagging and general river improvement have contributed to the degradation of many Australian rivers. In some cases de-snagging, especially when combined with channelisation, causes increases in current velocity. This can increase bank and bed erosion, especially in sandy-bed rivers (Bird 1980, Brookes 1985, Erskine 1990, Gippel et al. 1992, Shields & Gippel 1995). De-snagging and channelisation have also contributed to increased sedimentation and more severe flooding of downstream reaches (Zelman 1977, Brookes 1985).

River improvement 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 (Zelman 1977). 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).

Recent recognition of the role wood plays in river structure has resulted in several recommendations to restore snags to Australian streams (Lloyd & Walker 1986; Lawrence 1991; Gippel et al. 1996a, 1996b). In fact, snag restoration has already commenced at a number of sites in the Broken River catchment, Victoria (Tennant et al. 1996).

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, *Tandanus tandanus*, adults 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 snags (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

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 cm 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, LWD 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 s^{-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).

7.5 Effects of LWD on channel morphology

As well as providing direct habitat, LWD accumulations 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 debris depends on the orientation of key debris pieces (see Table 7.3).

Scour pools formed by LWD 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 LWD 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 LWD in the stream the bigger the pools (Carlson et al. 1990).

As is discussed in Chapter 2, at European settlement streams in the humid to semi-arid regions of Australia were full of fallen timber. Deflection around this LWD certainly caused local bank erosion, but this effect was moderated by the densely vegetated banks. There are numerous reports of dense layers of LWD incorporated in the sandy beds of lowland streams. De-snagging crews often removed several layers of large snags from sandy beds, which led to dramatic deepening. 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

Table 7.3 Habitat development as determined by snag orientation

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

Snags are important for creating a variety of flow conditions, Tumut River, NSW. Photo by Chris Gippel.

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.

LWD and channel erosion

LWD both increases and decreases local bank erosion in a number of ways:

~ by providing flow resistance in the channel, which reduces average flow velocity, *decreasing* 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 LWD even though the overall effect of LWD is probably to reduce bed scour).

Whether a given piece of LWD 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.

Most of these variables are in some way controlled by the size of the stream. There has been some research into the effects of LWD on bed scour (Cherry & Beschta 1989) 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 vegetation on erosion is by analogy with engineering structures in rivers (such as groynes, weirs and deflectors).

Some general principles

When considering the influence of LWD on channel morphology, a number of general rules (below) need to 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 LWD is almost complete. It is probably reasonable to assume that the erosion around LWD follows a negative exponential curve. This means that if a 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 LWD 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.

Large woody debris in a variable sizes, Tumut River, NSW. Photo by Chris Gippel.

- There is an infinite variety of snag sizes and orientations. The variables include the relative size of the snag to the stream, the length and diameter of the snag, 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 snag 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 debris 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 LWD on a bend will differ from that of the same snag 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 LWD on erosion decreases with the size of the channel. This can be demonstrated by considering the general planform of the channel. Although LWD 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 LWD which is, at most, a secondary impact on erosion processes. The same is not true of LWD in smaller streams. There is much literature (admittedly from North America) that demonstrates how LWD accumulations control the morphology of small headwater streams by producing large jams and accumulations of debris.

This chapter focuses on riparian vegetation and, in particular, LWD and its influence on river function and aquatic habitat. Guideline B in Volume 2 describes some options for managers attempting to restore river ecosystems affected by LWD or the loss of it.

Current research

The ecological basis for river habitat and in-stream flow management

This project is investigating the flow and habitat requirements of fish assemblages in Queensland coastal rivers.

Researchers: Professor Angela Arthington, Dr Brad Pusey, Mark Kennard, Griffith University

The importance of LWD in sandy river systems

This project is demonstrating the use of LWD rather than rock to create riffle pools on revegetated reaches of the Dandalup River in Western Australia, to provide pools that will not impede peak flood flows but will retain water during summer low-flows.

Researcher: Bill Till, Water and Rivers Commission (WA)

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CHAPTER 8

The role of vegetation in riparian management

Michael Askey-Doran, Neil Pettit, Lisa Robins, Tein McDonald

Summary

- Riparian land is often more diverse in flora and fauna and more productive than other parts of the landscape. Riparian vegetation is generally more dense, often contains a greater number of zones, and can be taller than nearby non-riparian vegetation.
- The high primary productivity of riparian lands is the result of soils which are richer in nutrients than those further upslope as well as a greater availability of water, shade and shelter. The composition and structure of riparian vegetation vary both locally and along the length of the river.
- Vegetation abutting waterways protects water quality; it filters water moving across the soil surface, via underground systems, and in the air. Fine leaves, twigs, coarser branches and trunks provide a source of both food and habitat for aquatic plants and animals. Removing or disturbing riparian vegetation can alter the physical and chemical properties of the adjacent water body, adversely affecting aquatic organisms. It can also cause the scouring and collapse of stream banks.
- Well-managed riparian zones can provide windbreaks, slowing the wind that would dry out pastures and crops and remove valuable topsoil. Riparian vegetation can further contribute to agricultural productivity and business profits by way of agroforestry, apiculture, forage production and storage, stock shelter, land value and ecotourism.
- Riparian environments are prone to both natural and human-induced disturbance. Significant natural and human-induced disturbances are associated with flooding, water regulation, fire, vegetation clearance and fragmentation, the introduction of plant species and livestock, and rising groundwater and salinity.

Some riparian environments are unable to recover naturally from disturbance, indicating that the impact of such disturbance has pushed the ecosystem beyond a threshold.

8.1 Characteristics of riparian vegetation

Riparian plant communities have higher plant species diversity and are often more productive than communities in adjacent upland areas. The high primary productivity of riparian lands is the result of the presence of soils which are richer in nutrients than those further upslope, as well as the greater availability of water, shade and shelter.

Flora diversity

Riparian land provides habitat for a wide range of plant species and is rarely homogeneous. The vegetation of a given site reflects past flood or other climatic events, as well as the history of erosion and deposition by the meandering channel. Its internal structure often reflects two major gradients: the longitudinal (along the stream) and the transverse (perpendicular to the stream) environmental gradients. These gradients interact with alluvial processes to contribute to habitat heterogeneity (Gregory et al. 1991). This, in turn, promotes increased species diversity and a complex vegetation mosaic (Malanson 1993). The complexity of vegetation is usually most evident on the broad floodplains of large lowland rivers.

Some plant species rely heavily on the particular characteristics and condition of riparian land, such as high soil moisture, nutrient status and disturbance through flooding, whilst others are less restricted in their preferences. Species such as river red gum, *Eucalyptus camaldulensis*, and black box, *E. largiflorens*, are closely adapted to the conditions which typify their environments (Dexter et al. 1986, Parson 1991). Other species such as the South-esk pine, *Callitris oblonga*, box micrantheum, *Micrantheum hexandrum*, and the midlands mimosa, *Acacia axillaris* (Askey-Doran 1993) typically occur in riparian lands (these examples in Tasmania). *Waterhousea floribunda*, water gum, *Tristania neriifolia*, *Potamophila parviflora*, *Tristaniopsis laurina*, *Callistemon viminalis* and *Casuarina cunninghamiana* are generally confined to riparian forests in the sub-tropical regions of New South Wales and Queensland (Raine & Gardiner 1995). The rainforest species *Tristaniopsis laurina* shows a strong preference for the conditions which characterise riparian environments. For some riparian species, successful seedling establishment is dependent on relatively high light requirements which can be maintained through flood disturbance (Mellick 1990).

Extreme environmental conditions, as they apply to factors such as drainage, climate, physical characteristics and disturbance regimes, can result in fairly distinctive community types. For example, in south-west Australia vegetation communities on low-lying areas may be characterised by the presence of *Eucalyptus rudis* (Boland et al. 1984), and in Tasmania by *Eucalyptus rodwayi* grassy communities (Askey-Doran 1993). In the Murray–Darling, river red gum (*Eucalyptus camaldulensis*) communities require regular flooding or the presence of adequate groundwater (Bren 1988).

Riparian land is an important refuge for endangered or vulnerable plants. A review of *Callitris oblonga* communities in Tasmania identified at least nine nationally listed endangered or vulnerable species occurring in those communities (Askey-Doran 1994). Similarily, the most extensive populations of the rare wattle *Acacia axillaris*, occur along rivers in the Tasmanian midlands. In Western Australia there are over 100 endangered species recorded along the State's rivers (Briggs & Leigh 1995). Thirty species from riparian communities in the Murray–Darling basin of New South Wales have been listed as endangered (Parson 1991).

It is important for managers to be aware of the species of flora that characterise their area before attempting to redress past management practices.

Eucalyptus rudis near the Brockman River, Darling Range, Western Australia. Photo by M.D. Crisp, courtesy of the Australian National Botanic Gardens.

Nutrient enrichment

Riparian soils receive nutrients from both land and water. Minerals, nutrients and sediments from upland areas are transported to lower-lying riparian areas of the catchment by surface runoff after rain, while stream nutrients are deposited along stream banks during floods (Cummins 1993). Flooding is particularly important in contributing to the enrichment of floodplain soils along large lowland rivers.

Water and moisture

Water and moisture, which are generally more available in riparian areas, occur as

~ surface water;
~ groundwater (including sub-surface flow);
~ soil moisture.

Moisture is replenished directly during rain events and indirectly during flooding and by groundwater flows toward the stream. The relationships between precipitation, over-bank flow, groundwater flow, soil moisture and standing water in the riparian areas are complex (Malanson 1993; see also Chapters 5 and 6).

Evidence suggests that riparian trees make variable use of stream waters (see, for example, Thorburn & Walker 1994) and probably obtain the majority of their moisture from groundwater. However, some of the plant diversity of riparian land is due to the presence of plants which are particularly adapted to wet or moist conditions, especially where this is associated with surface water rather than groundwater (Horton 1972). The water available in riparian areas is essential to riparian fauna, because it supports the special vegetation communities which provide them with food, refuge and breeding sites, as well as generally reliable drinking supplies.

Food and productivity

Riparian lands are amongst the most productive ecosystems on earth. The rich plant communities of riparian lands support diverse and abundant communities of animals that feed on the living plants and their products (such as leaf litter). Riparian vegetation may contain a greater number or greater diversity of flowering and fruit-bearing plants, or these plants may flower or fruit more frequently, as a result of the availability of water and nutrients. This provides food resources for a range of animals.

In Australia, many eucalypts shed leaves evenly throughout the year and these decompose slowly, providing a constant food supply. This may be important in maintaining healthy aquatic ecosystems throughout the year. Deciduous plants have a different pattern of leaf fall (generally seasonal) and their leaves decompose quickly in water, often providing abundant food but only for one to two months. The fallen branches of eucalypts may contain hollows which provide further terrestrial and in-stream habitat.

Shade and shelter

Dense riparian vegetation, particularly riparian forest, reduces the impact of wind and decreases the amount of solar radiation reaching understorey vegetation and the forest floor. The presence of surface water and evapotranspiration by plants contribute to the high local humidity often experienced in forested riparian habitats (Malanson 1993). The high humidity of the riparian microclimate may also be important to species which are sensitive to desiccation.

The maintenance of microclimates must be considered when managing riparian lands.

8.2 The contribution of healthy, natural riparian vegetation

Biological diversity

Riparian environments are storehouses of biological diversity—at the genetic, species and ecosystem levels. Riparian plant life is itself unique and biodiverse, and hence worth conserving in its own right. However, it also provides habitat for terrestrial and in-stream fauna (Catterall 1993, Collier 1994), which may move in and out of the riparian environment or be permanent inhabitants (LWRRDC 1996a).

Studies have shown that riparian land often has a more diverse flora and fauna than other environments and often harbours rare and threatened species (Briggs & Leigh 1995, Parson 1991). Riparian corridors are important links between parts of the landscape, supporting migration and recolonisation of species. Woody debris and shading from riparian

Riparian forest in south-west Western Australia. Photo by Ian Rutherfurd.

vegetation also contribute to in-stream habitat and to the maintenance of aquatic biota (see Chapter 7).

The recovery of plant and animal populations from natural or human-induced catastrophic events is more likely in riparian environments which are biodiverse. Populations that are degraded and isolated are less likely to recover, and species extinctions may result from further disturbance. Maintaining, removing or disturbing natural habitats can have implications for aspects of ecosystem function both close to and distant from the immediate area (Commonwealth of Australia 1993).

Water quality

Riparian vegetation acts as a water-purifying system, buffering the adjacent waterbody from contaminants and thus protecting water quality (Riding & Carter 1992). As water passes over or through soil it may collect a variety of substances, such as soil particles, bacteria, algae, dissolved and undissolved organic compounds and salts of various kinds. This material may be transported to a water body, either dissolved or in suspension (LWRRDC 1996b), and have wide-ranging, often deleterious, effects. Riparian vegetation can 'filter' some of these contaminants before the water reaches the stream.

Similarly, rain may contain dissolved or suspended contaminants, such as salt and chemicals, and wind may transport sediment in the form of fine particles, organic debris and chemical sprays. Riparian vegetation can help to trap these contaminants, so preventing their wider dispersal, (O'Loughlin & Cullen 1982; see also Chapter 5).

The removal or disturbance of riparian vegetation, which leads to changes in the natural concentrations of the physical and chemical properties of a waterbody, can have an adverse effect on the biological components and integrity of the aquatic system. Properties such as species abundance, distribution, frequency, fertility and mortality may be adversely affected (O'Loughlin & Cullen 1982).

Metals and toxic substances may be directly harmful to plant and animal life and often accumulate in tissue over time. Nutrients, particularly excessive nitrogen and phosphorus, can cause prolific plant growth (for example, cumbungi, *Phragmites* and algae) and water deoxygenation. Clearing of riparian vegetation and the associated increase in light levels reaching the water result in reduced shading and increased growth of aquatic macrophytes and algae.

Salts contribute to deoxygenation and temperature stratification. Suspended solids (plant matter, sand, silt and clay) cause siltation and degraded fish and invertebrate habitats (Weston et al. 1983). Poor water quality may also contribute to economic and social costs, such as those associated with water treatment, human and stock health problems, diminished fishery resources, and weed control.

Bank stability

The root systems of riparian vegetation stabilise banks by binding the soil. Fine roots are more important in this process than are thick roots. Surcharge—the weight imposed on a bank by vegetation—is an issue only when banks are vertical or nearly so. For sloping banks, vegetation will normally improve bank stability.

Stream banks from which vegetation has been removed can suffer from scouring and collapse (see Chapter 5). There are five key features of riparian vegetation that affect the incidence of scouring and collapse: root systems, surcharge, water use, buttressing, and the ability of vegetation to reduce the velocity of flow (LWRRDC 1996c).

Riparian vegetation, by using water and improving drainage, can help stabilise the bank and reduce the risk of sudden collapse. Riparian vegetation on the face of a stream bank may buttress the soil above it, also reducing the risk of collapse. The velocity of water flow in a channel can be decreased by vegetation growing either on the bank or in the water and by debris or sediment in the stream (Department of Conservation and Environment 1990, LWRRDC 1996c).

Food supply

Natural stream side vegetation contributes organic material (ranging from fine leaves and twigs to coarser branches and trunks that gradually decompose) as food and habitat for aquatic plants and animals. These riparian inputs are a major component of the diet of species of invertebrates, native fish and other aquatic vertebrates such as turtles. Riparian fruits can also be important, especially in tropical and sub-tropical regions. Some native fish feed exclusively on the insects and other land animals which fall, are washed or are blown into water. What goes into upper tributary streams may be an important food source in the lower reaches of the river (Commonwealth of Australia 1993, LWRRDC 1996d).

Climate moderation

Well-managed riparian vegetation can provide windbreaks, slowing the wind that would dry out pastures and crops and remove valuable topsoil. Riparian vegetation can also shelter stock from sun, heat and drought, and wind, cold and frost. This is especially important for dairy cattle, lambs and newly shorn sheep. Riparian vegetation may also be responsible for creating quite specific micro-climates which support organisms reliant on specific climatic conditions for their existence (Commonwealth of Australia 1993).

Farm productivity

As noted, riparian land management can directly, and indirectly, affect agricultural productivity and business profits by providing shade, shelter, reduced waterlogging and 'living haysheds' that can be used during times of fodder shortage. Riparian vegetation can also be managed as part of an agroforestry farming system for wood and non-wood products, such as nuts, oils and foliage (Robins et al. 1996). Similarly, the land may be used to operate apicultural activities, produce hay, shelter stock or provide ecotourism facilities. Healthy, vegetated riparian land provides habitat for insect-eating birds and insect parasites that can help to protect pastures and crops from damage (LWRRDC 1996c). Anecdotal evidence from real estate agents also suggests that healthy native riparian vegetation can increase property values by up to 10% ('Bushland boosts price of farms', *Weekend Australian*, 16–17 November 1996).

It is clear that intact, healthy riparian vegetation can provide a large number of benefits and 'environmental services'. Its careful management and conservation must be a high priority for all land managers.

8.3 Key concepts in riparian vegetation ecology

Ecological zonation

The composition and structure of riparian vegetation vary both locally and along the length of the river.

Longitudinal changes in the vegetation occur from the upper parts of the river (where first order streams arise) through to the floodplain. According to Malanson (1993), longitudinal changes are driven by variations in

~ climate (from cold to warm, dry to wet);

A range of successional rainforest species have been identified for the Manning catchment in northern New South Wales (Raine & Gardiner 1995). These species have been classified according to their regeneration stages as

~ stage 1—herbs and soft-wooded shrubs (0–2 years old)
~ stage 2—soft-wooded secondary shrubs or pioneers (2–15 years old)
~ stage 3—short-lived trees that are early secondary trees or 'nomads'
~ stage 4—long-lived mature-stage trees aged up to 100 years or more.

Stage 2 species are quick growing and produce large quantities of seed of long viability. These species do not regenerate in the shade and are replaced by stage 3 species. Stage 3 species are fast growing and light demanding. They produce seeds of long viability and have effective dispersal mechanisms using wind and animals (Kooyman 1991). Stage 3 species possess a range of characteristics which make them suitable for stream-bank revegetation (Raine & Gardiner 1995).

There are a range of species which actually help facilitate change at a particular site. These species possess characteristics which allow them to become established in relatively harsh environments and, over time, create conditions which allow other species to become established—often at the expense of the early colonisers. For example, silver wattle, *Acacia dealbata*, maintains a prolific seed bank and is relatively fast growing. Similarly, *Casuarina cunninghamiana* can be a prolific coloniser of recently created bare surfaces (Raine & Raine 1994).

Shading by these species reduces the opportunity for regeneration by their own progeny but creates suitable conditions for shade-tolerant species. Over time, the secondary species replace the early colonisers as the dominant species.

~ elevation;
~ hydrology (from intermittent first order streams to perennial high order rivers—see Chapter 2);
~ geomorphology (erosional to depositional).

Longitudinal changes in riparian vegetation can be at the broad scale, with large differences between the parts of a river which flow through constrained channels (in bedrock of the headwaters) and the parts which flow through lowland (open alluvial floodplain areas). As well, variation in communities can result from local changes in in-stream structures such as pools and riffles.

Local variations occur perpendicular to the channel and are responses to channel dynamics, floods and soil moisture, which are themselves inter-related. Disturbances which change channel dynamics can influence local vegetation patterns. In areas which experience repeated flooding, erosion and deposition change can be cyclical. In well-drained areas, clear zones exist from the frequently inundated stream side, dominated by herbaceous species, through to the better drained terraces, dominated by trees and shrubs (Askey-Doran 1993).

Moisture gradients

A gradient of moisture, influenced primarily by topography, exists within riparian areas. This gradient ranges from extremely dry sites, in which species must be able to take advantage of seasonal wetness, through to saturated sites, in which species must be able to withstand anoxic soil conditions (Malanson 1993).

The influence of moisture can be seen at both at the community level and in the internal structure of riparian communities. In Tasmania distinct communities exist at either end of a soil drainage gradient, ranging from low-lying floodplain areas to well-drained environments.

The influence of flooding and moisture availability on the composition of riparian plant communities is also related to adjacent land use (including grazing and recreational land use) and to factors such as fire and the regulation of water flows (Bren & Gibbs 1986, Roberts 1993, Roberts & Ludwig 1991). For many species which rely on rare events such as large floods to provide conditions for regeneration, the presence or absence of grazing following such an event can determine, for example, their long-term presence at a site. However, the high episodic rainfall that leads to large, infrequent floods also encourages higher stocking rates and an increase in rabbit populations (Roberts 1993).

Some riparian species are adapted to extreme changes in moisture availability. For example, in the river red gum (*Eucalyptus camaldulensis*) forests of the Barmah–Millewa forest of northern Victoria and southern New South Wales, periods of inundation of up to six months followed by up to six months of dryness appear to favour river red gum above virtually all other species. The river red gum is able to tap water from relatively deep aquifers to survive the dry period but is also adapted to long periods of inundation (Bren 1987).

Flooding influences the vegetation pattern largely by causing mechanical injury and oxygen depletion. The differing responses of species to the stress or damage caused by mechanical injury enable them to be segregated into areas with different flood impacts (Malanson 1993). Current and wave action were found to be major factors determining the floristic composition of four communities in wetlands of the River Murray (Roberts & Ludwig 1991).

The ground layer of river red gum communities may well indicate the degree of inundation occurring at a site (Chesterfield 1986). Sites with high flood frequencies are dominated by moira grass, whereas those with lower flood frequencies have a combination of moira grass and river red gum (Bren & Gibbs 1986).

River red gum. Photo courtesy of the Murray–Darling Basin Commission.

Succession

Succession can be most simply defined as the progressive change in species composition and/or structure that occurs following disturbance of a site. Disturbance is a temporally discrete event that causes substantial mortality (Fisher 1990). Natural and human-induced disturbances by flooding, water regulation, fire, vegetation clearance and fragmentation, introduced plant species, grazing, and rising groundwater and salinity are described in Section 8.4.

Two types of succession are recognised (Fisher 1990, Milner 1996):

~ primary succession—when a disturbance leaves no trace of the previous community and a bare surface for recolonisation (such as the formation of a new stream channel following severe flooding);
~ secondary succession—when soils or organic materials remain and recolonisation can occur.

Models of succession focusing on trajectories of change in communities are important to restoration for three reasons.

~ They can draw attention to any need for sequencing reintroductions (or for imposing additional disturbances to facilitate or delay successional processes) to avoid undesirable inhibition (Connell & Slatyer 1977, Gilpin 1987, Bradshaw 1989, Chambers et al. 1990).
~ They are fundamental to the concept of directing the restoration process for individual plant communities or vegetation types towards one of many alternative successional endpoints or away from undesirable stable states (Chambers et al. 1990, Luken 1990).
~ They can be useful in predicting whether a restoration project is ‘on track’ in meeting pre-determined goals (Chambers et al. 1990, Westman 1991, Cairns Jnr 1993).

