# Minimum width requirements for riparian zones to protect flowing waters and to conserve biodiversity: a review and recommendations

***With application to the State of Victoria***

Report to the Office of Water,
Department of Sustainability and Environment

**April 2010**

Birgita Hansen, Paul Reich, P. Sam Lake, Tim Cavagnaro
School of Biological Sciences, Monash University

MONASH University

## EXECUTIVE SUMMARY

Riparian (streamside) zones are massively degraded over a broad area of the state of Victoria. Millions of dollars are spent on restoring these systems on the assumption that many of the roles performed by intact riparian zones will alleviate and/or reverse the impacts of past and present disturbances. Yet the majority of restoration planning fails to rely on scientific guidance to make decisions about what widths are necessary to restore riparian zones to the point where they can perform these functions. Overseas studies have clearly demonstrated that intact riparian zones of any width are better than none. They have also demonstrated that riparian zones need to be restored to an appropriate width and reconnected to ensure they are fully ecologically and physically functional.

Riparian zones are the interface between aquatic and terrestrial environments. They exert important influences on the waterways they adjoin by mediating the bi-directional flow of matter and energy between the water body and the surrounding hinterland. Riparian research, both from Australia and overseas, demonstrates that intact riparian zones are critical to aquatic-terrestrial ecosystem function and ultimately, to waterway health.

Disturbance and modifications to catchments through clearing vegetation for agriculture and grazing of livestock have resulted in extensive degradation of riparian zones and their adjacent waterbodies. This is predominantly through increased transfer of nutrients, sediment and pollutants into streams, exacerbated bed and bank erosion, and loss of in-stream and terrestrial biodiversity via degradation of riparian and aquatic vegetation and loss of important habitat structure such as large wood.

The best opportunity for mitigation of catchment-scale disturbances is by the protection or rehabilitation of headwater systems due to their demonstrated capacity for greatest regulation of water quality and highest contribution to regional biodiversity. Thus, disturbance impacts on streams may be partially or totally alleviated by establishing riparian buffer zones that are laterally and longitudinally continuous, beginning in the headwaters and progressing downstream.

This report focuses on the ecological, biogeochemical and physical processes that govern riparian zone function and ultimately influence their effective width. On this basis, it makes recommendations for riparian widths to protect flowing waters and conserve biodiversity. It is structured to explicitly address how physical characteristics of the catchment and land uses

therein can influence the role of intact riparian zones and thus compromise many of their stated management objectives. Protection or restoration of riparian zones is viewed as a major step towards improving waterway health that should be accompanied by a broader suite of integrated catchment management activities.

There are seven common objectives that broadly capture the primary goals for riparian restoration (Section 1.6). These are (in no particular order) to:

- Improve water quality (reduce excess nutrient and contaminant inputs to waterways)
- Reduce streambank erosion and sediment inputs
- Increase shading and moderate water temperature
- Provide wood, leaf litter and other resource inputs to streams (i.e. facilitate resource transfers between the terrestrial and aquatic environment)
- Increase in-stream biodiversity
- Improve the structure and composition of riparian vegetation communities, and increase terrestrial biodiversity
- Increase lateral and longitudinal connectivity of biota and other material

For the purpose of making pragmatic width recommendations, we treat the capture and/or uptake of all non-point source pollutants (i.e. nitrogen, phosphorus and sediment) under the more general objective of improving water quality. Furthermore, as increasing riparian width does not necessarily relate to improving structural or hydrological connectivity, we do not attempt to develop width recommendations for connectivity-related management objectives.

The catchment setting, or landscape context, of a waterway will significantly influence the natural width of the riparian zone and the spatial hydrological influence of the waterway (Sections 2.4-2.6). Excluding urban and forested catchments (which are considered elsewhere and are therefore not discussed here), landscape contexts that exert the greatest influence over riparian zone function may be categorised as follows:

- Land use intensity (high, moderate and low: for definitions see Section 3)
- Steep and hilly low-order streams with adjacent land clearance
- Lowland floodplains, wetlands and off-stream waterbodies (including billabongs, anabranches, oxbow lakes)

In order to formulate a range of width recommendations that address the primary objectives of riparian zone management in each of the above set of landscape contexts, we have undertaken a comprehensive review of riparian studies from Australia and overseas. We have used the relevant information from this review to summarise quantitatively, widths necessary to restore or maintain single functions (e.g. water quality). Thus, we provide width recommendations (accompanied by the degree of scientific confidence) relating to these functions, for the maintenance or rehabilitation of riparian habitat and consequently the improvement of stream condition. The data used to make these recommendations (see table below) are based on studies investigating single riparian functions and therefore, should be considered as the minimum required to protect waterways from catchment disturbances.

Multiple functions are performed by intact riparian zones and, as it will be seen further on (Section 2.3), different functions will require different widths. Therefore, the wider the riparian zone the more functions are initiated or augmented. The specific ecological benefits accrued by increasing the width of a riparian zone will vary with the contexts outlined in this document. As the width recommendations provided here relate to single functions, to initiate or augment more than one function, greater widths may be necessary. Consequently, full riparian restoration and waterway protection may require widths that substantially exceed those recommended here.

The efficacy of riparian zone function of any width is strongly influenced by:

1. Hydrological regime (e.g. flow regulation, and the frequency and magnitude of overbank flows; see section 2.4.4)
2. The degree of fragmentation of the riparian zone (in terms of longitudinal connectivity of riparian vegetation; see sections 2.3.7, 2.6)
3. The presence of invasive plant species (e.g. willows; see section 2.5)

Where these factors are deemed influential, *a priori* decisions are necessary regarding the constraints they exert on initiating or augmenting riparian function and therefore, what benefits are provided for a given width in their presence. Importantly, land use intensity will govern the decision about which width is appropriate for a given location and management objective – in general terms, the greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications. Where best agricultural management practice is implemented (reducing impacts from farming on the waterway), the need for wider buffers will be reduced. It is important to note that, as riparian zones are inherently variable and spatially diffuse, regardless of country or landscape setting, any set of rules developed using data from different systems is always going to be overly broad and potentially inadequate in some locations.

The table below provides a summary of minimum width recommendations (in metres) for riparian zones in Victoria for some common management objectives under a range of landscape contexts. Each recommended width is accompanied by a level of scientific confidence (green=high, yellow=moderate, red=low), based upon published evidence from Australia and overseas. Pages 71-73 provide detailed definitions of confidence levels and land use intensities. Unless the catchment is unmodified (uncleared) on side of the waterway, widths will apply to both banks. Where more than one context applies, the most appropriate width will be the greatest. This is necessary to reduce the impacts of the most intensive land-use practice on the waterway.

| Landscape context / Management Objective | Land Use Intensity High | Land Use Intensity Moderate | Land Use Intensity Low | Wetland/ lowland floodplain/ off-stream water bodies | Steep catchments/ cleared hillslopes/ low order streams |
|---|---|---|---|---|---|
| Improve water quality | 60 | 45 | 30 | 120 | 40 |
| Moderate stream temperatures | 95 | 65 | 35 | 40 | 35 |
| Provide food and resources | 95 | 65 | 35 | 40 | 35 |
| Improve in-stream biodiversity | 100 | 70 | 40 | Variable * | 40 |
| Improve terrestrial biodiversity | 200 | 150 | 100 | Variable * | 200 |

* Variability in width is related to the lateral extent of hydrological connectivity and thus, any recommendation will be site specific.

The majority of riparian research is from North American systems (see sections 1.7 & 1.8, & Appendix 2), and while general physical processes are likely to be similar in both continents (particularly relating to nutrient interception and erosion control; see sections 2.3.1 & 2.3.6), some of the biotic processes are unlikely to be comparable. These considerations are critical to deciding the confidence with which we can extrapolate international research findings to Victoria in the absence of comparative data. Where information from overseas is used to guide riparian restoration, it is very important that post-works monitoring is undertaken to ensure that implemented widths are adequate for long-term maintenance of riparian function as well as the improvement of the current state of knowledge.

The ability to confidently determine appropriate widths for riparian zones in Victoria is hindered by the lack of relevant information. From a detailed assessment of riparian literature, a number of key knowledge gaps emerge that should be addressed in order to better inform the future management of riparian zones. These are:

1. Inadequate information available on the effectiveness of restoration projects (targeted monitoring)
2. The effects of flow regulation on riparian zone function are not well understood
3. Best strategies for managing riparian zones to achieve multiple objectives and the effectiveness of riparian management zones
4. Information about the relationship between stream size and riparian function would improve targeted management of riparian zones in different parts of the drainage network.
5. An understanding of what constitutes a self-sustaining riparian zone (for flora and fauna)
6. The applicability of international studies to Victorian systems
7. The performance of fragmented riparian zones and the relationship between riparian vegetation width and length. A better understanding of how riparian configuration and the relative influence of hinterland vegetation relates to riparian function.
8. Information about nutrient cycling and subsidies (the role of carbon in terrestrial-aquatic ecosystems, and the importance of intact riparian zones in different landscape contexts for mediating carbon and nitrogen fluxes)

In conclusion, it is recognised there will always be competing social and economic issues that will ultimately influence decisions about riparian width. This will place practical constraints on some of the riparian buffer widths recommended within this document. However, the primary purpose of this document is to review and present the current scientific understanding of riparian zone width as it relates to ecological function. Thus, any trade-offs for riparian set-aside below those recommended here may be done with the ecological consequences in mind.