Resilience

Many ecologists consider the term ‘resilience’ as interchangeable with ‘succession’ (McIntosh 1980, Luken 1990). Here, succession is used in reference to ecosystem development which reflects directional change, while resilience refers to recovery to a pre-existing state.

The forms of resilience are defined as follows (McDonald 1996):

~ resilience—the capacity of a community or species to recover after disturbance, whether natural or human-induced;
~ ecosystem resilience—the degree, manner and pace of restoration of the structure and function of the original ecosystem after disturbance (Westman 1978, 1991);
~ in situ resilience—propagules arising within the disturbed site (buried seed banks, resprouting, and in situ seed rain). In situ resilience potential is dependent on the presence and absence of persistent vegetation, suppressed root stocks and seed banks, as well as the conditions of the substrate and microniches (Grubb & Hopkins 1986);
~ migratory resilience—propagules entering from outside the disturbed area. Migratory resilience potential (or potential for colonisation of a site) is dependent on the site’s accessibility to more distant propagule sources and the dispersal potential of its pre-existing species. The rate of proliferation of species will also affect the elasticity or speed of migratory resilience (Grubb & Hopkins 1986).

Thresholds of recoverability

The concept of thresholds of recoverability has been defined as arising from rangelands ecology, finding its best expression in the ‘state and transition’ model of ecosystem decline and recovery (Malanson 1993). This model proposes that a linear decline does not usually occur; instead, progressive disjuncts or distinct transitional ‘states’ occur. Further, once a threshold has been exceeded, reversal of degradation can require considerably greater subsidy than merely the original stress (Westoby et al. 1989, Hobbs & Norton 1996).

While many thresholds may be permanent, in some cases autogenic recovery may ensue after interventions which somehow overcome the threshold by interventions which ‘kick start’ recovery processes (Westoby et al. 1989).

Recovery triggers

The ‘trigger factor’ (Winterhalder 1995, 1989) has been defined as a fusion of two concepts (McDonald 1996). The first concept is based on ‘colonisation bottleneck’ (Hedin 1992), which suggests that sometimes only unexpectedly small subsidies are needed to remove obstacles to colonisation. The second concept is based on ‘minimal intervention’, where ‘site preparation based upon ecological understanding of the colonisation process' can enhance nature's own recovery processes (Skaller 1981).

The concept of minimal intervention implies that restoration treatments are most effectively applied only to the extent necessary to enhance or set in motion natural colonisation and succession—rather than to an extent which does further damage to (or is intended to replace) these processes (Skaller 1981). This notion can be interpreted in terms of resilience theory, as advocacy of restoration interventions that provide critical dampening (or intervention), rather than under-dampening or over-dampening (Fox & Fox 1986).

The 'trigger factor' concept also has implications for determining whether thresholds of recovery have been exceeded. It implies that resilience manifestation may misrepresent resilience potential, unless potential for 'colonisation bottlenecks' or 'trigger factors' are used to test 'hidden' resilience potential at specific locations at a restoration site. This is particularly important considering the fact that resilience potential is often 'hidden' in soil seed banks or potential dispersal processes.

These concepts should be considered when planning to restore or better manage riparian vegetation. They should be incorporated in any plans to establish self-sustaining vegetation or to return a degraded site to healthy vegetation with minimum intervention (and cost).

8.4 Natural and human-induced disturbance to riparian vegetation

Flooding

Flooding is the most common form of natural disturbance experienced by riparian plant communities. Disturbance from flooding comes in a number of forms, including physical damage and removal, prolonged inundation, deposition of sediments and litter, and bank erosion. The impact will depend on the magnitude, timing and duration of the flood.

Generally, riparian plant communities are adapted to the consistent cycle of flooding and drying and are able to cope with the resultant disturbance. For example, a floodplain wetland and river red gum on the Murray River floodplain in eastern Australia both elevate seedlings from excessive waterlogging, and trap moisture, thus reducing desiccation in the dry period of the year (Bren 1988).

Rare, episodic or atypical flooding events have a much greater impact on vegetation, usually leaving extensive areas bare. These bare sites become available for recolonisation, mostly by pioneer plants, which take advantage of the open spaces created by the disturbance. Floodplain ecosystems tend to be disturbance dependent, with a high sub-system instability but a broader meta-system stability (Ward & Stanford 1995).

Flood damage, Oyster Cove Rivulet, Tasmania. Photo by Michael Askey-Doran.

Flooding disturbance may damage branches or kill individuals within stands of *Callitris oblonga*, facilitating seed release, dispersal and germination. On an ephemeral creek in the semi-arid region of eastern Australia, a study of *Eucalyptus coolabah* trees indicated that recruitment was episodic and related to past large rainfall events, with flooding considered important in replenishing soil moisture and allowing seedlings to survive (Roberts 1993). Such requirements may be common across much of inland Australia. In northern areas, the episodic events related to cyclone activity have a major effect on distribution and regeneration of riparian vegetation.

Water regulation

Recruitment, establishment and survival of riparian trees is thought to be closely tied to the hydrological regime, as discussed. In Australia over 400 major dams affect hydrological regimes and flood natural riparian environments (Commonwealth of Australia 1996). Victoria has 2430 impoundments (in 1992), flooding 83 400 hectares, while Western Australia's impoundments flood more than 80 000 hectares (WA SOE 1992). River regulation has significantly altered the hydrological regime of many waterways, influencing riparian vegetation recruitment, establishment and survival.

Seventy-three per cent of the length of the River Murray below its confluence with the Darling has been converted into a series of 10 weir pools (Thomas & Walker 1992). Recruitment of river red gum, *Eucalyptus camaldulensis*, seedlings on the floodplain of the Murray River is limited by poor establishment rather than by lack of seed germination. Establishment of the plant community in the littoral zone of the Murray's banks is dependent on falling water levels exposing new substrate for seed germination. Lack of recruitment in these forests has been attributed to increased flooding in summer due to river regulation (Bren & Gibbs 1986). Establishment is also affected by water currents, wave action and herbivore grazing (Roberts & Ludwig 1991).

Water regulators also use levee banks to protect agricultural and urban lands. Levee banks reduce the area of flooding during small and medium flood events, which in turn changes vegetation assemblages, prevents regeneration of many plants, and prevents recharge of wetland systems. Levees also result in excessive drying of neighbouring wetlands, often leading to their ultimate demise (Murray–Darling Basin Ministerial Council 1989).

The effective watering of red gum forests of the central Murray has been estimated to have reduced from a natural frequency of 61 out of 71 years to only 28 out of 77 years in the current situation. Irrigation releases during summer result in near constant inundation of lower lying areas, with regeneration inhibited, and degradation and sometimes death of some mature stands (Murray–Darling Basin Ministerial Council 1989).

Fire

Disturbance by fire, both natural and human induced, is discussed here in brief; more information on the impacts of human-induced fire is provided in Chapter 10.

Much of Australia's flora is adapted to fire, with particular plant communities being fire dependent. However, there is little information about the response of riparian vegetation (including rare and threatened species) to fire. Response to fire, whether natural or human induced, differs markedly across Australia, according to factors such as vegetation type and condition, climate, soil moisture, and the timing, frequency and intensity of fire.

Riparian vegetation being burnt (mainly *Pandanus spiralis*), Kapalga, Kakadu National Park, Northern Territory. Photo by Michael Douglas.

New vegetative shoots emerging from *Lomandra longifolia*, following fire. Photo by Michael Askey-Doran.

Fire may also play an important role in the removal or suppression of weeds such as pond apple (*Annona* spp.), which is invading lowland melaleuca forest, and lantana, which occurs in higher rainfall forests of coastal Queensland (Stanton 1995).

Riparian vegetation does not commonly experience fire because of its moist environment. As a consequence, it tends to be less adapted to fire, having less well developed lignotubers, thinner bark, and primary regeneration from seed (Commonwealth of Australia 1994).

However, many riparian species possess mechanisms allowing regeneration following fire. Dycotyledenous families (Myrtaceae, Proteaceae, Fabaceae) and monocotyledenous genera (*Lomandra*, *Poa*, *Themeda*, *Lepidosperma*, *Carex*, *Phragmites*, *Typha* and *Dianella*) are just a few of the groups of plants with species able to recover vegetatively following fire.

While many species are able to recover following fire, they do not necessarily benefit from it. Fire can initially reduce vigour and flowering potential and alter patterns of dominance within vegetation types.

Some species are fire-sensitive, such as cypress pine, *Callitris intratropica* (Anderson 1995) and river red gum, *Eucalyptus camaldulensis*, which lacks lignotubers (Parson 1991). Fires that are too hot will kill plants outright.

Few species can tolerate frequent burns, despite the ability of some species to recover following fire, either vegetatively or from the seed bank. Frequent burning inhibits successful regeneration as new growth or seedlings and seed stored in the soil are killed by the next fire. As a result, particular species can be lost from a site.

Fire that partially or totally removes vegetation cover will affect the shading characteristics of that part of the river. This in turn will affect the aquatic habitat. The filtering capacity of riparian vegetation will similarly be reduced, increasing the transport of sediment and nutrients to the water body. Many weed species will also be encouraged by the disturbance and initial input of nutrients that can result from fire.

Vegetation clearance and fragmentation

Over-clearance of riparian vegetation and its continued degradation through poorly managed grazing are primary causes of poor river health in Australia. The rate of clearance of native vegetation (including regrowth) across Australia is estimated to exceed 600 000 hectares per year. Riparian vegetation tends to be selectively cleared: land development concentrates on heavier soils of valley floors for agricultural purposes, and on the coastline for urban settlement. Clearance of native vegetation is occurring most extensively in Queensland and New South Wales. The Commonwealth of Australia (1995) provides a summary of recent native vegetation clearance by State and Territory.

Western Australia's state of the environment report indicates that the northern Kimberley, Central

Desert and Nullarbor Plain regions show few signs of disturbance or land clearing, with rivers retaining many of their natual values, while highly modified rivers generally characterise the south and west of the State (WA SOE 1992).

Vegetation clearance and fragmentation are the major causes of loss of biodiversity, particularly near large Australian cities (Commonwealth of Australia 1996). Clearing and fragmentation adversely affect those species dependent on native vegetation and increase those species dependent on the cleared agricultural matrix. The effects on biological diversity of vegetation clearance and fragmentation are exemplified in Kellerberrin, a shire in the central wheat belt of Western Australia, where native vegetation covers only 5% of the valley floors, compared with 63% of the highest parts of the landscape (Hobbs & Saunders 1993). The impacts of vegetation fragmentation on riparian wildlife are discussed more fully in Chapter 9.

Native vegetation that has become isolated will harbour more species than it is able to sustainably carry, so some species will be lost over time. The rate of loss will be greatest for those species that depend entirely on native vegetation, require large territories, and exist at low densities. The rate of loss will be least for eucalypts and other species with long generation times; for example, salmon gums (*Eucalyptus salmonophloia*). Isolated remnant vegetation is also more prone to degradation and species loss from the creation of edges, with an accompanying increase in edge specialists, weed infestation and nutrient enrichment (fertilisers and stock excrement) (Commonwealth of Australia 1996).

Vegetation clearance also has implications for microclimate. Loss of vegetation increases radiation at ground level and elevates soil temperatures. Cleared areas are exposed to a greater range of extreme temperatures, with loss of moisture resulting from higher ground wind speeds (Commonwealth of Australia 1996).

Introduced plant species

Extensive areas of Australia's river systems are infested with introduced plant species. Introduced plants are found in both riparian and aquatic environments and considerable money is spent annually in their control. The herbicides used to control weeds in riparian and neighbouring environments also often kills native species.

Key factors affecting weed invasion include the life cycle of the weed species, propagule sources, dispersal mechanisms, season, climatic conditions, and the nature of the riparian environment itself (disturbance, nutrient availability, and so on).

The very nature of rivers—a natural regime of disturbance by regular raising and lowering of water tables and a mechanism for dispersal of seeds and propagules by the water—encourages invasion by weeds (Humphries et al. 1991). Weeds may be dispersed by wind, carried by vectors (insects, stock or farm equipment) or transported from upstream, particularly during flood events.

These characteristics and the way in which Australia's rivers and land have been managed over the last 200 years (including fertiliser use, use of introduced species, stock access and vegetation clearance) have combined to produce conditions favourable to exotic species. For example, the combination of disturbance and high nutrient levels attributable to fertiliser application greatly increases the opportunity for exotics to establish and persist.

Although many weeds do not, generally speaking, pose a problem to riparian vegetation in healthy condition and with intact canopy, others are able to invade healthy vegetation. In such cases, removing the potential source of infestation early on is obviously the preferred management approach. Herbaceous species and pasture grasses are likely to be present in the riparian zone. However, these species are difficult to control and usually become a problem only when there is a disturbance regime or an elevation in nutrient availability, or both.

Exotic plant species compete with native species for resources such as space, light, nutrients and moisture. This competition may be especially effective against native species which have slow-growing seedlings or those which produce only limited numbers of seeds (Panetta & Hopkins 1991).

One-third of the species recorded in a survey of the Murray River were introduced species, compared with 10% for Australia as a whole (Margules et al. 1990). This survey found the following.

~ The proportion of weeds in semi-arid regions was low, with the weediest communities occurring in the higher rainfall, upper or lower reaches of the river.
~ Sites that experience regular flooding had a low proportion of weed species, possibly indicating a need for specialisation to survive in these more difficult environments (see also Chesterfield 1986).

In Tasmania there is a clear gradient, related to land use, where native-rich communities are replaced by exotic-rich communities. Generally, the upper reaches

In south-eastern Australia, willows (*Salix* spp.) form virtual monocultures along many lowland rivers. Originally planted for erosion control, the species has now replaced native riparian species. *Salix fragilis* is a vigorous coloniser, able to establish readily from vegetative material. Willows change the manner in which the riparian area functions. Being deciduous, they have a seasonal litterfall and alternates between providing full shade and full light. Streams dominated by native riparian species differ greatly in this respect because the species are evergreen. Introduced plant species are more suited to the seasonally variable light regime provided by willows and usually become the dominant species. Gorse (*Ulex europaeus*) is another species which dominates large areas of riparian land in south-eastern Australia, replacing native vegetation.

In northern Australia *Parkinsonia aculeata* is widespread, occurring along watercourses and floodouts (Humphries et al. 1991). *Mimosa pigra* infests more than 80 000 hectares of floodplains in the Northern Territory (ARMCANZ & ANZECC 1997). Rubber vine (*Cryptostegia grandiflora*) infests over 35 million hectares of north Queensland, where it is most prolific along watercourses (Humphries 1994). Rubber vine displaces gallery forests along rivers such as the Gilbert, Flinders and Leichardt on the eastern side of the Gulf of Carpenteria and forms impenetrable thickets up to 400 m wide on each side of the river bank (Humphries et al. 1991). Athel pine (*Tamarix aphylla*) is a threat to dryland watercourses in Central Australia. This tree is capable of displacing the native flora, reducing fauna habitat, lowering the water table, salinising the soil and changing river flow and sedimentation regimes (Humphries 1994).

Para grass (*Brachiaria mutica*), a species used in ponded pasture systems, is a major nuisance plant in streams of northern Queensland. It chokes the channels and traps large amounts of sediments, reducing channel capacity. Despite being an important major primary source of organic carbon, para grass does not contribute to the aquatic food web. The lack of any riparian canopy and abundant nutrients encourage its spread.

In the Manning River catchment, several introduced species are of concern—*Ligustrum sinense* and *Ligustrum lucidum* (privets), *Lantana camara* (lantana), *Rubus fruticosus* (blackberry) and *Anredera cordifolia* (Madeira vine) (Raine & Gardiner 1995). Other species of concern are *Tradescantia albiflora* (wandering Jew), *Ageratina riparia* (mist flower), *Ricinus communis* (caster oil plant), *Solanum mauritianum* (wild tobacco), *Macfadyena unguis-cati* (catsclaw creeper) and *Cardiospermum grandiflorum* (balloon vine). Camphor laurel (*Cinnamomum camphora*), a native of China, has invaded streams of northern New South Wales and south-eastern Queensland. This tall tree has a dense canopy which prohibits the growth of all aquatic plants (Sainty & Jacobs 1981).

Gorse and willow along the Prosser River, Tasmania. Photo by Michael Askey-Doran.

of the streams are dominated by a range of native plant communities. However, as the river descends onto the richer alluvial soils of the floodplains, where agriculture is the dominant land use, native communities become fragmented and weeds are common and often dominant (Askey-Doran 1993).

In some instances, weeds may actually be of benefit to native species. Gorse, for example, can provide a barrier to stock which might otherwise graze in the native riparian vegetation. In highly disturbed environments, exotic species are the only habitat which remains for a wide range of native animals. For example, gorse provides important habitat for the endangered eastern-barred bandicoot, *Perameles gunnii*. Poorly considered control or removal of exotic species can be quite detrimental to native flora and fauna. Although control or removal should be the long-term goal, careful planning is necessary.

Grazing

Disturbance by stock grazing is discussed here in brief; a fuller account is provided in Chapter 10.

Riparian land is typically more fertile and more moist than adjacent lands and consequently supports higher quality and more diverse forage than does upland areas. In the hotter seasons, stock are attracted to cooler microclimates and may spend extended periods loafing in the shade or standing in water. It is the combination of microclimate, forage, shelter and moisture that makes riparian land an area favoured by stock.

Overgrazing of riparian land generally results from unrestricted access by stock, usually arising from lack of, or damaged, fencing. When stock graze they preferentially select the more palatable species, either removing them from a site or reducing them to compact, low tussocks, coppices or rosettes. This prevents particular species from developing into fully grown trees, shrubs or tussocks and reduces the structural diversity of the site. Loss of species and absence of structural diversity within natural riparian vegetation leads to a loss of biodiversity, increased potential for weed invasion, and loss of habitat and wildlife values.

Trampling of riparian land during prolonged access by livestock results in soil compaction and physical damage to plants. Ground cover species, such as herbs, tufted grasses and tussock species, which slow overland flow and trap sediments, can all be damaged through trampling and excessive grazing. Soil compaction reduces the macrospore space in soil, reducing infiltration, root growth and overall plant production. The presence of a range of different plants influences the nature of the root zone and the depths to which roots penetrate. This in turn influences nutrient cycling and uptake, soil aeration, soil structure and levels of microbial activity.

Overgrazing by livestock opens up patches of bare soil which can then erode. Stock movement along the water edge disturbs and pugs the soil at the toe of the bank, making it prone to being washed away when rain increases the stream flow. The disturbance created by livestock through grazing of plants and opening up of bare ground, together with increased nutrient levels from animal faeces and urine, creates an ideal situation for the establishment of weeds. Weeds may also be spread directly by the animals, either through attachment to hair or skin or through their faeces. Damaging weeds can spread from riparian lands onto adjacent farmland.

Rising groundwater and salinity

The replacement of deep-rooted native vegetation with shallow-rooted annual vegetation and the irrigation of land have combined to cause rising groundwater levels and associated soil and water salinisation. Native vegetation is an efficient user of water and over-clearing has led to changes in rainfall interception and evapotranspiration, with more water flowing across the landscape and infiltrating the watertable (Murray–Darling Basin Ministerial Council 1989).

Salt stored in the ground is remobilised and transported to the soil surface by rising water levels. Salts resting on the soil surface or dissolved in groundwater may also be transported to surface waters, elevating in-stream salinity concentrations. The Commonwealth of Australia (1996) provides a national summary of irrigation-induced land degradation, dryland salinisation, rates of watertable rise, and salt loads in streams.

The impact on native vegetation of soil salinity or salinity of groundwater and surface water depends on the vegetation's position in the landscape. Water and salt tends to emerge from valley floors and sides, leaving salt crystals and pans. Riparian vegetation, being low in the landscape, may die off or be replaced by more salt tolerant species. Bare patches of soil may leave the site prone to erosion by water, wind and stock traffic (Commonwealth of Australia 1996).

Elevated water salinity may also affect downsteam riparian communities, particularly during flooding.

The tolerance of riparian species to salt concentrations also varies considerably. For example, salt river gum, *Eucalyptus sargentii*, has a high tolerance for salt, with salt encrustation generally found on the soil surface (Boland et al. 1984), as is the case for particular provenances, such as Albacultya red gum, *Eucalyptus camaldulensis*.

Climate

Australia is renowned for its highly variable climate. Although riparian vegetation is to some extent insulated from the full force of this, extended periods of well below average rainfall can have severe effects, leading to death of individuals and, in extreme circumstances, loss of drought-sensitive species. Atypical frosts can also be an important influence affecting the composition of riparian vegetation, and there is a strong link between climate and fire regimes.

As well as salt, groundwater may also carry nutrients and other contaminants (such as pesticides) that affect riparian vegetation. Increased levels of nitrogen transported to gully bottoms by groundwater have been implicated in poor health and insect attack leading to classic dieback symptoms.

8.5 Riparian vegetation restoration

Readers are reminded that, before planning to restore riparian vegetation, it is essential to check that the stream flow and its channel are broadly in equilibrium. There is no point in fencing and revegetating banks if an altered flow means that the stream is in the process of widening and deepening the channel or is depositing sediment.

This section on riparian vegetation restoration is drawn from McDonald's (1996) doctoral thesis (see references for details).

Classes of intervention

Without intervention, some degraded sites are unable to recover, indicating that the impact of natural or human-induced disturbance has pushed the community beyond a threshold. For instance, lack of seed sources or damaged substrates (topsoil washed away) can mean that substantial inputs are needed to achieve restoration. At other sites, lack of automatic recovery does not necessarily mean lack of resilience potential.

The three thresholds (and the classes of intervention that they divide) can be described as follows:

~ unassisted regeneration threshold—this cannot be overcome by autogenic processes (driven by processes operating within the plant community) alone but does not signal depleted in situ or migratory resilience. It is most likely to be due to the absence of deflection of dynamic processes or ecosystem functions due to inappropriate disturbance regimes or the presence of exotic organisms. Relatively low key (assisted regeneration) interventions may be able to correct these absences to enable autogenic recovery processes to be reinstated;

~ assisted regeneration threshold—may occur at the point at which assisted regeneration interventions fail to reinstate processes. This is likely to be due to depletion of organisms (for example, loss of soil's seed bank) or alteration of substrates. Beyond this point recovery is possible only after more wholesale reconstruction of substrates or organisms, or both, as well as appropriate reinstatement of processes;

~ reconstruction threshold—can occur where conditions are so altered that recovery of the pre-existing community is impossible or impracticable. In such cases, a community-type conversion (to one such as might naturally occur under similar site or climatic conditions in the regional landscape) may be considered.