**ACKNOWLEDGEMENTS**

We would like to thank Jan Smith, Laura Williams and Lori Gould for providing helpful comments on this report. We would also like to thank Kirsty Hopkins, Ian Rutherfurd, Peter Volleburgh and Sarina Loo for feedback throughout the project and comments on earlier drafts. Thanks to Inka Veltheim, Wayne Tennant, Ralph Mac Nally, Elise King, Kay Morris, Elisa Raulings, Susie Ho, John Morrongiello, and Janette Borley for helpful discussions relating to this project.

All photos are contributed by BH except where stated.

**TABLE OF CONTENTS**

# INTRODUCTION

## Preamble

The riparian zone (riparia) is the interface between aquatic and terrestrial environments (Naiman and Décamps, 1997) and it mediates the flow of energy, and physical and biotic vectors between the two (Lake, 2005, Naiman *et al.*, 2005). Consequently, riparia are often environments of exceptionally high diversity. The importance of intact riparian zones is universally acknowledged as critical to aquatic-terrestrial ecosystem function and ultimately, to waterway health. However, a clear distinction between the riparian zone and the adjacent landscape is often difficult to ascertain as these boundaries are typically diffuse, spatially and temporally dynamic, and very much context dependent. As such, the determination of a fixed standard width for delineating riparian zones will be inherently difficult. Any consideration of the role of the riparian zone as a buffer from catchment disturbances needs to consider the landscape context and incorporate the acknowledged interdependencies between the two. In doing so, the management basis for protection and restoration must be clearly articulated. In any management context, consideration must be given to both sides of the channel if restoration of riparian function is to be successful. Most importantly, a single fixed width for all Victorian riparian zones is scientifically-indefensible. This report is structured with these principles in mind, explicitly addressing how catchment and land use contexts can mediate the role of riparian zones and thus compromise many of the stated management objectives of these. Protection and restoration of riparian zones is viewed as one step towards improving waterway health that should necessarily be accompanied by a broader suite of integrated catchment management activities.

## Scope of report

The primary aim of this report is to make recommendations for minimum width requirements for riparian zones in the state of Victoria based upon the best available scientific evidence. To do this, factors and processes that affect or are affected by the width of riparian zones in Victorian catchments are identified. In this report we include riparian zones of all waterways in major land use categories, with the exception of land designated for forestry operations (which is covered under the *Code of Practice for Timber Production 2007*) and land within parks and reserves (which are under legislative protection by the *National Parks Act 1975*). Included in the definition of waterways are all permanent (perennial), ephemeral and intermittent creeks, streams and rivers, freshwater wetlands and associated billabong aggregates. Excluded from this report are standing (lentic) waterbodies, and estuarine and coastal riparian zones. While the focus of discussions about riparian zone function relates predominantly to streams and rivers, other lotic systems (e.g. lowland wetlands) are not exempt from the ecological considerations highlighted here. This document does not consider social or economic factors that may govern implementation of riparian width recommendations, but rather is limited to available relevant scientific data reported in the primary scientific literature.

This document focuses on both the in-stream and terrestrial benefits of intact riparian zones, at multiple spatial scales, from the river reach to the entire catchment. We consider this multi-scale approach important and necessary because factors that influence the role of intact riparian zones are not necessarily contained within or restricted to that part of the ecosystem. It is likely that most changes detectable at the terrestrial-aquatic interface are generated by impacts elsewhere in the catchment. Similarly, the deterioration of riparian zones is only one of many factors likely to have caused ecological decline in river systems. The most significant causes of these declines in Victoria's river systems are catchment scale phenomena such as land clearance, altered hydrology and increased sedimentation.

There is a substantial body of literature that addresses the ecological benefits of intact riparian zones. Many reviews have been undertaken in an attempt to quantify riparian widths required to meet specific management objectives. Most have been undertaken for systems in North America and, of these, many provide a prescriptive set of metrics for determining minimum riparian zone widths. At their best, these reviews and their recommendations focus on the role of riparian widths in achieving a clear (and usually limited) set of very specific management objectives (e.g. nitrogen reduction in waterways: Lowrance *et al*. 1997; or riparian shading to reduce temperature for improved salmonid habitat: Young *et al*. 1999, Welty *et al*. 2002) and are based on sound knowledge of a particular system. In most cases, however, the process undertaken for obtaining minimum riparian width requirements for various management objectives often involves exploiting information collected from other systems or recommendations developed elsewhere - often inappropriately. Importantly, the perceived management need to prescribe minimum widths overlooks the potential need for minimum lengths, which may often be the more appropriate goal.

In this report, we provide summaries of riparian buffer width recommendations made elsewhere and link these to Victorian systems, where appropriate. More detailed discussion about riparian buffers, especially in the context of improving water quality, can be found in other comprehensive reviews (Castelle *et al.*, 1994, Knutson and Naef, 1997, Wenger, 1999, Fischer and Fischenich, 2000, Parkyn, 2004, Mayer *et al.*, 2005). However, much of the data required to produce a set of minimum riparian widths for Victoria, which relate to every possible stated management objective, are not available. This is because the bulk of riparian research to date has been done overseas in ecosystems very different from Australian environments in terms of climate, water availability, soils, vegetation, nutrient levels and processing, ecological communities, among others.

While the report and guidelines provided here make use of data where appropriate to provide a framework for defining riparian widths, the best application of the findings in this report will be to identify knowledge gaps and prioritise research directions. In this sense, the guidelines accompanying this report clearly highlight where current knowledge is inadequate to confidently address width-related questions.

## Structure of report

As information from international studies is extensive, this report draws on information from Australian studies as much as possible and supplements this information with theory, concepts and data from international work where no specific Australian data are available.

This report has three specific objectives:

- to review the existing riparian literature focusing on information from Australian systems (where available);
- to make recommendations for minimum protected and restored riparian widths for Victorian riverine environments (for different land use contexts); and
- to develop a set of guidelines operable by land managers and field assessors to determine suitable fenced-off riparian zone widths.

This report comprises three sections, reflecting our approach towards addressing our three objectives.

Section one introduces riparian zones in Victorian catchments. Important land uses in Victoria that impact riparian function are summarised and are used to guide the formulation of appropriate management objectives for protecting waterways and maintaining riparian habitats. There is a brief discussion of the implications of narrow riparian widths.

Section two contains a detailed review of literature relevant to understanding the relationship between riparian width and the functions performed by the riparian zone. It provides a definition of the riparian zone, an overview of how the riparian zone functions and how functions relate specifically to width. Key riparian functions are then discussed in turn, clearly outlining fundamental principles and theory by drawing on examples from published Australian studies (where available), international research findings and reviews. The aim of this approach is to highlight existing Australian information and link it to data from overseas where possible. A summary of key factors (both natural and anthropogenic) that influence riparian function is then provided. These factors constitute the landscape context of a waterway, which is important in shaping riparian ecosystems, and ultimately determines the dominant management objective(s) and thus, minimum width requirement, for a given location .

Section three provides a synthesis and recommendations/guidelines for buffer widths in Victoria. Knowledge gaps and future research priorities are highlighted, and important research directions are identified.

Woady Yaloak Creek.

Details of findings from Australian and international research is provided in Appendices 1 and 2, respectively. A proposed approach for designing a tool for land managers to use when determining riparian zone widths is presented in the Appendix 3.

# SECTION 1. RIPARIAN ZONES IN VICTORIAN CATCHMENTS

## 1.1 Riparian zones and why width is important

Land use within a catchment probably has the most significant impact upon riparian function. Much of the land mass of Australia, New Zealand, North America and Europe (among others) has been massively altered by grazing, and by clearing for agriculture, timber production and urban development. Modifications to the Australian landscape due to anthropogenic activities have negatively impacted upon most waterways, creating serious issues including sedimentation, increased nutrient and pollutant loads and runoff, loss of in-stream habitat for aquatic biota and reductions in terrestrial riparian biodiversity (Australia State of the Environment 2006).

The effectiveness of riparian zones in mitigating anthropogenic impacts on waterways largely depends on their width on both sides of the waterway (Castelle *et al.*, 1994) and their longitudinal continuity from the headwaters to lowland reaches. Rehabilitation or protection of one side of the waterway and not the other will compromise management efforts, such that works on one bank are nullified by disturbances originating from the other. In a similar manner, degrading processes originating upstream like excess sediment and nutrient arising from headwater erosion, may compromise downstream restoration. Maximising lateral and longitudinal extent of intact riparian zones, starting in the headwaters, provides the best protection for the waterway (see Sections 2.3 and 2.6 for more details).