Sometimes the reinstatement of germination cues, microniche amelioration and dispersal attractants (as well as removal of competition from exotics) can be sufficient to 'kick start' the recovery process. In these cases, the apparent threshold is more likely to be driven by changes to dynamic processes within the community, rather than by the more irreversible lack of components or damage to substrates.

Restoration interventions can be seen as a means to overcome thresholds by either reinstating dynamic processes or overcoming gross changes to the physical environment or to the range of species available. In the first case (process-driven thresholds), only assisted regeneration interventions may be needed. In the second case (component-driven thresholds), larger interventions, including complete reconstruction, may be needed. Generally, however, sites contain a range of subsites representing a spectrum of degrees of degradation and requiring a spectrum of degrees of intervention.

Restoration and classes of vegetation type

Sclerophyll

It can be assumed from the resilience exhibited by sclerophyll species after natural disturbances (Noble & Slatyer 1977, Gill & Bradstock 1992, Keith 1996) that sclerophyll species are also likely to exhibit in situ resilience to one-off (or gradual) human-induced disturbances. Such disturbances include those which do not remove the root stocks of parent plants of resprouters, the juveniles of serotinous obligate seeders, or the seed bank of geosporous obligate seeders.

Due to the relatively low dispersal distances of sclerophyll species (Grubb & Hopkins 1986, Drake 1981), increments of migratory resilience after human-induced clearing are likely to be restricted to within 10 m of seed sources for shrubs or within 20 m for trees.

Field reports of germination of obligate seeders after natural disturbances suggest that some recovery could be expected after human-induced clearance of parent plants. This cannot, however, be assumed for a number of difficult-to-germinate species. Similarly, it follows that any such recovery would occur only if soils are conserved, if the period since last recharge of the soil seed bank is not excessive, and after any germination dormancies are satisfactorily broken.

The recovery of resprouting species after complete human-induced clearance of parent plants (including canopy seed banks and root stocks) would depend on reintroduction of propagules, or long-term colonisation from adjacent areas. Obligate seeders that store seed in the canopy and resprouters that do not store seed at all (including monocotyledons) would have no resilience to clearance of parent plants and would depend entirely on reintroduction or long-term colonisation from adjacent areas. Due to the low migratory resilience of sclerophylls, such recolonisation is likely to be extremely slow, particularly for species which exhibit poor germination characteristics.

The potential for artificial revegetation to compensate damage to resprouters is relatively high for many species that hold readily harvestable seed in the canopy. This will not be the case for resprouters that do not store seed or for obligate seeders that are difficult to germinate due to subtle or complex dormancy-breaking mechanisms (Bell 1994). However, due to their longevity, these resprouters make up a high proportion of plants in many communities. Special efforts to reintroduce these species artificially are therefore considered important (Vlahos & Bell 1986).

Over and understorey in a typical wet sclerophyll forest in alpine Victoria. Photo by Ian Rutherfurd.

Repeated biomass destruction beyond that which is characteristic of unpredictable natural regimes (which can occur as a result of frequent mowing, grazing or fire) will result in the loss of many species. This is particularly the case for those that do not resprout and that have a limited store of seed in the soil. Repeated fire is likely to cause more rapid exhaustion of soil-stored seed by stimulating its germination, with resultant seedlings only to be killed in the next fire. Repeated fire may also remove resprouting species with limited resprouting reserves, depending on the duration of continued disturbance. Conversely, fire exclusion that is extended well beyond natural regimes is likely to reduce the amplitude of resilience of a site (Keith 1996).

Preferential grazing will hasten this process for certain sclerophyll shrub and tree species and not for others. When combined with other facts, such as fire exclusion, these changes may result in marked compositional changes or shifts to alternative states.

Changes in substrate condition, such as loss of soil structure due to overgrazing or augmented nutrient or moisture status, may prevent recovery to pre-existing states (Hobbs & Norton 1996).

In addition to these constraints on natural recovery, human-induced disturbance may cause other changes. Prominent among these are invasions by exotic species, many of which are capable of displacing native species and altering community processes (Australian National Parks and Wildlife Service 1991). Changes in substrate conditions can also affect the availability of suitable niches or conditions for the recovery of the pre-existing plant community. Both these impacts are difficult to reverse, although human-induced changes in substrate conditions are considered to be more fundamental and more difficult to reverse than the removal of the biota alone (Hobbs & Norton 1996).

Rainforest

Rainforests are generally composed of two main groups of species: early phase species, which form persistent seed banks; and later phase species, which rely on resprouting or germination from fresh seed or stored seedlings and saplings ('advance regeneration'). These offer a mechanism for initiating rainforest community recovery after natural disturbances, in larger gaps and smaller gaps respectively (Garwood 1989).

The migratory resilience of rainforests is enhanced by the capacity for fleshy-fruited species (of which sub-tropical and tropical rainforests are largely composed) to be dispersed from neighbouring refuges by flying frugivores (Jones & Crome 1990, Whitmore 1991). This process of dispersal by birds (and possibly by bats) is greater if perch trees are present (McClanahan & Wolfe 1993, Whittaker & Jones 1994).

It can be deduced that rainforest species are likely to exhibit some resilience to human-induced disturbances. The degree of this resilience is likely to be limited insofar as these impacts resemble natural conditions. Impacts that degrade the fertility of soils, remove root stocks and seed banks, or create gaps that exceed colonisation distances will reduce resilience (Clusener Godt & Hadley 1993).

As the spatial extent of disturbance caused by human-induced clearing is usually far in excess of natural disturbances, it is likely that natural recovery will reflect compositional changes due to differences in species availability. In particular, large clearings that depend entirely on soil seed banks are likely to

Healthy riparian vegetation in the Mary River catchment, Queensland. Photo by Simon O'Donnell.

become dominated by early successional species and are also more susceptible to invasions by exotic species (Woodwell 1992, Kooyman 1996).

Restoration interventions that involve control of exotics, artificial reintroductions and the establishment of perch trees (to both ameliorate site conditions and attract the birds associated with seed dispersal) can accelerate recovery of the pre-existing community (Clusener Godt & Hadley 1993, Whittaker & Jones 1994, Kooyman 1996).

During the lengthy rainforest recovery process, perch-tree culling could further accelerate structural development by accelerating the rate of gap creation. The degree of this acceleration is likely to depend on the selection, order of introduction, and order of culling of particular species. Nonetheless, the length of time required for growth of long-lived mature-phase species, the natural re-sorting of planted species, as well as the reinstatement of the stature and distribution of the pre-existing plant community is likely to take centuries.

Grassland

Grassland species have a high propensity to recover from natural disturbances such as drought, fire and grazing. Mechanisms of recovery include resprouting from rootstocks for perennial species and germination from soil-stored seed, mainly for shorter lived species (Wilson et al. 1988, Rice 1989). Colonisation can be enhanced by relatively short primary and secondary juvenile periods for these species compared with trees and shrubs (Tongway & Hodgkinson 1992). Some potential may exist for wind and faunal dispersal, although this is little studied.

At least some recovery can occur on highly degraded grassland sites. The degree of this recovery depends on the effect of the impact on root stocks, soil seed banks and microsites. In less degraded cases, recovery can occur with little intervention other than the removal of the original stress factor.

For sites where perennial grasses are removed for one to (maximum) 10 years, recovery is sparse and dependent on migration or artificial reintroduction (Silcock et al. 1990, Tongway & Hodgkinson 1992). Storage duration for many perennial forbs is likely to be transient only or, at best, short-term persistent, indicating a lower threshold of irrecoverability for forbs after human-induced impacts destroy the parent plant (Tremont & McIntyre 1994, McDougall & Kirkpatrick 1994). Germination of annual grasses and forbs from older seed or soil seed banks is,

Grassland, Gibb River road, East Kimberley, Northern Territory. Photo by Michael Douglas.

however, common (J. Stol 1996, pers. comm., Silcock et al. 1990, Tremont & McIntyre 1994).

The rate of resprouting, germination and colonisation is likely to be lower in regions of low and irregular rainfall than it is in regions of higher rainfall. This increases the importance of microsite preparation in enhancing colonisation potential in semi-arid and arid areas (Cunningham 1987, Ludwig & Tongway 1996). The slower rate of colonisation is, however, more likely to be due to long inter-rainfall periods, as rapid proliferation can occur during a rainfall season in semi-arid areas (J. Stol 1995, pers. comm.).

Fire may not necessarily enhance seed germination of grassland species (except perhaps annuals) but may be necessary to promote flowering and to create suitable niches for their recovery and colonisation. Short-rotation fires, therefore, can be a useful restoration tool in grassland for increasing the diversity of desirable species (and reducing undesirable species). This applies only as long as fire and any herbicide treatment are matched to the phenologies of those species in a controlled manner; otherwise the reverse effect may occur.

The requirement for fire to maintain competition-free niches is likely to be greater in higher rainfall communities than in lower rainfall communities (although shrub domination of grassy understoreys can occur in the latter). This is because periods of dry weather alone can create open niches and because less rampant growth reduces competition. Post-fire fertility status can also enhance rapid vegetative growth.

Wetland

The literature and case studies on recovery mechanisms of individual freshwater wetland species show that many perennial emergent macrophyte species are rhizomatous or stoloniferous and are therefore capable of recovering or expanding from in situ vegetative components after disturbance. Many smaller seeded or shorter lived species can germinate from persistent seed banks (Chambers & McComb 1994).

Germination of perennial or annual species normally occurs in moist, bare sediments after drawdown. This is particularly the case for the smaller seeded and/or shorter lived species (van der Valk & Davis 1978, Froend et al. 1993). Propagules of many annual and perennial species are freely dispersed by wind and water. After high levels of damage that remove parent plants, resprouting species may be

Floodplain wetland at Jip Jip, south-east South Australia. Photo by Anne Jensen, courtesy of Wetland Care Australia.

missing from a site or require particular dormancy-breaking cues before seed will germinate (Froend et al. 1993).

Australian freshwater wetland species are capable of both relatively high levels of in situ and migratory recovery if rootstocks are preserved or propagules can be readily dispersed. The extent to which this resilience may survive to assist restoration after human-induced disturbance is likely to depend on the degree to which causal factors can be arrested as well as the degree of damage to substrates, water quality, residual rootstocks and seed banks. It will also depend on accessibility to nearby (or augmented) sources of wetland propagules.

Following low or intermediate levels of human-induced damage (such as changed hydrological regimes or exotic domination) some soil storage of both seed and rhizomes may be expected in freshwater wetlands. This may also hold for saline wetlands (McIntyre et al. 1988, Britton & Brock 1994, Brock & Britton 1995). Such areas may provide sources of propagules for restoration, particularly after the reinstatement of water levels or salinity levels to pre-existing ranges and after programs to control exotics. In freshwater wetlands, artificial drawdowns could be considered a device for promoting germination from stored soil seed.

After high-level impacts (such as land clearing and permanent flooding or draining) resprouting species are likely to have a lower capacity to recover than obligate-seeding species. This is due to their (presumed) capacity for only transient seed storage in the soil. At least some capacity for longer term soil seed store may exist for some species. This may be an important mechanism of recovery after catastrophic disturbance (Froend et al. 1993, Brock & Britton 1995). Soil seed banks are likely to provide important sources of shorter lived species (which are often neglected in plantings) and germplasm, as well as revealing clues to past vegetation. Further, they may provide detailed information on the layout of subsites of higher and lower degradation, which may guide a more informed planting plan.

Current research

A number of different demonstration and evaluation projects are being run across Australia to examine riparian vegetation management. These projects attempt to deal with a wide variety of problems; for example, streambank stability, salinity, vegetation establishment, native plant regeneration and stock management. The composition of problems being examined by each of these projects is site specific, with scientists, catchment-management groups, landholders and agency staff working collaboratively to design and implement their particular research plan.

The research being done is not limited to environmental problems—rather, in recognition of the interaction between environmental and socio-economic issues, many of the projects include a benefit–cost analysis. An additional requirement for these projects is to produce research results in forms that are easily applied and understood by local communities. Research from these projects is also being collated at the national level and produced in a range of forms for communication to a variety of target audiences. At present, research is being done in the Johnston River, the Mary River and Coopers Creek in Queensland, in Bega and Clarence in New South Wales, in Goulburn–Broken in Victoria, in the Midlands and Buckland in Tasmania, in the Mount Lofty Ranges in South Australia, and in Kalgan and Blackwood catchments in Western Australia.

Work is being done in south-western Australia in the Kalgan catchment to demonstrate and evaluate approaches to rehabilitating salinised riparian land. Direct seeding and planting of predominantly local indigenous species have been used to examine the effectiveness of a range of different preparatory ground treatments. Results have shown that initial density and distribution of germinants were highly variable between sites and between and within treatments. Further assessment and monitoring in future years will consolidate observations made in the first year of the project, especially in terms of growth and survival rates of different species over the treatments. A set of guidelines for landholders will be prepared, outlining the results of the research, with the sites being used as practical demonstrations of the techniques that can be used to rehabilitate salinised riparian land.

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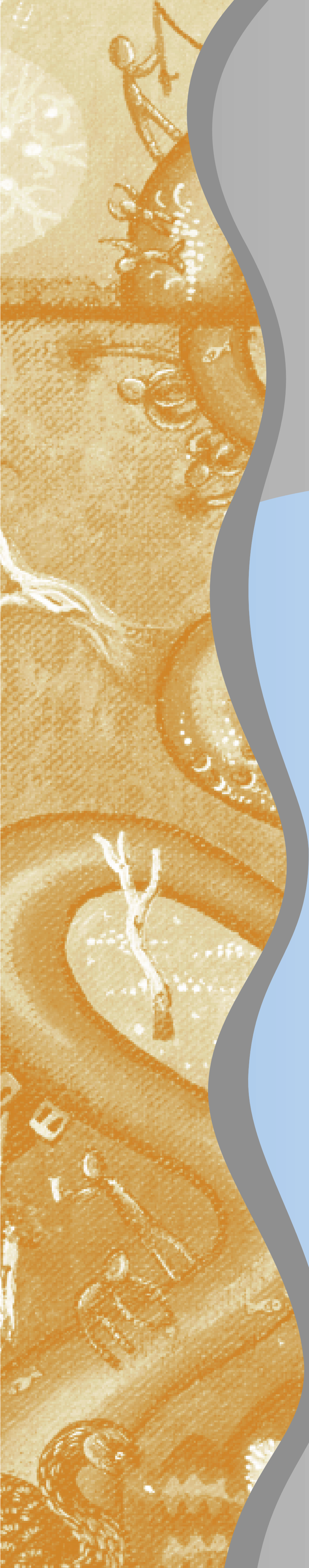


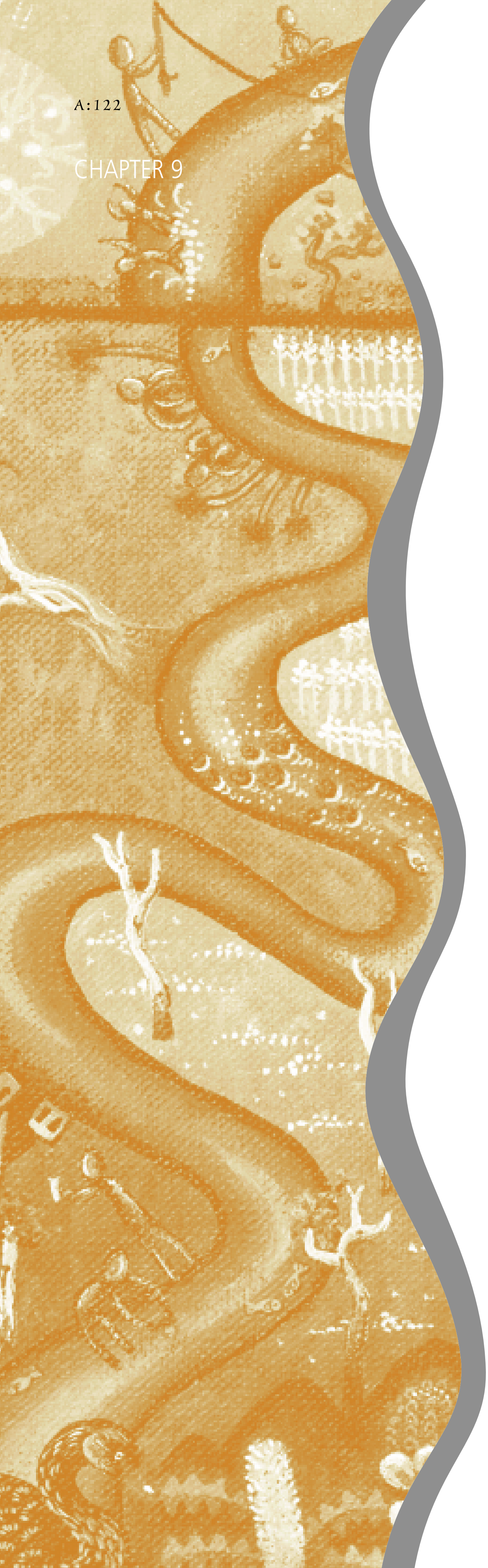
CHAPTER 9

Riparian wildlife and habitats

Romeny J. Lynch, Carla P. Catterall

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. When the native vegetation of riparian lands is cleared, these values are greatly diminished.
- 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.
- Management of riparian vegetation for its wildlife values depends on a knowledge of the habitat requirements and diversity of wildlife within any specific region. However, many species and ecosystems are poorly known, and there is large variation among Australia's bioregions. Immediate management priorities can be based on educated guesswork coupled with local knowledge, although this does not reduce the need for further research.



9.1 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. For example, in a study of the Blue Mountains in the north-west of the United States, Thomas et al. (1979) found that 75% of the 378 terrestrial species known to occur there were either dependent on the riparian zone or used it more than any other available habitat. The importance of riparian areas to wildlife has been noted in reviews and symposia dealing with riparian zone management (for example, Catterall 1993, Knopf et al. 1988, Kusler & Brooks 1991, Stevens et al. 1977, Warner & Hendrix 1984).

Little of this information comes from research within Australian ecosystems, although similar conclusions are likely to apply here. For example, a study of the highlands of eastern Australia listed 43 species of birds and 19 species of bats that are specifically associated with riparian habitats (Gregory & Pressey 1982). Forests that fringe waterways in the wet–dry tropics are an important habitat for many bird, mammal, reptile and frog species (Woinarski et al. 1989). Riverine habitats in inland eastern Australia have been recognised as key habitats for the conservation of reptiles and amphibia, with 30% of species occurring there (Sadlier & Pressey 1994).

Several studies have shown that riparian habitats are of particular significance to birds. For example, riparian and floodplain areas in the semi-arid channel country of inland Australia support a higher number of bird species and individuals than other major habitats (McFarland 1992, Wyndham 1978). In the eucalypt forests and woodlands of coastal eastern Australia, bird species richness and bird abundances are greater in riparian forests than on drier slopes and ridges (Bentley & Catterall 1997, Loyn 1985, Recher et al. 1991).

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 wildlife species depends on the structure and composition of native vegetation within the riparian zone. Riparian areas which have been cleared have significantly lower habitat value than those supporting native vegetation. In addition, when a waterway bordered by native vegetation runs within cleared or more open land, this vegetated riparian zone provides a corridor for wildlife movement as well as habitat for many species.

Throughout Australia, riparian lands are one of the most highly impacted, reduced and fragmented habitat types.

9.2 Habitat features of riparian lands

Vegetation structure and diversity

Riparian plant communities often have a higher plant species diversity than those of adjacent upland areas. The vegetation is often taller, more dense, and structurally more complex in riparian lands than in upslope areas (see Figure 9.1).

Riparian vegetation typically shows a high level of spatial variation, reflecting two major environmental gradients. First, there is a longitudinal gradient, from headwaters to the river mouth, which occurs as a result of differences in climate, elevation, hydrology and geomorphology between first order streams and the point where the river meets the ocean. Second, riparian lands are zones of cross-sectional transition between aquatic and terrestrial environments. There is a transition in plant communities from aquatic or semi-aquatic species adjacent to a waterway to fully terrestrial species on higher ground (see Figure 9.1). This gradient is complicated by a variety of local factors, including topographic variation, flooding and channel dynamics, which interact to increase spatial and temporal variability.

Riparian lands are also dynamic across time. Past flood events and the history of erosion and deposition by the meandering channel interact with longitudinal and transverse environmental gradients to create spatial heterogeneity in riparian vegetation, especially on the broad floodplains of large lowland rivers (Gregory et al. 1991, Malanson 1993). For instance, 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). Heterogeneity in vegetation structure and plant communities provides a diversity of wildlife habitats.

Figure 9.1
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).

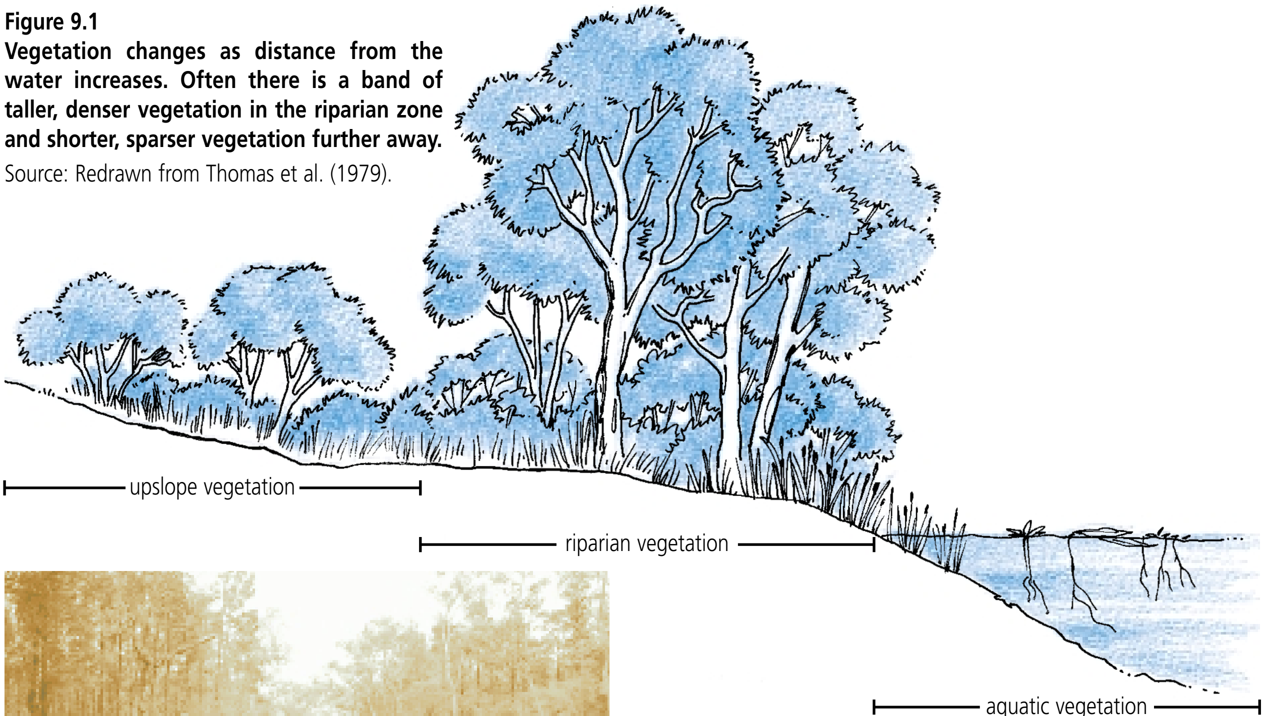


Photo: An example of vegetation zonation adjacent to a stream. Riparian species abundant in this habitat include Gilbert's dragon (Lophognathus gilberti), the pale-field-rat (Rattus tunneyi) and many frog species. Photo by C. Catterall; subcoastal southern Queensland.