Efficiency of riparian functioning increases with width. For example, a uniform grass filter strip 5-6 m wide may remove around 80% of incoming nitrogen from subsurface flows under controlled experimental conditions (Mayer *et al.*, 2005). However, widths greater than 30m are generally required for effective removal of subsurface nutrients across a wide range of riparian buffer types and land use contexts (Muscutt *et al.*, 1993, Mayer *et al.*, 2005). Similarly, riparian zones 15-30m wide may be suitable for erosion control, but widths greater than 100m may provide the additional benefit of allowing for lateral channel movement over extended time periods (Webb and Erskine, 2003). This latter example is particularly important when considering riparian land tenure and management over long time periods (see Gabriel-Jones, 2008). It is therefore important that riparian zones are wide enough to a) fully meet a desirable set of management objectives, and b) maintain a given function in perpetuity (without the need for substantial intervention at a later date).

The mathematical relationship between width and function is difficult to determine from existing information, with few exceptions. Nitrogen removal studies have demonstrated that in specific contexts (e.g. experimental uniform grass filter strips) attenuation occurs rapidly over the first few metres and subsequent width increases produce lesser gains (Dillaha *et al.*, 1988, Dillaha *et al.*, 1989, Jordan *et al.*, 1993, Vidon and Hill, 2004a, Mayer *et al.*, 2007). However, an asymptotic relationship between nitrogen removal and buffer width is only generalisable for subsurface flows, and total N removal over all flow paths may vary significantly with vegetation type and cover, soil type, subsurface hydrology and subsurface biogeochemistry (Mayer *et al.*, 2007). Thus, the highly variable nature of riparian zones precludes the development of a generic rule for the relationship between width and nitrogen-removal function in all contexts. For most other functions, the data to quantify this relationship do not exist. Therefore, it is often not possible to know how efficiently a riparian buffer performs a given function at a range of different widths.

In some contexts (e.g. climate or soil type) the relationship between increasing width and improved function may well be linear, or potentially even exponential. For example, the relationship between phosphorus removal and width will be sensitive to soil type, and where soils are predominantly sandy, phosphorus attenuation by the riparian zone may require large distances (tens of metres or more) before it exceeds a certain threshold, e.g. 50% (see Harris 2001, and McKergow *et al.*, 2003 for a discussion of phosphorus removal). Therefore, it is not sufficient to state that riparian zones narrower in width than the minimum recommended will perform the majority of nutrient attenuation. Similarly, the relationship between terrestrial riparian functions and width is unlikely to be asymptotic, and is potentially not even linear (e.g. provision of vertebrate breeding habitat) due to confounding influences like disturbance.

The designation of riparian zones using a fixed distance is the standard approach to riparian land management both in Australia and overseas. In Australia, riparian land was delineated in 1881, by the Governor in Council who made an order pursuant to Section 6 of the *Land Act 1869* to reserve all Crown frontages within a specified distance of a waterway (Gibney, 1977). In most cases this distance was 1 chain (ca. 20m) on both banks, but in the case of the Victorian side of the Murray River, the distance was 3 chains (ca. 60m).

The *Water Act 1989* designates the riparian zone as 20m either side of a waterway and does so for the 'declared' delivery of stability, conservation or functioning of the waterway. Equally, the floodplain extent is defined, based on the best estimate using available evidence, by a natural flood event that has a 1% probability of occurring in any one year. Under the Victorian Planning Scheme (*Planning and Environment Act 1987*) permits are typically required for works within 30m of a waterway, and subject to overlays of up to 100m depending on the zone use. It is of some concern that the recently amended federal water legislation, the *Water Act 2007*, no longer makes specific references to riparian zone set-aside, and instead embeds riparian zone management within other ecological considerations.

In each of the above cases, the decision-making process used to determine widths is not transparent and potentially very arbitrary. It is unlikely that the ecological functions of the riparian zone have been carefully considered, and therefore, the degree to which they are able to perform these functions is limited. A full re-appraisal of the role of intact riparian zones in mitigating deleterious impacts on Victorian waterways is necessary to ensure that fencing for livestock exclusion will allow for re-establishment of riparian functions.

## 1.2 Victorian landscape contexts

### The importance of landscape context in determining appropriate riparian zone widths in Victoria

All ecological, geomorphologic and hydrologic functions of the riparian zone are influenced by features of, and modifications to, the landscape within the catchment. Physical features of the landscape that affect natural riparian zone widths include slope, climate (rainfall), soils and parent material (i.e. physiography or physical geography). Human-generated modifications to the landscape that affect riparian zone widths are predominantly land use changes, both adjacent and upstream. The extent to which these unnatural changes in the catchment influence width will depend on the quality (in terms of function) of the existing riparian zone and the extent of riparian vegetation. As a general rule, the greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications and disturbances.

Major drivers of waterway and riparian degradation are loss of native vegetation and modification of channel form, regulation of flow, agricultural practices, urban development and invasive species. In Australia, modifications to the catchment landscape through agriculture (especially grazing) and urbanisation have had the most significant negative impacts upon waterways (Norris *et al.*, 2001). The Assessment of River Condition (ARC) was conducted to determine the aggregate impact of human resource use on Australian waterways in order to prioritise management strategies for their improvement (Norris *et al.*, 2001). The ARC found that greater than 80 percent of Australian river and riparian length is affected by human-generated catchment disturbance.

In Victoria, 79% of the area assessed by the ARC had moderately to severely modified environmental features (quantified by indices of catchment disturbance, hydrological disturbance, habitat and nutrient/suspended sediment load) and 23 % had significantly to extremely impaired aquatic biota (Norris *et al.*, 2001). The major issues identified were delivery of sediment, nutrients and water to waterways, which has occurred as a result of land use change in surrounding catchments.


Lachlan River. Photo: P. Reich

The role of the riparian zone in regulating and facilitating biotic, chemical, physical and hydrologic transactions, and in mitigating disturbance impacts, is severely compromised by livestock access (see Section 2.6.1 for more detailed discussion on grazing impacts). The direct influences of livestock are inputs of excess nutrients through faecal matter, destruction to and erosion of bed and banks through trampling, and damage to vegetation through grazing and suppression of plant recruitment. The indirect influences of grazing are increased sedimentation to streams through alteration of soil structure and loss of vegetation leading to increased overland flow, spread of invasive plant species, and changes to food webs and riparian subsidies (food web contributions) through damage to in-stream habitat, alteration of the bed profile and suppression of riparian vegetation recruitment and succession. The removal of livestock from streams addresses the majority of waterway environmental issues simultaneously, especially as Australian riparian ecosystems have evolved in the absence of large, hard-hoofed animals.

The detrimental consequences of livestock access to waterways have been quantitatively demonstrated in Australian and New Zealand systems (Reed *et al.*, 1994, Cooper *et al.*, 1995, Quinn *et al.*, 1997, Storey and Cowley, 1997, Nguyen *et al.*, 1998, Bell and Priestley, 1999, Jansen and Robertson, 2001b, Jansen and Robertson, 2001a, Bennett and Virtue, 2004, Rutherford *et al.*, 2004, Johnson *et al.*, 2007, Lunt *et al.*, 2007a, Lunt *et al.*, 2007b, Reid *et al.*, 2008a). In virtually all management scenarios attempting some level of restoration, it will be important to first exclude livestock from riparian zones on both banks before attempting to re-establish riparian function.

Riparian zone denuded of understorey by cattle. Lachlan River. Photo: P. Reich

In addition to agriculture and flow regulation, salinity has also seriously impacted Victorian catchments (Lamontagne *et al.*, 2005, Holland *et al.*, 2006), a problem exacerbated by flow regulation and water extractions (Roberts, 2004). These issues emphasise the magnitude of influence that landscape context has on riparian function.

Given the current condition of Victorian waterways, important landscape contexts that will need to be considered when assessing suitable riparian zone widths for each bank are:

- longitudinal continuity of the riparian zone;
- catchment land use (dominant form of land use, e.g. grazing);

- adjacent land use (agricultural activities that directly contribute pollutants, excess nutrients and sediment, and alter local hydrology through impoundments);
- waterway size and placement within the drainage network (e.g. small headwater streams are important for reducing nutrient exports downstream);
- flow regulation (the extent, timing and duration of flooding);
- climate (e.g. wet Gippsland *c.f.* dry Wimmera);
- soil type and catchment physiography (e.g. low calcareous dunes of the Mallee dunefields *c.f.* the fertile soils of the Victorian Riverina);
- proximity to source populations (connectivity to terrestrial and aquatic refugia); and
- salinity and groundwater depth.

Section 2.6 in the review provides more detail of these landscape contexts and their influence on riparian zones.

Landscape contexts that have the greatest influence on width decisions will depend on the major environmental problems and objectives (and thus, restoration goals) at a given location. When these are identified, it is important that restoration activities are conducted on both sides of the waterway to ensure that mitigation measures undertaken on one side are not nullified by environmental problems on the other. An example of how the process of considering landscape contexts might be undertaken is illustrated in Box 1.