Water and microclimate

Moisture is an important habitat feature of riparian lands, and occurs in a variety of forms (Malanson 1993):

~ surface water in the channel;
~ groundwater, including sub-surface flow when the channel appears dry;
~ surface water trapped in low areas of the riparian land;
~ soil moisture.

Water is directly important to a large proportion of riparian wildlife:

~ as drinking water (particularly important in arid and seasonally dry environments);
~ as habitat for larval stages of semi-aquatic organisms such as frogs and dragonflies.

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 9.2). 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 et al. 1991). 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 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 9.3).

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).

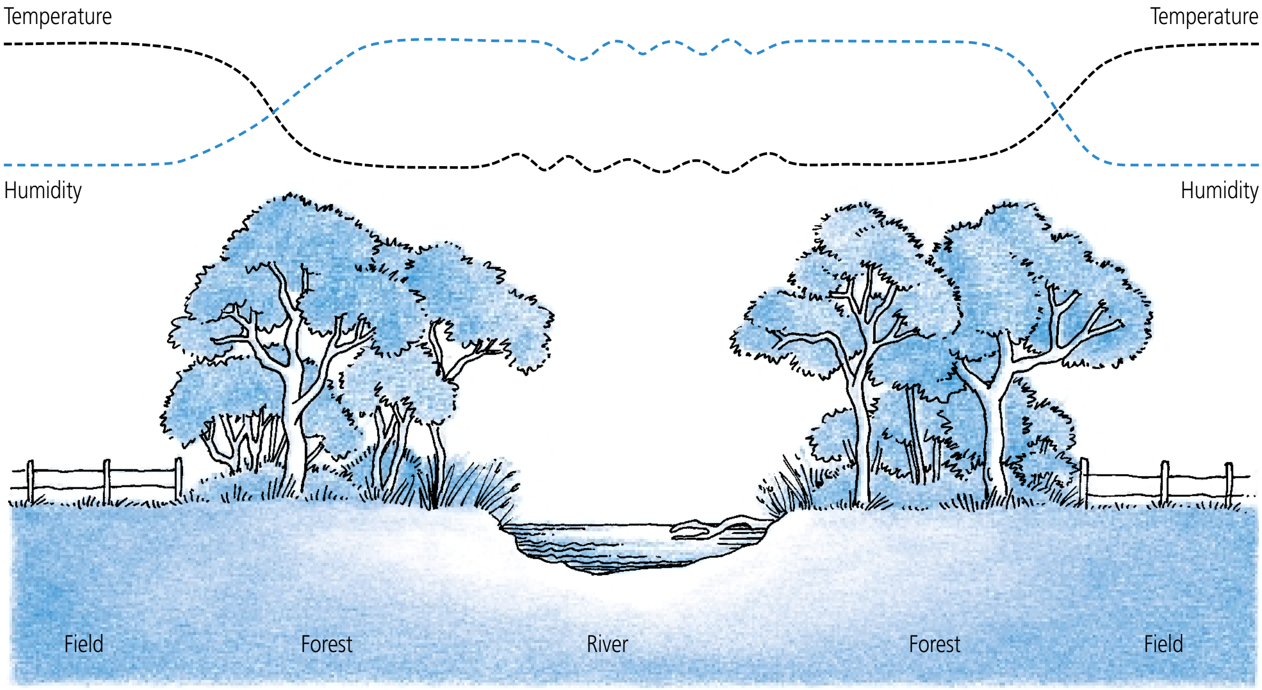


Figure 9.2 Riparian vegetation has a moderating effect on local microclimatic parameters such as air temperature and humidity.
Source: Redrawn from Malanson (1993).

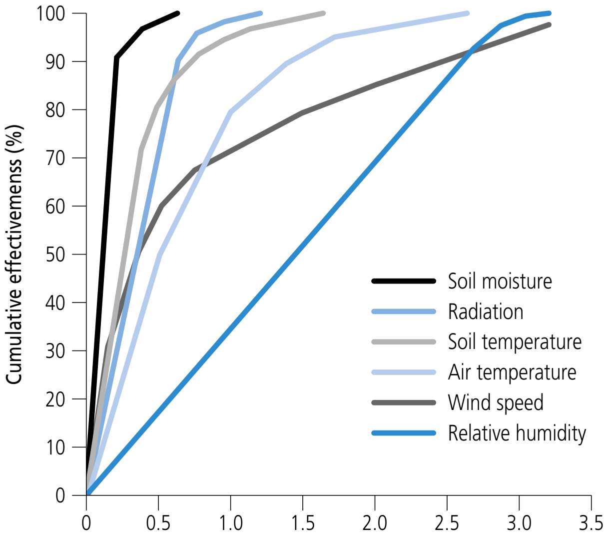


Figure 9.3 These generalised curves indicate the distance from the edge of a forest at which the effect on microclimate attributes is maximised.

Source: Redrawn from Collier et al. (1993).

Figs (*Ficus* spp.) are often common in riparian rainforest and their fruit are important in sustaining frugivores such as the fig parrot which is critically endangered in parts of its range due to forest clearing. Photo by Stuart Bunn.

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. Thus, 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 when these animals defecate. 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 generally highest close to the water in riparian habitats, and declines with distance from the edge of the stream (see, for example, Collier & Smith 1998, Jackson & Resh 1989). 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 riparian zone itself 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). Tall riparian trees are a source of nest hollows for birds, bats and arboreal mammals. The density and structural complexity of riparian forest also provide numerous protected perch and roost sites. Mobile species which feed in surrounding habitats may depend on riparian vegetation for roost and nest sites.

Leaf litter, fallen timber and flood debris accumulated in the riparian zone provide foraging sites and retreats for invertebrates, small mammals, reptiles and amphibians. 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.

9.3 Modes of use of riparian lands by wildlife

Riparian land supports both fully terrestrial wildlife and some aquatic organisms during particular stages in their life cycles. In some cases it is difficult to classify riparian fauna as aquatic, riparian or terrestrial, however three broad groups can be recognised: riparian-dependent aquatic species; riparian specialists; and riparian-dependent terrestrial species.

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 debris (such as 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.

The winged adult stages of many 'aquatic' insects remain close to the stream in riparian vegetation. Larvae of some species of aquatic insect also leave the water to pupate in the riparian zone. 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.

Degradation or loss of vegetated riparian habitats is likely to have a major impact on many of these aquatic species.

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). *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).

Riparian specialist species are particularly sensitive to disturbance and loss of riparian vegetation, and protection of riparian habitats is a priority in their conservation (see for example Geier & Best 1980, Pearce et al. 1994, Wardell-Johnson & Roberts 1991).

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 northern Australia, brown honeyeaters move from eucalypt woodlands into riparian forests in the late dry season when paperbarks begin to flower (Morton & Brennan 1991); and insectivorous bats visit riparian areas to drink and feed, but spend much of the day elsewhere in the landscape (see Strahan 1983).

In arid and semi-arid environments, riparian habitats may also provide 'refuge habitat' during times of drought or after fire. Even subtle variations in the availability of resources between riparian (or run-on) areas and other areas may be important to arid zone fauna.

Some 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 (see, for example, Bentley & Catterall 1997).

Loss of riparian vegetation is likely to have severe impacts on mobile fauna which depend on access to riparian lands on a daily, seasonal or life-history basis. These losses will also result in population reductions in species which, although able to survive without access to riparian lands, are typically most common there.

9.4 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.

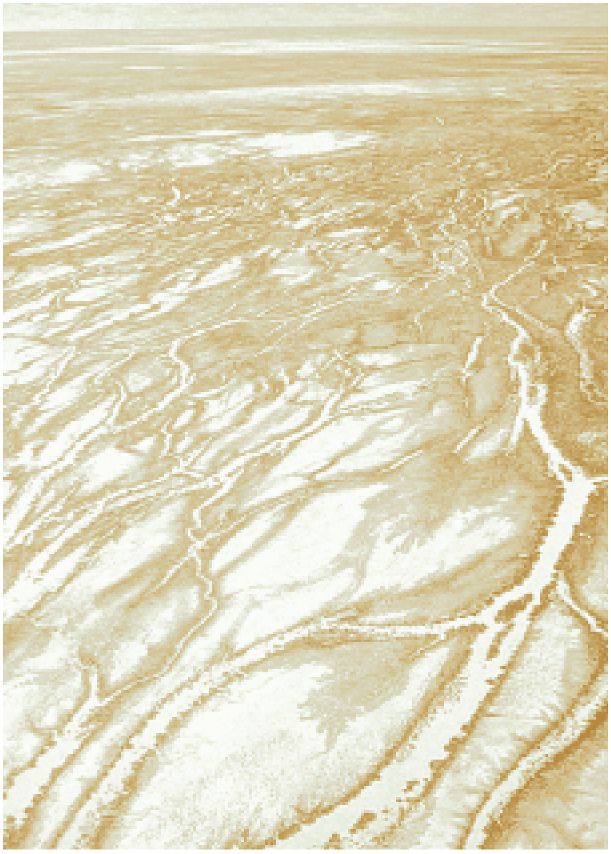
Riparian corridors in uncleared landscapes

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 mallee region of north-eastern Victoria, riparian forests along the Murray River provide corridors for colonisation by many species characteristic of higher rainfall areas of southern Victoria, such as the feathertail glider and the frog *Crinia signifera* (Robertson et al. 1989). Riparian forests in Australia's wet–dry tropics often contain monsoon rainforest tree species and may form corridors for movement of rainforest birds and bats between scattered rainforest patches.

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 depend on linking remnants into networks by means of habitat corridors (Merriam & Saunders 1993, Saunders et al. 1996, 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 9.4). Riparian areas are ideally suited to form the basis of linked wildlife habitat networks because: they form a hierarchy of



Riparian vegetation forms a natural network across the landscape in semi-arid areas such as the channel country of south-western Queensland. Photo by G. McTainsh.

Within cleared landscapes, corridors of native vegetation along watercourses may provide linkages among larger forest remnants. Photo by C. Catterall; coastal south-eastern Queensland.

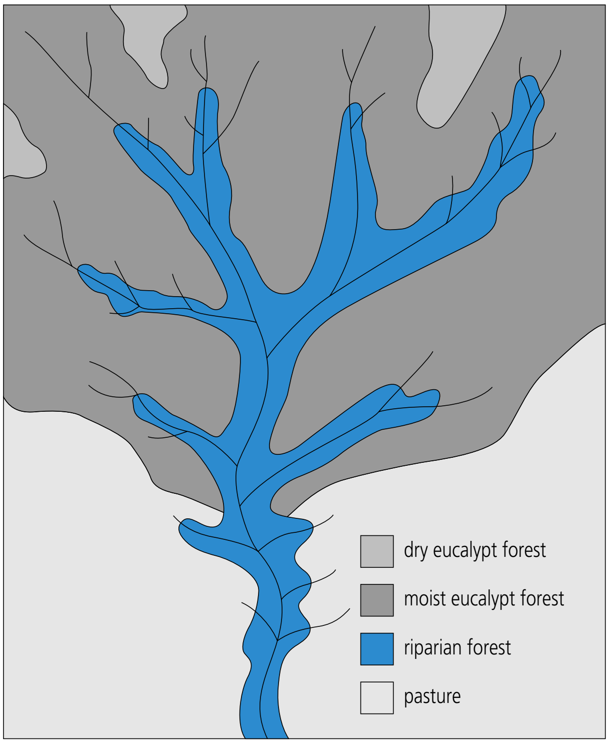


Figure 9.4 Riparian vegetation can provide a distinct habitat network in undistrubed landscapes and potential movement corridors within human-modified landscapes.

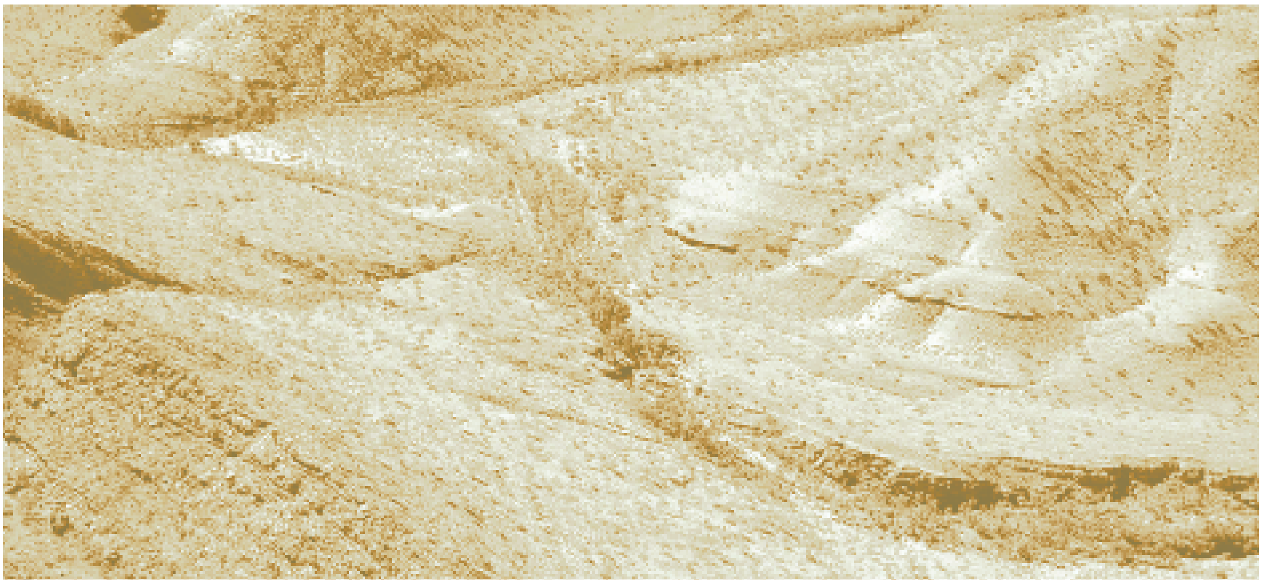
Source: Adapted from Thomas et al. (1979).

natural corridors throughout the landscape; they are used by most forest-dependent species; and also act as buffers to protect water quality and aquatic ecosystems (Bennett 1990). 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.

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 m 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). Narrow corridors of riparian forest within cleared lands are likely to experience edge effects, including altered microclimate, invasion by weeds, and altered interactions among species (Saunders & de Rebeira 1991, Saunders et al. 1991).

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.



A narrow band of riparian vegetation in the East Kimberley, Northern Territory, forms a corridor across an arid, sparsley-vegetated landscape. Photo by Michael Douglas.

Adult dragonflies frequently perch on riparian vegetation. Photo by Jon Marshall.

9.5 Specific requirements of wildlife in riparian lands

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. 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 an adequate native vegetation cover on riparian land. Some examples with particular reference to Australian ecosystems are provided below.

It must be noted that the ecology of Australian wildlife is very poorly known. A majority of insect species remain undescribed, and the life cycles, food and other habitat needs of most described species are unknown. Even among the vertebrates, there is little knowledge of the requirements of most species, especially those in northern Australia. This means that the formulation of specific management recommendations for riparian lands must often be a matter of educated guesswork.

Insects

Vegetated riparian lands support a diverse assemblage of herbivorous, detritivorous and predatory terrestrial insects, including a well-developed foliage-dwelling insect fauna and a variety of soil and litter invertebrates. Aquatic areas of the watercourse and off-channel pools are larval habitat for many taxa, whose adult stages also contribute to insect diversity and abundance in riparian habitats. In the wet–dry tropics, riparian forests have been recognised as important and distinctive habitats for terrestrial insects because they provide breeding sites in mud and moist litter, humid resting places, and dry-season refuges for many species (CSIRO 1972). Riparian lands in other parts of Australia are also potentially important areas for insect fauna, although little research has been done on this subject.

Many aquatic insects with terrestrial adult stages are 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. All damselflies and some dragonflies are 'perchers'; that is, the adults spend much of their time perched on the ground or on prominent stems or twigs from which they fly to intercept prey or engage in combat and courtship. 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 dependence of terrestrial insect species upon riparian lands is less well known. Some 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

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. Many species of butterflies, such as the Altona skipper butterfly, feed on plants which grow in swamps and riparian areas (Crosby 1990). 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.

Frogs

Most Australian frog species are dependent on surface water for reproduction, many species spend some part of their life close to waterbodies or watercourses. Riparian lands provide permanent habitat for adults of some species and breeding season habitat for species which usually occupy other habitats. Factors that make riparian lands, and particularly vegetated riparian lands, suitable habitat for many frog species include

Left: Habitat of the riparian specialist frog Geocrinia alba.
Above: A male at its breeding burrow. Photos by G. Wardell-Johnson.

- their dense vegetation, moist soils and humid microclimate;
- an abundance of crevices and hollows amongst vegetation, fallen timber and flood debris;
- a high abundance of insect prey.

Some frogs are 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). However, many species can survive considerable distances from free-standing water, but these may reach highest densities in riparian areas. 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). Riparian areas may also sustain populations during dry seasons or drought. In the wet–dry tropics where there is strong climatic seasonality and large variation in environmental conditions between years, riparian rainforest vegetation may be a seasonally important source of dry-season food and shelter for amphibian species which are usually found in eucalypt forest and woodland during the wet season (Martin & Freeland 1988).

In general, disturbance to riparian lands and loss of riparian vegetation would be expected to have significant impacts on many frog species, due to their high degree of dependence on these areas.

Reptiles

Many Australian reptiles are adapted to dry habitats, and riparian areas may have little or no value to these species. A small selection of species, many of which are semi-aquatic, are riparian specialists, and some favour riparian habitats but occur more widely. Riparian features of potential importance to reptiles include

- an abundance of invertebrate prey;
- an abundance of vertebrates, including small mammals, frogs and other reptiles providing prey for larger reptiles and snakes;
- a favourable microclimate for some small species;
- loose, friable soils and leaf litter providing suitable habitat for burrowing species;
- trees with hollows, fallen logs and flood debris offering an array of potential shelter and nest sites;
- deep fissures and cracks in the alluvial clay soils of floodplains.

Several species of Eulamprus are associated with riparian areas. Photo by Andrew Tatnell.

Several semi-aquatic reptiles exploit both terrestrial and aquatic food resources. These include two water monitors, *Varanus mertensi* and *V. mitchelli*, the water dragon and the water python (for example, Shine 1986). 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).

Birds

Of the taxa which inhabit riparian lands, birds have received most research attention. Riparian features of potential importance to avifauna include

- the presence of surface water for drinking;
- an abundance of insect prey from both terrestrial and aquatic environments;
- an abundance of small vertebrate prey (frogs, mammals, reptiles, smaller birds);
- a high structural diversity of vegetation, which provides a variety of foraging substrates;

White-plumed honeyeaters are common and conspicuous in riparian habitats of the inland. Photo by Andrew Tatnell.

~ a good supply of fleshy fruit and nectar-bearing flowers;
~ the presence of tall trees for perching, roosting and nesting;
~ a supply of hollows within mature trees;
~ dense canopy and ground-level vegetation offering nest sites that are shaded, humid and protected from predators.

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.

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 bird species may use riparian habitats for specific activities or at particular periods during their life. For example, riparian rainforest in the wet–dry tropics can provide dry-season food and shelter for birds that are typically found in eucalypt forest and woodland in the wet season. 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. 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 m of a waterway or waterbody (Burbidge 1985).

Grazing and trampling by stock and feral livestock has resulted in severe declines in some bird species that depend on riparian vegetation in northern Australia (Garnett 1992, Woinarski 1993). Clearing in southern and eastern Australia has affected many others (Garnett 1992). The retention of even narrow vegetated riparian buffers provides habitat that will be used by many forest-dependent species. However, breeding birds require larger areas than non-breeding birds and habitat that provides suitable nest sites, so buffer width, vegetation height and structure, and availability of tree hollows (or substitutes) must all be considered.

Mammals

Many mammal species favour riparian lands. For example, 17 of the 20 species of non-flying mammals likely to occur in one eastern Australian river valley, use riparian habitats (Gregory & Pressey 1982).

Riparian features of potential importance to Australian mammals include

- ~ surface water for drinking;
- ~ abundant high-quality foliage at both ground and canopy levels, providing food for herbivorous species;
- ~ an abundance of insect prey for marsupial carnivores and bats;
- ~ an abundance of small vertebrate prey for larger carnivores;
- ~ fleshy fruit and nectar-bearing flowers for omnivorous species;
- ~ loose, friable soil for burrowing species;
- ~ hollows within trees and fallen timber for roosting and nesting.

Australian mammals that are riparian specialists include native rodents, for example, *Rattus lutreolus*, *R. colletti* and the water rat. Some fruit bats favour riparian areas for their colonial roosts, choosing sites such as tall trees in swamps and mangrove islands in estuaries. Terrestrial mammals in drier parts of the continent may use riparian vegetation for shelter on a diurnal basis. For example, kangaroos and wallabies that range widely from dusk to dawn in search of food may retreat to the denser vegetation bordering waterways to rest under cover in the middle of the day (Coulson & Norbury 1988). 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). Riparian vegetation, typically found on high-nutrient soils, may also be important to other arboreal marsupials because of higher foliage nutrient quality (Braithwaite et al. 1983).

Degradation of riparian habitats in the Australian arid zone may have been a contributing factor in the decline and extinction of medium-sized mammal species. For example, the herbivorous rodent *Rattus tunneyi* has declined in the wet–dry tropics since European settlement, possibly because grazing by introduced herbivores has degraded riparian habitats which functioned as refuge areas during drought (Braithwaite & Griffiths 1996).

Incorporation of bands of riparian forest in a system of interconnected corridors has been suggested as a strategy for the conservation of arboreal mammals such as the koala and petaurid gliders (Pahl et al. 1990; Strahan 1983). Retention of adequate habitat area, using sufficiently wide riparian buffers, and ensuring that the vegetation structure includes nest and refuge sites are all important issues in managing riparian habitats for mammals.