Clearly, each landscape context must be considered in turn when determining riparian widths appropriate to protect the waterway or provide suitable riparian habitat. Some contexts will be difficult to quantify owing to their high spatial and temporal variation, e.g. flow regulation. Nevertheless, it is important that they form part of the decision-making process because they will exert an influence on the functionality of the riparian zone and the success or otherwise in reaching desired goals. Ultimately, it is the location of the riparian zone in the landscape (hence landscape context) that will dictate the width needed to protect the waterway.

*Box 1. The case of Curdies River*

Curdies River is located in the South Victorian Coastal Plain, within the jurisdiction of the Corangamite Catchment Management Authority. The dominant land use in the catchment is pasture improvement and livestock grazing (diary, beef and sheep) and there are significant in-stream issues with high nutrients and turbidity (see Australian Natural Resource Atlas website: www.anra.gov.au). In the upper part of the catchment, riparian and upslope vegetation has been mostly cleared, pasture irrigation is commonplace and riparian zones are dominated with invasive plant species like willows.

Pasture irrigation adjacent to Curdies River at the confluence of Bostock and Burnip creeks.

Given these issues, the primary objectives for riparian restoration might be:

- reducing excess nutrient inputs to streams;
- moderating stream temperatures;
- facilitating resource transfers to the aquatic environment (and *visa versa*); and
- increasing both in-stream and terrestrial biodiversity through rehabilitating or restoring indigenous riparian vegetation communities


To achieve these restoration objectives, a number of landscape contexts need to be first considered. These are slope (many reaches occur in valleys with steep slopes that increase the rate of delivery of nutrient- and sediment-bearing flows), climate (the frequency of heavy rainfall events that might delivery nutrient pulses via overland flow to streams), and soils (the permeability of the substrate, which dictates water retention time in the riparian zone). In addition, the presence of invasive species will substantially compromise riparian function. Most importantly, the dominant land use constitutes high intensity agricultural practices (see Section 3 for definitions).

If one moves downstream to the mid part of the catchment of Curdies River, the landscape context of the river changes. There are numerous wet sclerophyll remnants, which are patchily distributed along the waterway and occur in gullies and drainage lines. These gullies are interspersed with mixed agriculture, including livestock grazing.

The primary management objectives in the middle of the catchment will differ slightly from those in the upper catchment, and restoration efforts will probably focus on:

- reducing nutrient and sediment inputs;

- providing resources to the aquatic environment (which will include providing carbon inputs to facilitate in-stream retention); and

- increasing both in-stream and terrestrial biodiversity through improved structure and composition of riparian vegetation communities

Middle reaches of Curdies River.

Land use intensity adjacent to the waterway is generally lower than in the upper reaches and thus, the nutrient inputs are likely to be less. However, there exists the opportunity to increase local biodiversity by re-connecting wet sclerophyll remnants long the river which have been punctuated by clearing for grazing. Nutrient and sediment exports from the upper catchment may be partially intercepted by increasing wood and other organic matter inputs to the middle reaches, in order to increase retention times. Valley slopes remain steep along middle reaches, but many have intact vegetation, reducing the need to consider overland flows.

In the lower reaches of Curdies River, the floodplain is wider and there are areas of adjacent swamps and paddocks subject to inundation. The presence of grazing on or adjacent to floodplains reinstates the need to establish riparian buffers to reduce nutrient inputs. However, there is an additional need to protect aquatic biota in off-stream waterbodies and wetlands from trampling and wallowing of livestock.


Lower reaches of Curdies River at Curdie Vale.

The primary management objectives in the lower catchment will thus change to:

- reducing excess nutrient inputs;

- facilitating resource transfers to the aquatic environment through augmenting floodplain vegetation; and

- increasing in-stream and off-stream aquatic biodiversity (this may include the seasonally variable provision of habitat for estuarine species)

To conclude, minimum riparian zone widths will need to be wide in the upper catchment to protect the waterway from inputs from high intensity agriculture (≥60m), they may be reduced in the middle catchment (35-40m) but be continuous to re-connect remnant patches, and then need to increase again in the lower catchment to protect the floodplain and the upper estuary (≥120m).


Curdies River Estuary.

Future planning for riparian management would benefit from a more strategic approach to restoration prioritisation, using landscape information contained in currently existing GIS databases. Information about contexts like land use, vegetation cover, elevation, nutrient loads, climate, roads and ecological vegetation classes (for assessment of vegetation quality) can potentially be used in spatial analyses to develop indices of quality or disturbance, which can then be translated into a width recommendation (*sensu* Wissmar *et al*., 2004). Alternatively, this information can be used to identify priority areas for restoration works to meet a clear set of local or regional management objectives for the catchment. For example, software like SedNet can be used to identify and target areas of high sediment export (Wilkinson *et al.*, 2005). This approach is discussed in more detail in Appendix 3.