Current research

Investigations of the ecology of riparian wildlife and of the ecological links between riparian and adjacent upland ecosystems, are widely scattered and not currently a major focus of any specific research sector or funding body. This is an unfortuate situation given the important role that riparian lands play in terrestrial ecosystems; it has arisen at least in part because of a lack of integration of research and development into aquatic and terrestrial systems at the organisational level. A variety of individual researchers are, however, conducting specific projects on the ecology of wildlife in riparian lands.

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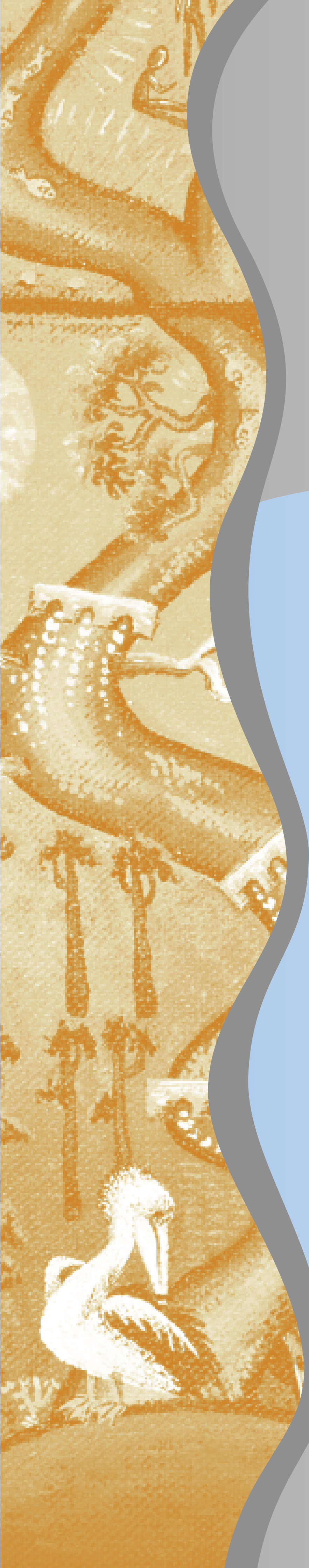

CHAPTER 10

Some impacts of human activity on riparian land

Michael Askey-Doran, Neil Pettit

Summary

- Human use of riparian land can often lead to such land becoming degraded; grazing, in particular, can cause problems.
- When allowed uncontrolled access to riparian land, stock can contribute to the degradation of riparian vegetation by grazing and trampling as well as to consequent increases in rates of erosion, to changes in floral communities by way of preferential grazing and the differing responses of species to grazing, to invasion by exotic weeds, to increased stream turbidity, and to increased input of nutrients and bacteria into the stream. Such disturbance of the stream can have deleterious effects on aquatic ecosystems and downstream users.
- Control of stock access to riparian land, by means of fences, can allow riparian vegetation and riparian habitats to recover, although a return to pre-disturbance conditions does not always occur. The process of regeneration depends on past and current land use, availability of propagules, and the composition and regeneration characteristics of the vegetation.
- Human-induced changes in fire regimes can have major impacts on the health of riparian vegetation.

CHAPTER 10

Riparian land constitutes some of the most productive land in the landscape, and is often heavily used by humans for agriculture, grazing, urban development and recreation. Such uses put pressures on natural systems and can, when poorly managed, lead to problems.

This chapter focuses almost exclusively on the impacts of grazing on riparian land, with some information on fire effects. Other issues, such as the impact of recreation, of sand and gravel mining, and of urban development are not covered. We welcome information on the impact on riparian land of these and other human actvities.

10.1 The use of riparian land for grazing

Grazing stock use riparian lands for a number of reasons and, depending on the season or climatic region, can spend significant amounts of time there. 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 et al. 1985, Platts & Nelson 1989). In the hotter seasons, stock are attracted to the cooler microclimates which characterise riparian lands and may spend extended periods loafing in the shade or standing in pools found there. Work in the rangelands of the western United States has demonstrated that use of riparian land by stock will be influenced by the quantity and quality of forage available in upland areas, the amount of shelter available to stock (Marlow & Pognacik 1986, Goodman et al. 1989) and the availability of water.

The influence of these factors in attracting stock to riparian land will vary in Australia according to season and location. Shelter from wind and forage quality may be important in the south, while shade and water are major attractions to stock in the tropics.

Stock access to riparian land may be either controlled or uncontrolled. Controlled grazing usually involves regulation of the season of access, time of grazing and stocking rates. Uncontrolled grazing involves unrestricted access by stock to riparian land and usually arises because the area is unfenced.

The impact of stock

The impact of stock on vegetation

Livestock have a variety of impacts on vegetation. The most obvious impact is associated with the direct grazing of ground covers and shrubs. Undisturbed vegetation often 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. When stock graze they preferentially select the more palatable species, either removing them from a site or reducing them to compact, low tussocks, coppices or rosettes.

Trampling by stock damages the vegetation and leads to soil compaction. The loss of ground covers leads to an increase in the amount of bare ground and a consequent increase in erosion and runoff of sediments and nutrients. Soil compaction reduces the macropore space in soil and this reduces infiltration, root growth and overall plant production (Bohn & Buckhouse 1985). 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 (see Chapter 6). Plant diversity influences nutrient cycling and uptake, soil aeration, soil structure and levels of microbial activity (Earl & Jones 1996).

The response of vegetation to grazing is likely to vary according to the length of the growing season. For example, in warm climates with long growing seasons the amount of foliage may actually increase despite grazing, whereas in cooler, temperate climates, which have shorter growing seasons, it may decrease. Plants with different life forms respond to grazing in different ways. Grazing may favour sedges and grasses (which are able to survive, albeit with reduced vigor) over other life forms.

Shrub and tree species may be unaffected in the short term but damaged over time. The absence of a tree or shrub canopy may then favour the development or expansion of ground covers (Trimble 1994), which further restrict germination of woody species (Kirkpatrick 1991). The loss of important species or functional groups 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.

Over time, heavy grazing can result in the development of even-aged stands of vegetation or a reduction in species diversity, or both. Overgrazing restricts the recruitment of most riparian plants, particularly that of 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. Species composition may shift, changing the patterns of dominance to favour species which can tolerate grazing (Gregory 1981). The lack of regeneration of tree and shrub species may result in a reduction in canopy cover and, consquently, an increase in the levels of light and temperature reaching streams (see Chapter 3 for a discussion of the impact of light and temperature on stream ecosystems).

A comparison of the vegetation on grazed and ungrazed riparian land around the Blackwood River, Western Australia, showed a decline of native species, particularly perennial shrubs and herbs, in the grazed area. This coincided with a dominance of exotic annual grasses and herbs, as well as a decline in species richness and diversity. Analysis of the age structure of perennial species on riparian land indicated a lack of recruitment, particularly of overstorey species. Although germination of seeds is taking place, seedlings rarely, if ever, reach the juvenile or adult stage (Pettit, unpublished data).

Research in grazed upland woodlands in Western Australia indicates that seedling survival is reduced not only by direct grazing pressure, but also by the indirect effects of livestock on soil, such as increased surface compaction and increased water repellancy (Pettit et al. 1995).

Germination studies of Tasmanian riparian land indicate that the recruitment of woody species after grazing is excluded is a lengthy process. After almost three years of exclusion there has been only limited recruitment of woody species in the monitored plots (Askey-Doran, Potts & Lambourne, unpublished data). 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.

In combination with fire, grazing can further restrict native perennial species and promote the establishment of ruderal species (for example, grasses), which in turn promote fire. A recent burn treatment in one of the exclosures in Tasmania has resulted in the germination of *Eucalyptus* and *Acacia* species in the moist, organic-rich soils occurring under now dead, dense shrubs directly adjacent to the stream. However, in burnt riparian areas away from the stream, germination is confined to herbaceous species, with some procumbent, woody shrubs regenerating vegetatively.

Livestock can also promote invasion of weeds (usually annual, ruderal species), which can bring

Uncontrolled stock access to a stream in north-east Tasmania.
Photo courtesy of Ian Bell and Tom Priestley.

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 (in their faeces or by attachment to the animal). Stock faeces and urine also contribute nutrients to the soil, which further encourages the growth and spread of weed species.

The impact of stock on stream-bank stability

The degree to which stock contribute to stream-bank erosion and soil degradation depends on

- soil type;
- soil moisture content;
- size of stream;
- regional climate;
- intensity and duration of grazing;
- type of stock;
- grazing history;
- condition and type of vegetation.

Grazing by stock removes or inhibits vegetation which helps bind the stream-bank soils. Trampling opens up bare ground, creating focal points for erosion. Stock create tracks through riparian vegetation and these become pathways for sediments and nutrients to enter streams. Tracks created along the edges of stream banks crack, and may eventually slump into the stream. In the Kimberley region of north-western Australia, cattle overgrazing the native vegetation have caused major erosion and river siltation problems (Williams et al. 1996, Winter 1990).

The impact of stock is greatest when soil moisture levels are greater than 10% (Marlow & Pognacik 1985). At such moisture levels, any reduction in stock numbers is likely to have little effect. Fewer stock will mean that damage to localised sections of the stream bank is limited, but it will still occur. 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 et al. 1996). Grazed stream banks may erode three to six times faster than ungrazed stream banks (Trimble 1994). This erosion originates from ramps cattle create in accessing streams and can result in losses of about 40 m^3 a year.

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 et al. 1992). Small streams have low stream banks and shallower water, allowing easier stock access at many points. Larger streams have steeper banks, which limit stock access. 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 along 150 m of stream bank (Frankenberg 1994). By contrast, ungrazed banks protected by *Phragmites australis* show only minimal erosion and no undercutting.

The impact of stock on water quality

Livestock grazing can affect both the shape and quality of the water column (Kauffman & Krueger 1984). Changes in water quality associated with uncontrolled access by stock include

- increased water temperatures and light through loss of shade;
- an increase in sediments and nutrients resulting from erosion and from the loss of the filtering capacity of the vegetation;
- increased bacterial counts from faecal contamination;
- increased sediments entering streams as upland and riparian areas are subjected to erosion caused by stock;
- increased water turbidity, which affects the habitat of aquatic plants and animals;
- increased input to streams of contaminants flowing down tracks created by stock;
- increased input of phosphorus and nitrogen from stock urine and faeces.

Livestock wastes may 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, gastroenteritus, typhoid fever, hepatitus A, amebiasis and viral gastroenteritus (Splichen 1992). The use of riparian buffers and the exclusion of stock from the riparian zone can reduce faecal inputs by up to 90%.

Stock not only affect water quality but are also affected by it. Work in Canada has demonstrated that gains in stock performance of up to 25% can be achieved through the provision of managed watering systems such as troughs (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 kg more body weight and consumed 33% less water than those drinking solely from fresh water (Parlevliet 1983).

When stock are excluded from riparian land

In environments that have had a long history of grazing and where the vegetation has adapted to this form of disturbance, the exclusion of livestock may result in changes to the vegetation structure, such as the invasion of 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 et al. 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 the winter-rainfall areas of Australia exclusion of grazing for the summer period (when most damage to the vegetation and the stream bank is done) may be enough to prevent further degradation (L. Pen, Western Australian Water and Rivers Commission, pers. comm.). However, 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 (Wellington & Noble 1985, Enright & Lamont 1989), and intermittent grazing may interfere with any such 'window of opportunity' for recruitment. 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 form a seed bank.

In a study on remnant woodlands, both life form and reproductive strategy were found to be important in determining species persistence under livestock grazing disturbance (Pettit et al. 1995).

After one year of excluding stock in a grazing exclusion experiment on riparian land on the Blackwood River in Western Australia, native perennial herbs have shown the greatest increase in vegetation cover (see Table 10.1). This was due mainly to the rapid increase in biomass of the native

Table 10.1
Comparison of vegetation between fenced and unfenced degraded riparian areas, 12 months after fencing

Vegetation characteristic	Fenced	Unfenced
Species richness per site	26	21
Mean species richness per 100 m²	17.3 ± 2.3	14 ± 1
Mean no. native spp. (per 100 m²)	7.6 ± 0.5	7 ± 1.2
Mean no. exotic spp. (per 100 m²)	8.6 ± 0.3	7 ± 1.1
Species diversity	1.81	2.11
Species evenness	0.55	0.69
Total vegetation cover (%)	80.2	69.7
Native species cover (%)	35.7	7.5
Exotic species cover (%)	44.5	62.2
Age structure (mean/100 m²)		
seedlings	0.0	0.0
juvenile	9.3	0.0
mature	0.6	1.3
Mean top height of *Casuarina obesa* saplings (m)	1.19 ± 0.12	0.0
Mean area of *Gahnia* spp. clumps (m²)	1.79 ± 0.22	0.23 ± 0.04
Mean % bare ground	23.3	20.0
Mean % ground litter	1.3	8.3

Note: Data taken from five 10 m x 10 m plots in each of the fenced and unfenced areas.

Source: Neil Pettit, unpublished data.

Buffalo Brook, Tasmania in 1986 (above) and in 1996. Photos by Michael Askey-Doran.

sedge *Gahnia trifida* (mean size of individuals was 1.8 m^2). On the grazed plots, where heavily grazed individuals were persisting, the mean size was only 0.13 m^2. There has also been successful recruitment of the overstorey species *Casuarina obesa* in the exclosure plots, with a mean of 9.5 seedlings per 100 m^2, compared with zero seedlings in the grazed plots (N. Pettit, unpublished data).

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 have 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*. 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 path of regeneration.

10.2 The impact of fire on riparian land

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 the floristic and structural composition of riparian communities and on the intensity and frequency of burning. Different species respond differently to fire, some being advantaged and others suffering. 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 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 (Nadolny & Benson 1993).

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 fires burn intensely and produce embers which can be blown into riparian areas or the fires can burn into the riparian zone (Askey-Doran 1993).

Succession following vegetation clearance and/or grazing usually only occurs once the cause of the disturbance is removed. For example, grazing pasture will need to be fenced to exclude stock before secondary succession of native species can occur. Attempts to regenerate native species on formerly cleared sites can be overwhelmed by the regeneration of introduced species. This is especially the case in areas that have had a long history of introduced species and/or are far from a propagule source. For these sites some form of direct intervention is usually required, either to initiate regeneration or to reduce the impact of exotic species.

Riparian vegetation being burnt (mainly *Pandanus spiralis*), Kapalga, Kakadu National Park, Northern Territory. Photo by Michael Douglas.

Current research

Watercourse management of deeply incised streams

This research, which is being undertaken in the Mount Lofty Range of South Australia, demonstrates the principles of watercourse rehabilitation for deeply incised streams in low-rainfall agricultural landscapes. The work will also monitor the efficacy of 'minimal intervention' techniques for rehabilitating highly degraded watercourses through longitudinal and cross-sectional surveys. The results of this work will be published in easy to use 'do-it-yourself' farmer-friendly guidelines.

Researchers: Department of Environment, Heritage and Aboriginal Affairs

The impact of stock on riparian lands

Three landholders in Coopers Creek, Queensland, are working with their local catchment group to compare controlled versus uncontrolled grazing and watering access to waterholes. Stock numbers will be counted and photographic records of riparian vegetation will be taken monthly, with benthic processes and water quality in the waterholes assessed twice yearly.

Researchers: Cooper Creek Protection Group

The management of riparian vegetation along stream frontages

Work similar to that just described is being done in the Goulburn–Broken region of Victoria, with the management of riparian vegetation along stream frontages the research focus. The impact of stock and grazing pressure on stream frontages will be assessed through the use of a range of different grazing treatments. Monitoring of stream stability, weeds and vermin will take place, with an economic analysis also being undertaken to assess the benefits and costs to landholders of implementing particular riparian vegetation-management strategies.

Researchers: Goulburn–Broken Catchment Management Authority

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GLOSSARY

A

Absorbed	Nutrient that is bound to mineral or organic sediment and therefore only dissolves into water under particular chemical conditions.
Adsorbed	The linking of a particle or ions to another particle by adhesion or penetration.
Aerobic decomposition	The breakdown of complex organic molecules in the presence of free (gaseous or dissolved) oxygen.
Aggregate	Cluster of soil particles which adhere to each other and consequently behave as a single mass.
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.
Anastomosing channel	A channel that irregularly splits and rejoins.
Anoxic	Deficient or absence of free (gaseous or dissolved) oxygen.
Aquiclude	A rock or soil layer of low permeability. Opposite of an aquifer.
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.
De-snagging	Removal of snags.
Detritus	Organic debris from decomposing organisms and their products. A major source of nutrients and energy for some aquatic food webs.
Diatoms	The common name for the algae of the division *Bacillariophyta*.
Distributaries	Branch of river that does not return to the main river.
Drip line	The limit of a tree canopy, defined by the pattern of drips from the canopy.

E

Ecotone	The transition between two or more diverse communities, for example forest and grassland.
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

Fluid shear	The force per unit area exerted by water as it shears over a surface.
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.

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.

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.
Microtopography	Variations in topography of the ground surface at the scale of centimetres to metres.

O

Organic colloids	Small, low-density particles that can be transported easily by overland flow.
Overburden	Burial by deposited sediment.

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.
Refractile riparian particles	Particles of organic matter with low nutrient concentrations and often high levels of lignin (associated with cellulose).
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.
Serotinous plants	Plants (usually trees) that retain seeds in hard enclosing structures (for example, cones) that are not dispersed until after some event, especially forest fire.
Shear stress	See fluvial shear.
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.
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.
Sub-aerial 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.

Riparian Land Management
Technical Guidelines

Volume One

Part B:
Review of Legislation Relating to Riparian Management

Land & Water Resources
Research & Development Corporation

RiverLandscapes

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

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Riparian Land Management Technical Guidelines.
Volume One, Part B: Review of Legislation Relating to Riparian Management

Report for the Land and Water Resources
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Compiled by Emily Cripps BScLLB, Grad Dip (ASOS) (Hons)
Edited by Siwan Lovett and Chris Pirie

CONTENTS

1 Introduction

Management of the riparian environment is subject to legal constraints, and land managers need to know what these constraints are. This document reviews the legal requirements that apply in the various Australian jurisdictions.

Although riparian management is a specific aspect of land management, it is not recognised as such in the legislation, so we have to look more broadly at legislation dealing with land use and land management. In general, the application of this legislation is wide-reaching and encompasses riparian management and the protection of those pristine riparian zones that remain. Legislation relating to water management is also applicable.

It is important to note that some of the terms used in the legislation have a definition that differs from that applying outside the legal arena. For example, in legal terms a 'riparian right' is defined as the right to use water for household purposes and for the watering of a domestic garden, although the precise definition varies from State to State. A riparian right may also embody the absolute right to control and use water in a stream or creek. It is thus vital that the legislative requirements of each jurisdiction are made clear.

Although the legislation may not at first glance appear relevant to practical management, this is not the case. Legislation is important: it defines what a person—be they a landholder or a local government officer—can legally do. Prescribing a strict management regime for riparian areas is of little use if it is not legally enforceable.

The legislation also describes how managed riparian areas can be protected, in the short term or in the long term. And it may provide mechanisms by which landholders can seek assistance. Another important element of this review is that it outlines the steps a person other than the landholder can take, ranging from the provision of management advice to practical assistance and long-term protection.

Most of Australia's States and Territories do not have legislation that deals specifically with riparian management; instead, other legislation—such as that dealing with land use and planning, native vegetation, pastoral lands, and Crown land—must be relied on. Legislation relating to ecologically sustainable development (ESD) may also be relevant. Definitions of 'ecologically sustainable development' make reference to the precautionary principle, conservation of biodiversity and ecological integrity, and intergenerational equity. The management of riparian areas is vital to catchment management and water quality and this ought to be taken account of when considering ESD because it affects the conservation of biodiversity and ecological integrity. It might be argued that ESD legislation should play a much more active role in riparian management.

Few pieces of legislation can be invoked to provide specifically for the management of riparian vegetation and areas. The main trigger relates to threatened species: if a threatened species occurs in a particular area legislation can be invoked to provide for the protection and continuing management of that area. In addition, some State legislation relating to native vegetation may require that a permit be obtained to clear certain areas. But, overall, the approach seems piecemeal, and the current legislation should be amended to include specific reference to riparian management.

Chapters 2 to 9 review the legislation relating to riparian management in each of the Australian States and Territories.

2 New South Wales

A range of New South Wales legislation is relevant to riparian management. In many cases, the legislation is concerned with the establishment of a body to manage a particular catchment and provide, in particular, for the use of water and water rights for irrigation. The most pertinent legislation is that concerned with land use and planning and vegetation management in general. The *Native Vegetation Conservation Act 1997*, which came into force on 1 January 1998, will probably become increasingly influential.

The following is the legislation that is most applicable to riparian management:
~ *Catchment Management Act 1989*
~ *Crown Lands Act 1989*
~ *Environmental Planning and Assessment Act 1979*
~ *Local Government Act 1993*
~ *Native Vegetation Conservation Act 1997*
~ *Rivers and Foreshores Improvement Act 1948*
~ *Soil Conservation Act 1938*
~ *Water Administration Act 1986*
~ *Western Lands Act 1901*.

The following legislation may also be applicable:
~ *Coastal Protection Act 1979*
~ *Coastal Protection Amendment Act 1998*
~ *Commons Management Act 1989*
~ *Fisheries Management Act 1994*
~ *Forestry Act 1916*
~ *Irrigation Act 1912*
~ *Murray–Darling Basin Act 1992*
~ *National Parks and Wildlife Act 1974*
~ *New South Wales – Queensland Border Rivers Act 1947*
~ *Protection of the Environment Operations Act 1998*
~ *Rural Fires Act 1997*
~ *Rural Lands Protection Act 1989*
~ *Threatened Species Conservation Act 1995*
~ *Water Act 1912*
~ *Wilderness Act 1987*.

2.1 The Catchment Management Act

The *Catchment Management Act 1989* allows for the establishment of catchment management committees and seeks to achieve total catchment management, which is described as the 'coordinated and sustainable use and management of land, water, vegetation and other natural resources on a water catchment basis so as to balance resource utilisation and conservation' (section 4).

Catchment management committees have a number of functions, among them promoting and coordinating total catchment management; providing advice about natural resource management and catchment needs and performance monitoring; and providing a forum in which conflicts about resource use and management can be resolved. Provision of advice about the management of riparian vegetation is an essential part of their total catchment management functions.

The Act also allows for the establishment of catchment management trusts, which are to provide for the construction and maintenance of buildings and work, to generate revenue by imposing levies, and to provide assistance to mitigate the effects of flood or drought.

2.2 The Crown Lands Act

The *Crown Lands Act 1989* deals with the management and administration of Crown land. This includes the conservation of natural resources wherever possible and the sustainable use and management of the land in question.

Crown land can be leased or a licence can be granted for carrying out a specific activity on the land. In the case of leasing, the Crown can impose conditions relating to vegetation management and conservation. The Act also allows for the provision of local land boards for each land district of Crown land.

2.3 The Environmental Planning and Assessment Act

The *Environmental Planning and Assessment Act 1979* is the primary piece of land use and planning legislation in New South Wales. It allows for the creation, at various levels of government, of environmental planning instruments to control land use and planning. State environmental planning policies, regional environmental plans, local environmental plans, development control plans, and council codes and policies can all be established under the Act.

State environmental planning policies are formulated by the State Government to deal with matters of State concern. Among those that may affect riparian management are SEPP 14, dealing with coastal wetlands, and SEPP 19, dealing with bushland in urban areas.

Regional environmental plans are formulated by the State Government to deal with regional matters. Among those that are relevant are REP 17 Kurnell Peninsula, which aims to protect the natural environment, especially the wetlands, on the Kurnell Peninsula; REP 20 Hawkesbury–Nepean River, which integrates planning with catchment management; and Murray REP 2, designed to coordinate planning along the Murray River and incorporate the requirements of the Murray–Darling Basin Commission.

Local environmental plans are developed by local governments to control land use and planning in their municipality or part of their municipality. They define the types of land uses that are permitted, discretionary or prohibited in a certain region and incorporate the requirements of relevant regional vegetation management plans, which are developed under the *Native Vegetation Conservation Act 1997*. Through local environmental plans local government can play an active role in riparian management.

Development control plans and council codes and policies can also be important, particularly if they are related to riparian management or the assessment of development applications. If a proponent seeks consent for a proposed development, their application is considered by the local government, in accordance with any relevant State environmental planning policies, regional environmental plans, local environmental plans, development control plans, regional vegetation management plans, council codes and council policies. If the proposed development might cause environmental harm, an environmental impact assessment is also necessary. Section 79C of the Environmental Planning and Assessment Act lists the requirements that must be considered by the authority charged with granting or refusing consent.

In granting consent, a council can impose conditions that restrict specific activities (such as vegetation clearing) or that require certain activities to be carried out (such as management of the land for vegetation conservation).

A process of integrated assessment of development proposals now operates to reduce the number of bodies from which consent must be sought.

2.4 The Local Government Act

The *Local Government Act 1993* creates local governments and grants them the power necessary to perform their functions, among which are the management, development, protection, restoration, enhancement and conservation of the environment of the area the local government is responsible for, in a manner that is consistent with and promotes the principles of ecologically sustainable development. The *Local Government (Ecologically Sustainable Development) Act 1997* amended the Local Government Act so that ecologically sustainable development, including the sustainable use of resources, is now a guiding operational principle.

2.5 The Native Vegetation Conservation Act

The *Native Vegetation Conservation Act 1997* replaces SEPP 46, dealing with native vegetation. The Act allows for the preparation of regional vegetation management plans, establishes regional vegetation committees, and contains provisions relating to property agreements. Section 3 outlines the Act's objectives—among them providing for the conservation and management of native vegetation on a regional basis; encouraging native vegetation management in the social, economic and environmental interests of the State; protecting native vegetation of high conservation value; encouraging revegetation; preventing inappropriate clearing; and promoting the importance of native vegetation as a part of ecologically sustainable development.

Under the Act the Minister has the power to declare certain land to be State-protected land. This can be land that has a surface slope greater than 18 degrees; land that is situated within, or within 20 metres of, the bed or bank or any part of a river or lake; and any land that is in the Minister's opinion environmentally sensitive or affected or liable to be affected by soil erosion, siltation or land degradation. State-protected land can be cleared only in accordance with a development consent that is already in force.

A person may clear native vegetation only in accordance with a development consent or if permitted to do so under a regional vegetation management plan, which is prepared by a regional vegetation committee and, once approved, will contain provisions relating to the clearing of all native vegetation covered by the plan. It may require that all clearing or the clearing of specific vegetation be subject to the granting of a permit. The provisions of a regional vegetation management plan must be incorporated in the local environmental plans for the areas to which the regional plan applies.

The Act also provides that a landholder and the State Government can enter into a property agreement. This is a voluntary agreement that deals with the management of vegetation on private land; it may also enable the landholder to apply for financial assistance from the Native Vegetation Management Fund or to seek technical aid.

2.6 The Rivers and Foreshores Improvement Act

The *Rivers and Foreshores Improvement Act 1948* allows for the carrying out of works to remove obstructions from and improve rivers and foreshores and to prevent erosion caused by tidal and non-tidal water. The Act covers the removal of vegetation, sand, gravel or rocks from the bed or bank of a river, lake or lagoon; the changing of the course of a river; the prevention of erosion and siltation; and the deepening, widening or improving of the course of a river. The 'constructing authority' (the Minister for Public Works or the Department of Public Works) may carry out work provided for under this Act. In particular, where river flow is or is likely to be obstructed or detrimentally affected, the obstruction may be removed.

2.7 The Soil Conservation Act

The *Soil Conservation Act 1938* is primarily concerned with the conservation of soil and the prevention of erosion. A soil conservation commissioner may be appointed to protect proclaimed works, notified catchment areas, rivers, lakes, dams, creeks, lagoons and marshes from the effects of soil erosion, land degradation, siltation and sedimentation. In an area where a project is being carried out the Minister may enter an agreement or covenant with a landowner to limit the number of livestock or for other land management purposes. A soil conservation notice may be issued if a landholder has done or is likely to do something that will lead to land degradation. The notice may require that the landholder not do or do certain things.

If the Minister considers that the stability of a river, lake, lagoon, creek, swamp, marsh or catchment is adversely affected or liable to be adversely affected by soil erosion, siltation or land degradation, this may be notified in the government *Gazette*. Further, if the Minister considers that anything done or proposed to be done is likely to cause soil erosion or siltation in a catchment area and that damage or siltation may be avoided, the Minister may serve a notice on the landholder requiring them to do or not do that thing.

Section 23A of the Act allows for the creation of catchment committees. Such a committee can provide advice to the Minister, assist in the identification of problems within the catchment, and arrange voluntary land management agreements between landholders.

The Soil Conservation Act is thus important for the management of riparian vegetation, particularly because it allows the Minister to exert control over the activities or proposed activities of a landholder if they are likely to cause land degradation or siltation of a river or lake.

2.8 The Water Administration Act

The *Water Administration Act 1986* relates primarily to the use and allocation of water resources. It establishes the Water Administration Ministerial Corporation to administer the Act; this administration must be consistent with ecologically sustainable development.

2.9 The Western Lands Act

The *Western Lands Act 1901* applies to land that is outside the area of a local government. The Western Lands Commission is responsible for land use and planning in the region, which is known as the Western Division of New South Wales. Land in the region is primarily leasehold, so land use can be controlled through conditions imposed on leases. The Commissioner can direct a lessee to preserve trees, shrubs and other vegetation. Land that is protected under the Native Vegetation Conservation Act can be cleared only in accordance with the provisions of that Act.

2.10 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in New South Wales.

~ The *Coastal Protection Act 1979* applies to the coastal zone of New South Wales, as defined in the Act.
~ The *Coastal Protection Amendment Act 1998* amends the *Coastal Protection Act*.
~ The *Commons Management Act 1989* deals with the establishment and management of commons by trusts established under the Act.
~ The *Fisheries Management Act 1994* deals with matters related to the dredging of waterways and the reclamation of land.
~ The *Forestry Act 1916* provides for the declaration of areas as State forests, timber reserves and flora reserves and for the control and management of these areas.
~ The *Irrigation Act 1912* deals with matters related to irrigation, including the construction, control and management of works for water conservation, irrigation and water supply.
~ The *Murray–Darling Basin Act 1992* provides the legislative basis for the Murray–Darling Basin Agreement between the Commonwealth, New South Wales, Victoria, Queensland and South Australia.
~ The *National Parks and Wildlife Act 1974* deals with the creation of numerous types of reserves, among them national parks, nature reserves and wilderness areas.
~ The *New South Wales – Queensland Border Rivers Act 1947* implements an agreement between the two States concerning the Severn, Dumaresq, Macintyre and Barwon Rivers and underground water.
~ The *Protection of the Environment Operations Act 1988* includes provisions relating to environmental offences and allows for the making of 'protection of the environment' policies.
~ The *Rural Fires Act 1997* deals with bushfire fighting and prevention, including hazard-reduction burning.
~ The *Rural Lands Protection Act 1989* establishes the Rural Lands Protection Board.
~ The *Threatened Species Conservation Act 1995* covers the protection of listed species and the listing of species as endangered, extinct or vulnerable.
~ The *Water Act 1912* deals with water rights, water drainage and artesian wells. It allows a person to take water from a river or lake for domestic uses.
~ The *Wilderness Act 1987* provides for the permanent protection and proper management of wilderness areas.

2.11 Further information

For further information, contact

~ your local government
~ the catchment management committee in your area
~ your regional office of the Department of Land and Water Conservation—http://www.dlwc.nsw.gov.au

Copies of legislation can be bought from the Government Information Service offices in Parramatta and Sydney City (telephone 02 9743 7200) or by mail order (Government Information, PO Box 258, Regents Park NSW 2143).

3 Victoria

A large amount of Victorian legislation may be relevant to riparian management. The land use and planning provisions are important, in particular those in the *Planning and Environment Act 1987*, which allows for the zoning and control of land use by local governments. The *Catchment and Land Protection Act 1994*, the *Land Conservation Act 1970*, and the *Heritage Rivers Act 1992* are also important.

The following is the legislation that is most applicable to riparian management:

~ *Catchment and Land Protection Act 1994*
~ *Coastal Management Act 1995*
~ *Conservation, Forests and Lands Act 1987*
~ *Flora and Fauna Guarantee Act 1988*
~ *Heritage Rivers Act 1992*
~ *Land Conservation Act 1970*
~ *Planning and Environment Act 1987*
~ *Water Act 1989*.

The following legislation may also be applicable:

~ *Alpine Resorts Act 1983*
~ *Crown Land (Reserves) Act 1987*
~ *Environment Protection Act 1970*
~ *Forests Act 1958*
~ *Groundwater (Border Agreement) Act 1985*
~ *Land Act 1958*
~ *Local Government Act 1989*
~ *Melbourne Water Corporation Act 1992*
~ *Murray–Darling Basin Act 1993*
~ *Snowy Mountains Engineering Corporation Act 1971*
~ *Water (Rural Water Corporation) Act 1992*
~ *Water Industry Act 1994*.

3.1 The Catchment and Land Protection Act

The objectives of the *Catchment and Land Protection Act 1994* are as follows:

> (a) to establish a framework for the integrated and co-ordinated management of catchments which will—(i) maintain and enhance long-term land productivity while also conserving the environment; and (ii) aim to ensure that the quality of the State's land and water resources and their associated plant and animal life are maintained and enhanced ...

The Act establishes the Victorian Catchment and Land Protection Council, among whose functions is the operation of regional catchment and land protection boards. Areas can be declared catchment and land protection regions by the Governor in Council, and a regional catchment and land protection board can then be established for that region. Among other things, a regional board prepares a regional catchment strategy and coordinates and monitors the strategy's implementation.

The Act also places an obligation on all landowners to take 'all reasonable steps to avoid causing or contributing to land degradation which causes or may cause damage to the land of another landowner …' (section 20).

Part 4 of the Act requires that a regional catchment strategy be prepared and be used to assess the land and water resources and their uses and the nature, causes, extent and severity of land degradation; to identify areas for priority attention and objectives for the quality of the land and water resources; to set a program for promoting improved use of land and water and reducing land degradation; and to specify procedures for monitoring the strategy's success. A strategy may also provide for land use planning, incentives for better management, and the establishment of a land management advisory service. The board that prepares the strategy may recommend changes to a planning scheme to give effect to the strategy.

Section 26 of the Act states that in carrying out a function involving land management, the Minister or public authority must have regard to any regional catchment strategy applying to the land. A board may recommend to the Minister that land in its region be declared a special area, so that it can then be classified as a special water supply catchment. In considering the recommendation, the Minister must have regard to the quality and condition of the land, the water quality, and aquifer recharge and discharge areas. The Minister may then recommend that the Governor in Council make an order under section 27 and declare the land to be a special area or revoke or amend such a declaration.

A special area plan must then be prepared. It must identify the problems to be dealt with in the plan, the action to be taken to deal with those problems, and the targets; it may also identify the most suitable land uses for the area and say what land can be used for. If land use conditions are specified, the plan must describe the properties to which they apply and the general nature of the conditions. A planning scheme may be amended on the board's recommendation to give effect to the special area plan.

In carrying out a function involving land management, a public authority must have regard to the special area plan applying to that area. Land use conditions may be applied to landowners. These conditions may prohibit certain acts, such as exploration or mining, and they are binding on that landowner and all subsequent ones.

The Act allows for the issuing of a land management notice if the landowner fails to comply with certain provisions. Such a notice may prohibit or regulate land use or land management practices and it may require specific actions to be taken to minimise land degradation or rehabilitate degraded land. Interim land management notices may be issued if there is an immediate and serious threat of land degradation that might be prevented.

3.2 The Conservation, Forests and Lands Act

The *Conservation, Forests and Lands Act 1987* aims 'to provide a framework for a land management system and to make necessary administrative, financial and enforcement provisions …' and it does this through a system of cooperative agreements.

The Act outlines several types of activities that are not permitted without a plan being submitted by the local government to the Director-General of Conservation, Forests and Lands for comment and advice. Among these activities are work requiring the disturbance of soil or vegetation above 1220 metres in altitude, the construction across waterways of dams or other structures that have the potential to interfere with the passage of fish or the quality of the aquatic habitat, and the carrying out of development within a critical habitat listed under the *Flora and Fauna Guarantee Act 1988*. Unless there is no prudent or feasible alternative, it is an offence for the local government to act contrary to the Director-General's advice.

The Director-General and a landholder may enter into an agreement 'relating to the management, use, development, preservation or conservation of land in the possession of the land owner or otherwise to give effect to the objects or purposes of a relevant law relating to land in the possession of the land owner' (section 69). An agreement may restrict the use of the land; require the landholder to refrain from certain activities or place conditions on certain activities; require the landholder or Director-General to carry out certain work for the management, use, development, preservation or conservation of flora and fauna; require the landholder to allow the Director-General to inspect the land; require the landholder to indemnify the Director-General for work carried out on the land; specify the way a grant is to be used by the landholder; and provide for any matter relating to the management, use, development, preservation or conservation of the land. Such an agreement may be expressed to be binding on the title and will thus bind future owners of that land. The agreement can also allow for rate relief.

An agreement can be varied or revoked with the agreement of the landholder and the Director-General or by order of the Supreme Court, the Minister or the Administrative Appeals Tribunal.

3.3 The Crown Lands (Reserves) Act

The *Crown Lands (Reserves) Act 1987* deals with the reserving of Crown land for public purposes; in particular, for the 'protection of the beds or channels and the banks of waterways … preservation of areas of ecological significance … the conservation of areas of natural interest or beauty' and 'the preservation of species of native plants' (section 4). Either the land is reserved by the Minister after public notice has been given of the proposal or the Governor in Council may order the land to be reserved under the Act.

Once the land is reserved regulations relating to the care, protection and management of the land can be made. A management committee can be appointed for the reserve; it has a duty to manage, improve, maintain and control the land for the purpose for which it is reserved. It can also grant licences to enter and use the reserved land, in accordance with the provisions for which it was reserved. If no management committee is appointed, the land can be managed by the Director-General of Conservation, Forests and Lands.

3.4 The Planning and Environment Act

The purpose of the *Planning and Environment Act 1987* is to provide for a system of planning schemes, based on municipal districts, as the main way of controlling land use and ensuring that the effects on the environment of a proposed development are considered. Local government is responsible for land use and planning within its municipality, and planning schemes are the primary mechanism for this. The Minister can prepare and approve standard provisions, which are referred to as the Victoria Planning Provisions.

A planning scheme must seek to further the objectives of planning in Victoria, must contain a municipal strategic statement, and may regulate or prohibit the use or development of any land within the municipality. It must also contain local provisions and the Victoria Planning Provisions. The municipal strategic statement describes the land use and development objectives and strategies for achieving those objectives. A planning scheme may also apply to land reserved under the *Crown Land (Reserves) Act 1978*.

The general requirements of the Victoria Planning Provisions are contained in the State Planning Policy, which includes, for example, the requirement that authorities must have regard to the relevant aspects of regional catchment strategies under the *Catchment and Land Protection Act 1994*. More specific provisions are provided in the environmental significance overlays, which must be included in planning schemes. One important overlay is the vegetation protection overlay: it protects areas of significant vegetation by ensuring that development minimises vegetation loss and encourages revegetation. In most situations a permit is required to clear vegetation; in deciding on an application for a permit, the responsible authority must take account of the proposed activity's potential effects on the vegetation and the need to maintain vegetation where the ground slope is greater than a set level, where the proposed activity is within 30 metres of a watercourse, and where the land may become unstable or subject to salinisation if it is cleared.

The Act also provides for a council and a landowner to develop a management agreement in relation to prohibiting, restricting or regulating the use or development of land. Once entered into, the agreement can be registered with the Registrar of Titles; it is then binding on successive title holders.

3.5 The Heritage Rivers Act

Schedule 1 to the *Heritage Rivers Act 1992* identifies specific areas of land as heritage river areas. A heritage river area's management authority must take all reasonable steps to ensure that the significant nature conservation, recreation, scenic or cultural heritage attributes of the area are protected. It must also prepare a management plan, which must be approved by the Minister after public consultation. Several land- and water-related activities are prohibited in heritage river areas, among them the construction of artificial barriers or structures that hinder the passage of water fauna and the significant impairment of the area's nature conservation, recreation, scenic or cultural heritage attributes. Further, the diversion of water from rivers in heritage areas is subject to restrictions. Clearing indigenous flora, harvesting timber, establishing plantations and grazing domestic animals are not permitted in a natural catchment area.

3.6 The Flora and Fauna Guarantee Act

The *Flora and Fauna Guarantee Act 1988* establishes a legal and administrative structure to promote flora and fauna conservation and provides for a choice of procedures that would encourage and facilitate this process. Section 4 of the Act recognises the need for incentives and cooperative management agreements to encourage conservation. The Act relates to threatened species and allows for the listing of threatened species and potentially threatening processes. The Director-General of Conservation, Forests and Lands is required to prepare a flora and fauna guarantee strategy outlining how the flora and fauna conservation and management objectives are to be achieved. The Director-General can also prepare a management plan for a threatened community or species or in relation to a threatening process. The plan must be prepared in consultation with any landholder or water manager who has interests that may be directly and materially affected by the plan; alternatively, a management agreement may be entered into with a public authority, such as a local government. There must also be a process of public consultation and notification.

The Act enables the Minister to issue interim conservation orders for conservation of the critical habitat of a listed species on Crown or private land. Such orders can prohibit certain activities and limit use of the land; they operate for a maximum of two years. There are, however, provisions that allow a landholder to seek compensation for any financial loss suffered as a natural, direct and reasonable consequence of the making of an interim conservation order.

If, under the Act, a person is found guilty of an offence such as taking, keeping or trading in protected flora without a licence or permit that person may be required to carry out restoration work or pay compensation to the Director-General.

Schedule 3 to the Act lists the potentially threatening processes, among them the removal of wood debris from streams, alteration to the natural flow regimes of rivers and streams, and the degradation of native riparian vegetation along rivers and streams.

3.7 The Water Act

Section 7 of the *Water Act 1989* confers on the Crown the right to the use, flow and control of all water in a waterway and all groundwater. A person has the right to take, free of charge for their domestic and stock use, water from a waterway or bore to which they have access by means of a public road or reserve, because they occupy the land on which the water flows or occurs, or because they occupy land adjacent to a waterway. Section 30 of the Act deals with the development of a groundwater management plan. Section 36(1) concerns applications for bulk entitlement to water by local governments or other authorities; in considering an application made under this section, account must be taken of existing authorised water uses, the drainage regime and the environment (including riverine and riparian environments), among other things. Account must also be taken of other legislation concerned with riverine and riparian environments. Section 64A of the Act deals with water resource management plans, and section 64B allows for an area to be declared a water resources management area.

3.8 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in Victoria.

- ~ The *Alpine Resorts Act 1983* removes declared alpine resorts from local government control.
- ~ The *Coastal Management Act 1995* allows that land declared coastal Crown land be subject to the Victorian Coastal Strategy. When making a decision affecting coastal land, local government must act to further the purposes of the Strategy. Regional coastal boards can also be declared under the Act.
- ~ The *Environment Protection Act 1970* establishes the Environment Protection Authority and the Environment Protection Board. It also allows for

the making of State environment protection policies and the issuing of abatement and infringement notices for causing pollution and other offences.

~ The *Forests Act 1958* covers the creation of parks within reserved forests. A management or an advisory committee may be established for each site.
~ The *Groundwater (Border Agreement) Act 1985* approves the Border Groundwater Agreement between South Australia and Victoria and brings the Agreement into effect. The Agreement deals primarily with the extraction of groundwater from bores and the rate at which this can occur.
~ The *Land Act 1958* deals with the sale and occupation of Crown land. General conditions may be imposed on a lease or a licence relating to Crown land; these may be concerned with the retention or clearance of native vegetation and the control of land degradation.
~ The *Land Conservation Act 1970* deals with the management and conservation of public land.
~ The *Local Government Act 1989* allows, among other things, for the granting of a rebate or concession in relation to any council rate or charge to preserve places in the municipality that are of environmental interest.
~ The *Melbourne Water Corporation Act 1992* establishes the Melbourne Water Corporation.
~ The *Murray–Darling Basin Act 1993* provides the legislative basis for the Murray–Darling Basin Agreement between the Commonwealth, New South Wales, Victoria, Queensland and South Australia.
~ The *Water Industry Act 1994* covers applications for water, sewerage, drainage or sewage-treatment licences.

3.9 Further information

For further information, contact

~ your local government
~ your local catchment management authority
~ your regional office of the Department of Natural Resources and Environment
~ the Department of Natural Resources and Environment, Catchment Management and Sustainable Agriculture Branch, Level 13, 8 Nicholson Street, East Melbourne Victoria 3002—telephone 03 9637 8366; http://www.nre.vic.gov.au

Copies of legislation can be bought from Anstat—telephone 03 9278 1133 or 03 9278 1144.

4 Queensland

In Queensland a broad range of legislation may need to be considered when planning for the management and control of riparian land. The *Land Act 1994*, which controls vegetation clearance, relates to land owned by the Crown, although the the State's Broadscale Clearing Guidelines have been adopted by many local governments and so apply to some freehold and all leasehold land.

The following is the legislation that is most applicable to riparian management:

- *Coastal Protection and Management Act 1995*
- *Environmental Protection Act 1994*
- *Fisheries Act 1994*
- *Integrated Planning Act 1997*
- *Land Act 1994*
- *Local Government Act 1993*
- *Nature Conservation Act 1992*
- *River and Improvement Trust Act 1940*
- *Soil Conservation Act 1986*
- *Water Resources Act 1989.*

The following legislation may also be applicable:

- *Murray–Darling Basin Act 1996*
- *Rural Lands Protection Act 1985*
- *South-East Queensland Waters Act 1979*
- *Wet Tropics World Heritage Protection and Management Act 1985.*

4.1 The Coastal Protection and Management Act

Under the *Coastal Protection and Management Act 1995* the coastal zone is defined to include 'coastal waters; and all areas to the landward side of coastal waters in which there are physical features, ecological or natural processes or human activities that affect, or potentially affect, the coast or coastal resources' (section 11). The Act allows for the preparation of State and regional coastal management plans, and a 'control district' may be declared by regulation or under a regional plan. A control district can be declared over coastal waters, over a foreshore (up to 400 metres inland from the high-water mark), a river mouth or estuarine delta (up to 1000 metres inland from the high-water mark) or along tidal rivers, saltwater lakes and other bodies of internal tidal water (up to 100 metres from the high-water mark along the river, lake or water body). This allows for large areas of land near the coast to be covered by the Act. It is also possible to control activities through the regional coastal management plans, and orders to remedy or restrain an offence, or a potential offence, under the Act can be issued.

4.2 The Environmental Protection Act

The *Environmental Protection Act 1994* is designed to regulate activities that may cause harm to the environment. Among other things, the Act defines 'environmental harm', 'environmental nuisance' and 'material environmental harm' and prescribes the penalties that may be imposed for causing such harm. It also allows for the development of environment protection policies, dealing with land, air or water quality, and so could be used to control the clearing of riparian land.

Further, the Act imposes a general duty: 'A person must not carry out any activity that causes, or is likely to cause, environmental harm unless the person takes all reasonable and practicable measures to minimise the harm' (section 86). If it can be shown that the clearing of riparian land causes environmental harm, that clearing, if carried out without a permit under the Act, would constitute a breach of this general duty.

4.3 The Fisheries Act

The *Fisheries Act 1994* is concerned with the protection and management of the State's freshwater and marine fish resources, including their habitats. Clearing of marine plants, including plants in tidal areas, is controlled through the requirement to apply for a permit.

4.4 The Integrated Planning Act

The *Integrated Planning Act 1997* is the primary piece of legislation dealing with land use and planning in Queensland. It allows for an integrated system of development approvals—involving the State Government and local governments—which is referred to as the 'integrated development assessment system'. Local governments can control land use through planning systems and can declare and impose development constraints. Planning schemes must state the desired environmental outcome for the areas they cover. Development permits must be obtained from local governments for developments that are classified as 'assessable developments'; they are not required for 'self-assessable developments' or 'exempt developments'. The Act also takes account of ecological sustainability, which includes the protection of ecological processes and natural systems, maintenance of the life-support capabilities of soil and water, and the conservation of biological diversity.

4.5 The Land Act

As noted, the *Land Act 1994* relates mainly to Crown land; it applies to some private land in limited circumstances. In administering land under the Act, regard must be had to sustainability, evaluation, consultation, development, community purpose, and the protection of the land. Crown land can be leased and it can be reserved for use as a quarry, for a public purpose, or for mineral or petroleum exploitation. All leases, licences and permits issued under the Act are subject to the condition that the lessee, licensee or permit holder has a duty of care in relation to the land and must control noxious weeds.

Part 6 of the Act relates to tree management. A tree-clearing permit is required and, when considering an application, the chief executive of the Department of Natural Resources must consider the protection of the catchment and land vulnerable to degradation. Conditions may be imposed on a permit—detailing how the clearing is to occur, for example. Section 271 of the Act allows for the development of a broad-scale tree-clearing policy, which must be approved by the Governor in Council and must include matters relating to tree-clearing guidelines, maximum slope limitations, and watercourse buffers. Several local governments have adopted the idea of a broad-scale clearing policy, imposing clearing restrictions and permit requirements on landholders in their jurisdiction.

The Act also allows for land to be declared a critical area by regulation if it is considered to be highly vulnerable to degradation or of high conservation value or if it is protected under the *Nature Conservation Act 1992*.

4.6 The Nature Conservation Act

The *Nature Conservation Act 1992* provides for areas to be declared a national park, a national park (scientific), a national park (Aboriginal), a conservation park, a resources reserve, a nature refuge or a wilderness area. Each type of declared area has different management requirements but must be managed in accordance with the overall principles stated in the Act. A resources reserve allows for the recognition—and, if necessary, the protection—of areas of natural resources, to control land use and ensure that the land remains predominantly in its natural condition. The Act also classifies species as vulnerable, rare, and so on, and in so doing provides protection for them. This can be encouraged through recovery plans, conservation plans and voluntary conservation agreements between a landholder and the Department of Environment and Heritage.

4.7 The River and Improvement Trust Act

The *River and Improvement Trust Act 1940* allows for the establishment of a river improvement trust, which permits the undertaking of work to repair or prevent damage to a river bed or bank; to remove vegetation, gravel, sand or soil that is impeding the flow of a river; or to alter or prevent a change in the course of a river and prevent erosion or siltation. Such a trust also has power to issue an improvement notice prohibiting an act that has occurred or that is contributing to damage to a river bank. Failure to comply with such a notice is an offence; restoration may be required. A trust can be established for each river improvement area. Two or more local governments may apply to the Minister for the establishment of a trust.

4.8 The Soil Conservation Act

Management of riparian land is integral to soil conservation. The *Soil Conservation Act 1986* contains provisions relating to the development of property plans, which must specify soil conservation measures and can influence clearing practices and other aspects of land management. More detailed provisions can be included in a project plan. Soil conservation orders—preventing or requiring a specific activity—can also be issued by the Soil Conservation Commissioner.

4.9 The Water Resources Act

The *Water Resources Act 1989* deals with the construction, control and management of works relating to water conservation and protection, irrigation, water supply and drainage, and protection and improvement of watercourses' physical integrity. It also covers the law relating to rights in water.

The Crown is given the power to take control of a watercourse or lake and to declare areas 'catchment areas'. In addition, the Act preserves ordinary riparian rights such as the right to use water for domestic services and other domestic purposes. A licence is required to do specific things—construct a dam, for instance—and these activities can be subject to conditions. The Act also prohibits the destruction of vegetation, excavation, and the placing of fill without a permit. When considering an application for a permit, account must be taken of the possible effects of the removal of vegetation, the position of the watercourse, and other possible long-term or cumulative effects. Part 9 of the Act deals with irrigation, the declaration of irrigation areas, and the management of areas that are important for water conservation.

4.10 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in Queensland.

~ The *Local Government Act 1993* gives local government broad powers relating to land use and management.
~ The *Murray–Darling Basin Act 1996* provides the legislative basis for the Murray–Darling Basin Agreement between the Commonwealth, New South Wales, Victoria, Queensland and South Australia.
~ The *Rural Lands Protection Act 1985* deals with the control of declared plants and animals on public, private and local government land.
~ The *South-East Queensland Waters Act 1979* establishes the South-East Queensland Water Board to manage water supply and conservation.
~ The *Wet Tropics World Heritage Protection and Management Act 1985* establishes the Wet Tropics Management Authority, among whose responsibilities are the preparation and implementation of management plans.

4.11 Further information

For further information, contact

- ~ your local government
- ~ the Queensland Government's general inquiries desk—telephone 07 3227 7111
- ~ the Department of Environment and Heritage—http://www.env.qld.gov.au—or the regional extension officer in your area
- ~ the Department of Natural Resources—http://www.dnr.qld.gov.au—or the stream control officer in your area
- ~ the Department of Primary Industries—http://www.dpi.qld.gov.au; Primary Industries Building, 80 Ann Street, Brisbane Queensland 4000; call centre within Queensland (telephone 132 523, fax 07 3404 6900) or outside Queensland (telephone 07 3404 6999); or write to GPO Box 46 Brisbane Queensland 4001

Copies of legislation can be bought from GOPRINT—telephone 07 3246 3399 or 1800 679 778 for callers outside the Brisbane area; email goprint_retail@goprint.qld.gov.au

GOPRINT's retail bookshops are at 371 Vulture Street, Woolloongabba Queensland 4102 and 135–147 George Street, Brisbane Queensland 4000.

5 Western Australia

Riparian management in Western Australia is primarily dealt with under the *Conservation and Land Management Act 1984* and the *Soil and Land Conservation Act 1945*. A range of other legislation may, however, be applicable.

The following is the legislation that is most applicable to riparian management:

~ *Conservation and Land Management Act 1984*
~ *Country Areas Water Supply Act 1947*
~ *Metropolitan Region Town Planning Scheme Act 1959*
~ *Soil and Land Conservation Act 1945*
~ *Waterways Conservation Act 1976.*

The following legislation may also be applicable:

~ *Aboriginal Affairs Planning Authority Act 1972*
~ *Agriculture Act 1988*
~ *Agriculture Protection Board Act 1950*
~ *Bush Fires Act 1954*
~ *Environmental Protection Act 1986*
~ *Parks and Reserves Act 1895*
~ *Town Planning and Development Act 1928*
~ *Water and Rivers Commission Act 1995*
~ *Water Boards Act 1904*
~ *Water Corporation Act 1995*
~ *Water Services Co-ordination Act 1995*
~ *Wildlife Conservation Act 1950.*

5.1 The Conservation and Land Management Act

The *Conservation and Land Management Act 1985* makes provision 'for the use, protection and management of certain public lands and waters and the flora and fauna thereof …' The Act applies to State forest, timber reserves, national parks, conservation parks, nature reserves, and other land vested in the Lands and Forests Commission created under this Act. State forest and timber reserves are reserved through the Act. The executive director of the Lands and Forests Commission may enter into an agreement with the owner, lessee or licensee of any land for management of that land by the Department of Conservation and Land Management, for the land to be used as a forest or reserve, or for some other public purpose under the Act. It is also possible for a lessee to agree that land under a pastoral lease be managed by the Department. The Act establishes various bodies, among them the Lands and Forest Commission, the National Parks and Nature Conservation Authority, the Forest Production Council, the Marine Parks and Reserves Authority, the Reserves Scientific Advisory Commission, and the Department of Conservation and Land Management.

Part 5 of the Act deals with the management of land. The body controlling a reserve must develop and implement management plans that define the policies and guidelines to be followed and summarise operations to be undertaken.

A management plan for a State forest or timber reserve must specify the purpose for which the land is reserved, which can be for timber production or water catchment protection or as otherwise provided. Land may be classified under the Act as a wilderness area, a limited access area, a prohibited access area, a temporary control area, or a recreation area.

Permits and licences can be issued for the removal of forest products from reserved areas and land can be leased for forest removal. It is an offence to unlawfully (that is, without a licence or permit) remove forest products.

This Act would be applicable to the management of riparian land if, for example, control over land in the riparian zone were to be vested in the Lands and Forests Commission, which would then be responsible for managing the land for water catchment and protection.

5.2 The Country Areas Water Supply Act

The *Country Areas Water Supply Act 1947* provides for the supply of water and allows for the declaration of areas as country water areas, catchment areas or water reserves. Section 12A states that it is an offence to clear controlled land (that is, land within a catchment area or water reserve), except in accordance with section 12C, which allows for clearing if it is in accordance with a clearing licence that has been issued or in a situation that poses a threat to life. A person who controls or owns controlled land may seek a clearing licence from the Water and Rivers Commission.

The Act also covers the construction of works for the supply of water and the payment of rates for that supply.

5.3 The Metropolitan Region Town and Planning Scheme Act

The *Metropolitan Region Town and Planning Scheme Act 1959* operates in conjunction with the *Town Planning and Development Act 1928*. The Metropolitan Region Planning Authority, established under the former Act, is responsible for the metropolitan region planning scheme, which is similar to a municipal planning scheme. If a metropolitan region scheme exists, a town planning scheme made under the Town Planning and Development Act will be approved by the Minister only if it is in accordance with the regional scheme.

Part IVA of the Act relates to planning control areas. The Western Australian Planning Commission is able to declare land part of a planning control area if that land is required for a purpose stated in Schedule 2 to the Act—providing parks, recreation areas, State forest and water catchments. Once an area is declared a planning control area, a development in the area can be initiated only with the approval of the local government and the Commission.

5.4 The Soil and Land Conservation Act

The *Soil and Land Conservation Act 1945* defines 'land degradation' as soil degradation and 'the removal or deterioration of natural or introduced vegetation where it diminishes the future use of the land' (section 4). This is obviously applicable to riparian vegetation since clearing would generally cause soil degradation.

The Act establishes the Soil and Land Conservation Council, among whose functions are the 'prevention and mitigation of land degradation; [and] the promotion of soil conservation'. The State Governor, by order in council, can declare an area to be a land conservation district and a land conservation district council can be appointed to manage that area. The Governor can also make recommendations covering things such as the lighting of fires and interference with vegetation in the declared area.

The imposition of rates (soil conservation rates) comes within the Act, and Part IVA deals with conservation: a landholder can enter into a conservation covenant or a conservation agreement to cover a portion of their land.

5.5 The Waterways Conservation Act

The long title of the *Waterways Conservation Act1976* explains that the Act's purpose is 'to make provision for the conservation and management of certain waters and of the associated land and environment, for the establishment of a Rivers and Estuaries Council and certain Management Authorities'. The Governor in Council can declare any area containing one or more river, estuary, lake, and so on, to be a management area for the purposes of the Act and can appoint a management authority for that area. The area can contain land that is necessary for the proper management of the waters; this would include the riparian land.

Among other things, the Rivers and Estuaries Council has a duty to preserve and enhance the quality of the environment, provide information for good management and conservation, and control or prevent any activity that may cause pollution of the waters. Section 31 provides for the Water and Rivers Commission or a management authority to enter into an agreement with a landholder in relation to the control and management of the land in accordance with the Act. Management programs can be prepared for areas under the Commission's control.

Section 9 defines a riparian right as the right to take water for domestic purposes and for the watering of stock (if the land owned adjoins a watercourse) and for a garden (if the garden is less than 2 hectares and is used in connection with the dwelling). Any person can take water for domestic use from Crown land via a public road, but there is no right to take or divert a lake or watercourse permanently other than in accordance with the Act. Section 12 provides that a landowner may seek a special licence to divert a watercourse. Section 25 states,

> A person shall not, except as authorized by or under this or any other Act, obstruct, destroy, or interfere with the waters, bed, or banks of any water-course flowing through or over, or lake, lagoon, swamp or marsh situate wholly or partly on, land that has not been granted or demised by the Crown.

Licences and permits may be issued for an activity that would otherwise be an offence under the Act.

The Act also covers irrigation districts, the taking of water for irrigation, information about fire regimes, and the conservation of flora and fauna.

5.6 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in Western Australia.

- The *Aboriginal Affairs Planning Authority Act 1972* allows for consultation with and the representation of Indigenous Australians in planning matters and establishes the Aboriginal Affairs Planning Authority.
- The *Agriculture Act 1988* outlines the functions of Agriculture Western Australia, which include safeguarding the environment, soil and vegetation.
- The *Agriculture Protection Board Act 1950* establishes the Agriculture Protection Board of Western Australia and provides for the management of specific weeds and feral animals.
- The *Bush Fires Act 1954* establishes the Bush Fires Board and deals with requirements for burning, restrictions on burning, and so on.
- The *Environmental Protection Act 1986* establishes the Environmental Protection Authority, which has two objectives: protection of the environment and prevention and abatement of pollution. The Act also deals with environmental impact assessment.
- The *Parks and Reserves Act 1895* establishes boards for the control and management of parks and reserves.
- The *Town Planning and Development Act 1928* deals with land use and planning. Statements of planning policy can be made and can cover any subject that may come within a planning scheme. In preparing a planning scheme, a local government must have regard to planning policies: a planning scheme will not be approved if it is inconsistent with State policy. Once a scheme has been approved, it will control land use and planning.
- The *Water and Rivers Commission Act 1995* establishes the Water and Rivers Commission, among whose functions are conservation of water resources, prevention of pollution, and assessment of licences.
- The *Water Corporation Act 1995* establishes the Water Corporation, among whose functions are the acquisition, storage, treatment and distribution of water and dealing with waste water.

~ The *Water Services Co-ordination Act 1995* covers the coordination and provision of water services and the licensing of service providers.
~ The *Wildlife Conservation Act 1950* is similar to the threatened species legislation in other States; it is linked to the Conservation and Land Management Act and covers the declaration of flora and fauna as threatened species.

In March 1997 the Commissioner of Soil and Land Conservation, the Environmental Protection Authority, the Department of Environmental Protection, Agriculture Western Australia, the Department of Conservation and Land Management and the Water and Rivers Commission signed a memorandum of understanding that regulates clearing in rural-zoned lands in southern Western Australia. If a landholder proposes to clear more than 1 hectare of native vegetation, they must submit a 'notice of intent to clear' to the Commissioner of Soil and Land Conservation. Proposals are considered against a series of criteria, among them the likelihood of land and water degradation, waterway and wetland protection, water resource protection, biological diversity, geological importance, European heritage and Aboriginal heritage.

5.7 Further information

For further information, contact
~ your local government
~ your district office of the Department of Conservation and Land Management http://www.calm.wa.gov.au
~ the Waters and Rivers Commission—telephone 08 9278 0300, http://www.wrc.wa.gov.au
~ the Office of the Soil Commissioner, Agriculture Western Australia—telephone 08 9368 3282

6 South Australia

In South Australia legislation dealing with vegetation clearance has been in force since the 1970s. Before that time, clearing vegetation was a condition for leases of Crown land. Nowadays, permits are necessary to clear vegetation and the Heritage Agreement Scheme operates for vegetation conservation.

The following is the legislation that is most applicable to riparian management:

~ *Development Act 1993*
~ *Native Vegetation Act 1991*
~ *Pastoral Land Management and Conservation Act 1989*
~ *Soil Conservation and Land Care Act 1989*
~ *Water Conservation Act 1936*
~ *Water Resources Act 1997.*

The following legislation may also be applicable:

~ *Country Fires Act 1989*
~ *Crown Lands Act 1929*
~ *Environment Protection Act 1993*
~ *Forestry Act 1983*
~ *Ground Water (Border Agreement) Act 1985*
~ *Irrigation (Land Tenure) Act 1930*
~ *Irrigation Act 1994*
~ *Local Government Act 1934*
~ *Metropolitan Drainage Act 1935*
~ *Murray–Darling Basin Act 1993*
~ *National Parks and Wildlife Act 1972*
~ *Public and Environmental Health Act 1987*
~ *South Eastern Water Conservation and Drainage Act 1992*
~ *Waterworks Act 1932*
~ *Wilderness Protection Act 1992.*

6.1 The Development Act

The *Development Act 1993* is undergoing substantial review as part of the review of the Local Government Act.

The Development Act requires the preparation of a planning strategy for the State or parts of the State. The strategy is a statement of policy and can include planning or development objectives relating to ecologically sustainable development and the management, conservation or use of natural resources. Development plans can then be prepared with a view to controlling development in a particular area. Development is permitted only if it is approved under a development plan. A development can be classified as complying or non-complying, and conditions can be imposed on the development. Section 57 of the Act provides that the Minister or a local council can enter into a land management agreement with a landowner for the preservation or conservation of the land. The Minister or council has power to carry out work on that land, as required by the agreement. If requested by a party to the agreement, the agreement can be noted on the land title.

6.2 The Native Vegetation Act

The *Native Vegetation Act 1991* allows for the provision of incentives and assistance to landholders to facilitate preservation and conservation of native vegetation, to limit clearance of vegetation, and to encourage revegetation. The principles for the clearance of vegetation are stated in Schedule 1 to the Act. They relate to the conservation of biodiversity and specifically to riparian vegetation: it is stated that vegetation should not be cleared if, in the opinion of the Native Vegetation Council established under the Act, the vegetation is growing in or in association with a wetland environment or 'the clearance of the vegetation is likely to cause deterioration in the quality of the surface or underground water'.

Part 5 of the Act states that it is an offence to clear vegetation except in accordance with the Act; this means that vegetation can be cleared only with the Native Vegetation Council's permission or if the vegetation is of a prescribed class (such as exotics) or in prescribed circumstances (for example, for the maintenance of a firebreak). The Act also enables the Minister to enter into a heritage agreement with a landowner. After consultation with the Native Vegetation Council, an agreement may be entered into restricting the use of the land to which it applies, requiring specific work be done, providing for the management of the land and native vegetation, or relating to financial incentives such as the remission of rates.

6.3 The Pastoral Land Management and Conservation Act

The *Pastoral Land Management and Conservation Act 1989* is designed to ensure that all pastoral land is managed in such a way as to provide a sustainable yield and to allow for the monitoring of the land's condition, the prevention of degradation and the rehabilitation of land. A general duty is imposed on lessees to prevent land degradation and to pursue good land management practices. A lease can also contain conditions concerning the rehabilitation of degraded land, and the lessee may be required to prepare a property plan, which must be approved by the pastoral board established under the Act. The Act also requires that, when exercising any powers relating to a pastoral lease, an agency must act in accordance with the principles established by the soil conservation authority and the planning authority and must seek to further the objectives of the Act.

6.4 The Soil Conservation and Land Care Act

The *Soil Conservation and Land Care Act 1989* recognises the inherent value of the land, soil, vegetation and water and that degradation of the environment has occurred and continues to occur. It has four main aims: to ensure that land is used within its capacity; to ensure that land conservation becomes an integral part of land management; to provide for monitoring of the condition of the land; and to encourage implementation of procedures designed to reduce land degradation. Section 8 of the Act imposes on landowners a duty 'to take all reasonable steps to prevent degradation of the land'.

On the recommendation of the Soil Conservation Council, the Minister for Primary Industries can establish soil conservation districts, each of which may have a soil conservation board whose task is to help increase people's awareness of land conservation and to provide advice and assistance for landholders. A board must also develop and implement a district plan that assigns land to various classes, outlines the capability and preferred uses of that land, identifies the nature and extent of degradation, and describes land management processes and measures for preventing further degradation. Thus, for example, a district plan may require that a band of riparian vegetation 30 metres wide be retained on either side of a creek or river to reduce erosion and soil loss. The board can then encourage each landholder to enter into a voluntary property plan outlining land management procedures.

A soil conservation order can be issued to prevent further or proposed acts that would cause land degradation. Such an order may require that vegetation be replanted or cleared or that other specific action be taken or not taken.

6.5 The Water Conservation Act

The *Water Conservation Act 1936* allows for areas to be declared water districts. These may be placed under the control of a local government, and it is an offence to pollute water in these districts.

6.6 The Water Resources Act

The *Water Resources Act 1997* replaces the *Catchment Water Management Act 1995* and the *Water Resources Act 1990*. Its purpose is to provide for sustainable management of the State's water resources. In honouring their obligations under this Act, catchment water management boards and others with relevant responsibilities must act in a way that furthers the purposes of the Act, taking action to protect watercourses from degradation and to reverse degradation where it has already occurred. The Act protects the right of a person to take water from a watercourse to which they have access, so long as this will not detrimentally affect the rights of others and the water is not taken from a prescribed watercourse. Water may be taken for the purpose of domestic use or for watering stock, but not where intensive farming occurs. Unless it is for domestic use water must not be taken from a prescribed watercourse without a water licence. A permit can be sought under section 18 of the Act and a licence (such as a well-drilling licence or a licence for taking water from a prescribed watercourse) can be sought from the Minister.

The Act makes it an offence to clear vegetation contrary to a water plan. It also places an obligation on landholders to maintain a watercourse within their control in good condition and to take all reasonable steps to prevent damage to the bed or banks of a watercourse.

Section 49 establishes the Water Resources Council; section 53 provides for catchment water management boards. These boards have several functions, among them the preparation and implementation of catchment water management plans, and the promotion of public awareness. A water resources planning committee can be established to prepare water allocation plans. When exercising its powers, a local government must have regard to and act consistently with the catchment water management plan.

The State Water Plan, signed by the Minister in 1995, outlines the policies for achieving the objectives of the Act. A catchment water management plan can outline desirable changes to the development plan that applies to the area and can contain information about the quality of water resources and their uses; in addition, it can describe the economic, environmental and social factors that the board will consider and outline the board's program for implementing the plan. Each local government can prepare a local water management plan, which must be consistent with the State Water Plan, the catchment water management plan, and the water allocation plan for the area.

6.7 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in South Australia.

~ The *Country Fires Act 1989* relates to the clearing of land for fire prevention and control.

~ The *Crown Lands Act 1929* deals with matters ranging from the compulsory acquisition of land to the granting of leases, including pastoral leases.

~ The *Environment Protection Act 1993* has among its objectives the promotion of ecologically sustainable development, including the management of resources, intergenerational equity, and 'safeguarding the life supporting capacity of air, water, land and ecosystems'. The Act provides that a person must not engage in an activity that pollutes or might pollute the environment unless that person takes all reasonable steps to minimise or reduce the environmental harm that may occur. It also establishes the Environment Protection Authority.

~ The *Forestry Act 1983* deals with the creation and management of forestry reserves.

~ The *Ground Water (Border Agreement) Act 1985* regulates the use of bore water within 1 kilometre of the South Australia – Victoria border.

~ The *Irrigation Act 1994* provides for the irrigation of land in private and government irrigation districts. A landholder has a right under the Act to use the water allocated to their property for the purpose for which it was allocated.

- The *Local Government Act 1934* is undergoing substantial review.
- The *Metropolitan Drainage Act 1935* allows for the construction of works to provide drainage for areas flooded by the Torrens and Sturt Rivers and Keswick and Brownhill Creeks.
- The *Murray–Darling Basin Act 1993* provides the legislative basis for the Murray–Darling Basin Agreement between the Commonwealth, New South Wales, Victoria, Queensland and South Australia.
- The *National Parks and Wildlife Act 1972* deals with the creation of parks and reserves and allows for the management and control of those reserves by the Director of National Parks and Wildlife. It also covers the conservation of native plants, including endangered, vulnerable and rare species.
- The *Public and Environmental Health Act 1987* is used by local governments to prosecute polluters of watercourses.
- The *South Eastern Water Conservation and Drainage Act 1992* covers matters relating to the conservation and management of water and the prevention of flooding of rural land in the south-east of the State. The South Eastern Water Conservation and Drainage Board, established under the Act, is responsible for managing water in the region and has the power to make arrangements with landholders.
- The *Wilderness Protection Act 1992* provides for a wilderness code of management (dealing with things such as the conservation of ecosystems and the restoration of land to its pre–European settlement condition) that is applicable to the management of wilderness protection areas declared under the Act.

6.8 Further information

For further information, contact

- your local government
- your local catchment water management board
- the Community Liaison Manager, Catchment Water Management Boards, 4 Greenhill Road, Wayville South Australia 5034—telephone 08 8271 9190; facsimile 08 8271 9585; email mforan@cwmb.sa.gov.au
- the Department for Environment, Heritage and Aboriginal Affairs—http://www.dehaa.sa.gov.au

7 Tasmania

In Tasmania Crown land is covered by the *Crown Lands Act 1978* and privately owned land is covered by the land use legislation.

The *Water Act 1957* is being reviewed at present. The new legislation will replace a number of existing Acts, including the *Water Act 1957*, and will focus largely on regulating water use in Tasmania's streams, bringing water regulation into line with accepted policies under the National Competition Policy. An important function that will be more effectively dealt with under this new legislation is the protection of environmental flows.

A number of river management functions of the present Act, such as the control of works by individuals along rivers (other than dams and weirs) will be transferred to other existing acts, for example, control of works to the *Land Use Planning and Approvals Act 1993* or *Environmental Management and Pollution Control Act 1993*.

As with the current Act, the new Act will also provide for formal schemes for river rehabilitation works by local or catchment river management bodies such as councils or trusts. Wider catchment management and water quality provisions of the existing Act will not be retained in the new water legislation, with water quality functions left with the *Environmental Management and Pollution Control Act 1993*.

The following is the legislation that is most applicable to riparian management:

~ *Crowns Lands Act 1978*
~ *Land Use Planning and Approvals Act 1993*
~ *Local Government Act 1993*
~ *State Policies and Projects Act 1993*
~ *Water Act 1957*.

The following legislation may also be applicable:

~ *Environmental Management and Pollution Control Act 1994*
~ *Farm Water Development Act 1985*
~ *Forest Practices Act 1985*
~ *Groundwater Act 1985*
~ *Hobart Regional Water (Arrangements) Act 1996*
~ *North Esk Regional Water Act 1960*
~ *North West Regional Water Act 1987*
~ *Northern Regional Water (Arrangements) Act 1997*
~ *Rossarden Water Act 1954*
~ *Sewers and Drains Act 1954*
~ *Water Resources Investigation Act 1937*
~ *West Tamar Water Act 1960*.

7.1 The Crown Lands Act

The *Crown Lands Act 1978* concerns the management and use of Crown land, including land leased by the Crown. Land can be reserved under the Act for the purposes of land conservation and the preservation of a water supply. It is an offence to cut, remove, take or damage any trees or vegetation on Crown land.

In the case of Crown land leased under the Act, it is possible to place conditions on that lease; these conditions could relate to the management or protection of riparian land.

7.2 The Land Use Planning and Approvals Act

The *Land Use Planning and Approvals Act 1993* is the main piece of legislation supporting Tasmania's Resource Management and Planning System. The Act contains provisions relating to the preparation of planning schemes by local government. A planning scheme must seek to further the Resource Management and Planning System's objectives: to promote the sustainable development of natural and physical resources; to provide for the fair, orderly and sustainable use of the air, land and water; to promote shared resource management; and to promote economic development in accordance with these objectives. 'Sustainable development' is defined as involving safeguarding the life-supporting capacity of the air, water and land; avoiding or mitigating any adverse effects on the environment; and sustaining the environment's potential to meet the needs of future generations.

The Act provides for several ways in which the clearing and management of riparian land can be controlled and managed. Planning schemes must be consistent with State policies and may cover the development, use, protection or conservation of any land in the area in question. Generally, a planning scheme classifies land into zones and states the uses or developments that are permissible in those zones. Some activities will be permissible without consent, some will be prohibited, and others may be subject to local government approval. A planning scheme can restrict or limit the clearing of vegetation on land within a certain distance from a river, stream or lake and may be able to require an application for clearing, which can then be assessed before the work is allowed to proceed. If a planning scheme contained such a provision an application would have to be made to the local government, which, in determining the application, must seek to further the objectives of the Resource Management and Planning System. A permit may be granted by the local government or it may be refused or granted with conditions.

The Act also provides that the clearing of vegetation may be controlled through agreement between a local government and a landholder or potential landholder. Such an agreement may prohibit or restrict the use of the land or any matter that would advance a State policy. Once reached, the agreement can be lodged with the Recorder of Titles and will be registered on the title to the land.

7.3 The Local Government Act

The *Local Government Act 1993* provides for the establishment of local governments and describes their powers and responsibilities. It grants local governments the power to make by-laws, which may relate to the management and use of riparian lands under their control. It also gives a local government power to form a joint authority with another council; such an authority would be suited to the management of riparian lands that extend beyond the boundaries of a single municipality.

7.4 The State Policies and Projects Act

The *State Policies and Projects Act 1993* is part of Tasmania's Resource Management and Planning System and has the same general objectives as the *Land Use Planning and Approvals Act 1993*. Once in operation, a State policy binds the Crown and will override a planning scheme to the extent of any inconsistency. A planning scheme must be amended to implement a State policy as soon as possible. Among those State policies that are relevant to riparian management are the State Policy on Water Quality, the State Coastal Policy and the draft State Policy on Agricultural Land. Consideration is being given to an Integrated Catchment Management Policy.

7.5 The Water Act

The *Water Act 1957* is being reviewed. It deals with the use of water in the State and establishes the Rivers and Water Supply Commission to control the use of water. The Commission can take all steps it deems necessary to maintain the natural drainage system and to prevent or reduce flooding, siltation, erosion or blocking of channels by vegetation. The Act also allows the Hydro-Electric Commission to enter land and take action to protect the banks and beds of rivers and to clear and deepen the channels of rivers. In addition, a municipality can remove, cut and trim trees, shrubs and bushes growing on the bed or bank of a river or lake, deepen or widen the beds of rivers, and plant vegetation on river banks. The Act relates principally to the provision of water, so such action would be taken to protect an area's water supply.

The Act creates several offences, among them the removal or destruction of trees or undergrowth along a river where a scheme provides that the river is to be left in its natural state. It also contains provisions relating to irrigation and riparian rights—a riparian right is defined as the right to use water for domestic purposes, such as household supply and watering a domestic garden—and provisions that allow the disposal of waste into rivers with the permission of the Rivers and Water Supply Commission.

7.6 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in Tasmania.

~ The *Environmental Management and Pollution Control Act 1994* deals with protection of the environment and prevention of pollution.
~ The *Farm Water Development Act 1985* makes provision for financial assistance to landholders for the development of water resources for farm use.
~ The *Forest Practices Act 1985* makes provision for the management of private timber reserves.
~ The *Groundwater Act 1985* confers a general right to take groundwater for reasonable uses.
~ The *Hobart Regional Water (Arrangements) Act 1996* makes provision for the administration and supply of water for Hobart.
~ The *North West Regional Water Act 1987* establishes the North West Regional Water Authority for the administration and supply of water for the north-west of the State.
~ The *Sewers and Drains Act 1954* deals with, among other things, town drainage.

7.7 Further information

For further information, contact

~ your local government
~ the Department of Primary Industry, Water and Environment—http://www.dpiwe.tas.gov.au; 134 Macquarie Street, Hobart Tasmania 7000 or GPO Box 44A, Hobart Tasmania 7001; telephone 03 6233 8011.
~ Copies of the legislation can be bought from Government Publications, Printing Authority of Tasmania, 2 Salamanca Place, Hobart Tasmania 7000; telephone 03 6233 3289; http://www.thelaw.tas.gov.au

8 Australian Capital Territory

The position in the Australian Capital Territory differs from that in other jurisdictions. The most obvious difference is the small amount of legislation relevant to riparian management, which is perhaps best explained by the fact that there are no local governments in the Territory. The most important pieces of legislation are the *Environment Protection Act 1997*, the *Lakes Act 1976* and the *Land (Planning and Environment) Act 1991*. The Territory Government is responsible for land use and planning, and this is primarily done through the Territory Plan, for which provision is made in the Land (Planning and Environment) Act.

The following is the legislation that is most applicable to riparian management:

~ *Environment Protection Act 1997*
~ *Lakes Act 1976*
~ *Land (Planning and Environment) Act 1991*
~ *Water Resources Act 1998.*

The following legislation may also be applicable:

~ *Australian Capital Territory (Planning and Land Management) Act 1988 (Cth)*
~ *Canberra Water Supply (Googong Dam) Act 1974*
~ *Commissioner for the Environment Act 1993*
~ *Cotter River Act 1914*
~ *Energy and Water Act 1988*
~ *National Land Ordinance 1989*
~ *Nature Conservation Act 1980*
~ *Protection of Lands Act 1937*
~ *Public Parks Act 1928.*

8.1 The Environment Protection Act

The *Environment Protection Act 1997* came into force on 1 July 1998. Among its objectives are ecologically sustainable development and the protection of the environment. Section 11 of the Act establishes the Environment Management Authority.

The Act imposes a general duty on people to 'take such steps as are practicable and reasonable to prevent or minimize environmental harm or environmental nuisance caused, or likely to be caused, by an activity conducted by that person' (section 22). Environment protection policies can be prepared: they provide guidelines concerning a particular matter and how the Environment Management Authority will deal with it. The Act also contains provisions relating to accredited codes of practice, economic measures, environment protection agreements, environment improvement plans, and environmental audits. In addition, it creates offences such as serious environmental harm and material environmental harm and requires people to seek authorisation to engage in specific activities.

8.2 The Lakes Act

The *Lakes Act 1976* deals with the administration, control and use of specific lakes. The right to use the water of a lake and the right to the flow of a lake are vested completely in the Territory.

8.3 The Land (Planning and Environment) Act

The *Land (Planning and Environment) Act 1991* is the primary Act relating to land use and planning. As noted, it provides for the Territory Plan, which controls land use in a manner similar to a planning scheme; no plan that is inconsistent with the Territory Plan can be approved. The ACT Planning Authority administers the Territory Plan. The Act also provides for the preparation of a register of heritage places and for environmental impact assessment.

Land in the ACT is leased from the Commonwealth and when it is subdivided the leases are auctioned. Lease conditions can be imposed: the inclusion of provisions relating to riparian management as a lease condition or as part of the zoning of land under the Territory Plan warrants consideration.

Under the Act, land included in 'river corridors' is to be protected from urban development and used primarily for recreation while at the same time ensuring that stream flow and water quality are conserved. All uses in river corridors are subject to restrictions in order to protect the area's ecology.

The majority of land in river corridors is identified as public land. This mechanism allows for plans of management to be prepared by the Conservator of Wildlife in consultation with the public and adds a further layer of protection.

8.4 The Water Resources Act

The Legislative Assembly passed the Water Resources Act in December 1998 but there is a transitional period of 12 months before all the Act's provisions come into operation. The Act provides the legislative framework for the sustainable use and management of the Territory's water resources and sets the legal basis for the allocation of water, drillers' licences, bore-construction permits, and permits for the building of water-control structures.

Importantly, the Act requires the preparation of 'environmental flow guidelines', which specify the flow regimes that must be provided for the environment before water can be allocated for other uses. There are also specific provisions in the Act to prevent wastage of bore water and damage to the beds and banks of waterways.

8.5 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in the Australian Capital Territory.

~ The *Australian Capital Territory (Planning and Land Management) Act 1988*, a Commonwealth Act, establishes the National Capital Authority, which is responsible for land declared to be National Land and used by the Commonwealth.

~ The *Commissioner for the Environment Act 1993* creates the position of Commissioner for the Environment with responsibility for investigating complaints about the Territory Government's management of the environment.

~ The *Cotter River Act 1914* is concerned with preventing pollution of the Cotter River.

~ The *National Land Ordinance 1989* is concerned with the management of National Land.

~ The *Nature Conservation Act 1980* deals with the conservation and protection of native flora and fauna and allows for the creation of reserves for that purpose.

~ The *Protection of Lands Act 1937* deals with the removal of materials such as stone, sand and gravel from land.

8.6 Further information

For further information, contact

~ Environment ACT—telephone 02 6207 9777; http://www.act.gov.au/environ

9 Northern Territory

As in the Australian Capital Territory, the Northern Territory has a limited amount of legislation relevant to riparian management, again a consequence of the absence of local governments. Nevertheless, riparian management is dealt with in the land use legislation.

The following is the legislation that is most applicable to riparian management:

~ *Pastoral Land Act 1992*
~ *Soil Conservation and Land Utilisation Act 1970*
~ *Territory Parks and Wildlife Conservation Act 1977*
~ *Water Act 1992.*

The following legislation may also be applicable:

~ *Bushfires Act 1980*
~ *Conservation Commission Act 1980*
~ *Crown Lands Act 1992*
~ *Environmental Assessment Act 1982*
~ *Parks and Wildlife Commission Act 1980*
~ *Planning Act 1993*
~ *Power and Water Authority Act 1987*
~ *Stock Routes and Travelling Stock Act 1954*
~ *Water Supply and Sewerage Act 1983.*

9.1 The Pastoral Land Act

The *Pastoral Land Act 1992* aims to provide a way in which Crown land can be used sustainably for pastoral purposes. Its objectives are prevention or minimisation of degradation, monitoring of the land's condition, creation of rights of access to water and places of interest and, for Indigenous Australians, rights to use the land. The Act imposes a duty on lessees to conduct pastoral activities in such a way as to prevent land degradation and improve the condition of the land as far as is reasonably possible.

Pastoral districts may be declared, and the Act establishes the Pastoral Land Board. Among the Board's functions are monitoring the condition of the land, monitoring the number and species of feral animals and stock on the land, and assessing the suitability of Crown land for a new pastoral lease. Conditions can be imposed on a lease—for example, 'that the lessee will not clear any pastoral land except with and in accordance with the written consent of the Board or guidelines, if any, published by the Board' (section 38(1)(h)). This condition could be used to restrict the clearing of riparian vegetation. There are also conditions relating to the condition of the land—including taking all reasonable measures to conserve and protect areas of environmental, cultural, heritage or ecological significance—and to allow the fencing of land.

Leases can be granted in perpetuity or for up to 25 years. If the land has become degraded the lessee may be required to submit a remediation plan to the Pastoral Land Board, detailing the steps that will be taken to rehabilitate the land.

The Act provides that any person must be able to have access to perennial water supply, including a lake or the sea, that comes within pastoral land.

9.2 The Soil Conservation and Land Utilisation Act

The long title of the *Soil Conservation and Land Utilisation Act 1970* explains that the Act's purpose is 'to make provision for the prevention of soil erosion and for the conservation and reclamation of soil'. The Act establishes the Soil Conservation Advisory Council, which is responsible for providing to the Minister for Lands, Planning and Environment information about soil erosion, erosion control, and so on. The Council can also assist landholders; this may involve an agreement between the landholder and the Commissioner for Soils for the carrying out of treatment works. The Commissioner can issue a soil conservation order if, in his or her opinion, a danger of soil erosion would be created by the destruction or removal of timber, scrub or other vegetable cover. Such an order may prohibit the removal of or interference with vegetation. This could be of use in preventing the clearing of riparian vegetation.

The Minister can also order that land subject to soil erosion, or likely to become so, be declared an area of erosion hazard. Steps can then be taken to reduce that hazard. If a landholder fails to comply with such an order, they may be guilty of an offence under the Act. Further, land can be declared a restricted use area, in which case it is an offence to remove or damage any vegetation.

9.3 The Territory Parks and Wildlife Conservation Act

The long title of the *Territory Parks and Wildlife Conservation 1977* explains that the Act's purpose is 'to make provision for and in relation to the establishment of Territory Parks and other Parks and Reserves and the Protection and Conservation of Wildlife'. Timber can be felled in a park or reserve only in accordance with the plan of management for that reserve. A wilderness zone must be retained in its natural state.

Sections 12 and 22 cover the declaration of areas for the purpose of protection generally or for particular species of flora or fauna. Section 18 provides that as soon as practicable after a reserve or park has been declared the Parks and Wildlife Commission must prepare a management plan for the area. It is an offence to take wildlife from a protected area without a licence issued under the Act. Section 45 allows for the declaration of plants as protected or specially protected, and a permit or licence is required for the taking of those plants.

The Act also allows the Commission to negotiate and enter into an agreement with a landowner in relation to protecting and conserving wildlife in and the natural features of their land. This agreement may extend to the provision of financial assistance and is binding in perpetuity.

9.4 The Water Act

The long title of the *Water Act 1992* explains that the Act's purpose is 'to provide for the investigation, use, control, protection, management and administration of water resources, and for related purposes'. Section 9 of the Act states, 'Subject to this Act, the property in and the rights to the use, flow and control of all water in the Territory is vested in the Territory and those rights are exercisable by the Minister in the name of and on behalf of the Territory'. Despite this, any person may take water for domestic use or for the watering of stock and a person on land adjacent to a watercourse may take water for drinking and domestic purposes, for the watering of stock, and for a domestic garden of less than 0.5 hectares. They can also take groundwater for these purposes.

It is an offence under the Act to cause or allow water to become polluted. The Minister may establish a water control district and appoint a water advisory committee for the Territory or part of it.

9.5 Other legislation that may be applicable

The following legislation may also be applicable to riparian management in the Northern Territory.

~ The *Bushfires Act 1980* establishes the Bushfires Council and covers fire bans and permits for burning off.
~ The *Conservation Commission Act 1980* establishes the Conservation Commission of the Northern Territory, among whose functions are the promotion of conservation and protection of the natural environment and the establishment and management of parks, reserves and sanctuaries.
~ The *Crown Lands Act 1992* primarily deals with the sale and lease of Crown land.
~ The *Environmental Assessment Act 1982* requires that the possible environmental impacts of a proposed development be assessed. In particular, consideration must be given to whether the development could reasonably be assumed to be capable of having a significant effect on the environment.
~ The *Parks and Wildlife Commission Act 1980* establishes the Parks and Wildlife Commission.
~ The *Planning Act 1993* deals with land use and planning. Control plans regulate permissible development in an area and 'development' is defined to include the clearing of vegetation. The clearing of riparian land may therefore require a permit.
~ The *Power and Water Authority Act 1987* establishes the Power and Water Authority, which is responsible for the sale and management of electricity and water supplies.
~ The *Stock Routes and Travelling Stock Act 1954* deals with the management of reserves and watering places for livestock.
~ The *Water Supply and Sewerage Act 1983* deals with the supply of water and sewerage services.

9.6 Further information

For further information, contact

~ your local government
~ the Department of Lands, Planning and Environment—telephone 08 8999 4568