## 1.3 Management objectives for Victorian catchments

Catchment management may have several ecological objectives including improvement of waterway quality, maintenance or restoration of habitat for biota and protection of water resources. The number of management objectives that can be achieved at a given location will depend on the width of the riparian zone on both banks and the landscape context. Conversely, the riparian zone width required to protect the waterway will be dependent on stream and site conditions and on the specific management objectives (Brosofske *et al.*, 1997). Therefore, defining management objectives for the initiation or augmentation of multiple riparian functions is important to ensure that fencing of riparian zones does not result in widths that are too narrow. If the riparian zone is too narrow, perhaps because a single management goal has been prioritised over others (e.g. reducing nitrogen inputs), the stream may not be fully protected from other catchment disturbances (e.g. sediment inputs). This is due to the inherent variability in riparian buffering performance that results from landscape variations, e.g. topographic convergences or "gaps" along the length of the buffer (see Weller *et al.,* 1998). Therefore, by increasing the riparian width the probability one or more management objectives are met will also increase.

Land and Water Australia developed width recommendations based upon a set of management objectives that are considered appropriate for Australian waterways (Price *et al.*, 2005). On this basis, we have defined a similar set of objectives for Victorian riverine systems, refining them slightly to reflect the dominant environmental issues (as identified by the ARC and other State Government resources; see Table 1) in the state. These are (not in any ranking order):

- Improve water quality (reduce excess nutrient inputs to waterways);
- Reduce streambank erosion and sediment inputs;
- Increase shading and moderate water temperature;
- Facilitate transfers of nutrients and resources between the terrestrial and aquatic environment;
- Provide in-stream habitat and increase in-stream biodiversity;
- Provide terrestrial habitat and increase terrestrial biodiversity, including improving the structure and composition of riparian vegetation communities
- Increase lateral and longitudinal connectivity of biota and other material

Each, and possibly all, management objectives will apply to every region of Victoria, owing to the widespread modifications to the landscape through human activities and the recognised need to rehabilitate or restore degraded waterways. Of all environmental issues that occur in Victoria, agriculture, particularly grazing, is known to have some of the most serious and extensive impacts on riparian zones and adjacent waterbodies. This is predominantly through increased nutrient, pollutant and sediment input to streams, increased bed and bank erosion and loss of in-stream and terrestrial biodiversity via degradation of riparian and aquatic vegetation and loss of habitat components like large wood.

Land clearance, which is closely linked to development of agriculture and other production industries, has resulted in less than 6% of native vegetation cover remaining in the north-central region of the state (Bennett *et al.*, 1998, Lada and Mac Nally, 2008). Removal of vegetation has exacerbated salinity issues and altered surface and subsurface hydrology, both of which have consequences for the capacity of riparian zones to regulate nutrient inputs to streams and the quality of riparian vegetation (thus, terrestrial biodiversity). Vegetation removal also dramatically impacts food webs by reducing the quality and frequency of carbon inputs like leaves and branches (Reid *et al.*, 2008b), alters in-stream processes like respiration and primary production through shading, and potentially fragments populations of biota.

Water extractions and storages for irrigation have exerted massive changes to the natural hydrology of the majority of Victorian rivers. Flow regulation has resulted in the loss and degradation of wetlands and floodplains (Kingsford, 2000) impacting aquatic and terrestrial biodiversity, catchment hydrology, increasing salinity, impacting food webs, and reducing the capacity of wetlands to act of nutrient and sediment sinks.

On this basis, all seven management objectives will form part of the guidelines for determining minimum riparian zone widths. However, it is not possible to generalise which management objectives are most important in a particular region or waterway. At any given location, one or more of the seven management objectives outlined above will be the primary goal for protecting waterways and restoring riparian zones (Table 1). In many areas, all may apply, requiring a trade-off between the choice of best width and the number of management objectives that can be successfully met. In these situations, it will be the responsibility of the land manager to decide on the primary goals of management works in order to prioritise the objectives that can be reasonably met for a given width on each bank.

The general "rule of thumb" should be, the wider the riparian zone on both banks, the greater the likelihood that more objectives will be met and the higher the probability that the riparian zone will not require significant management intervention at a later date.


Riparian restoration. Photo: L.Gould

Table 1. Major physiographic regions (bioregions) of Victoria, the dominant land uses and environmental issues in each and the most likely management objective(s) for disturbance mitigation at any given site within that region.

| Physiographic region | Dominant land uses | Major waterway issues | Major terrestrial issues | Management objective most likely to predominate | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Water quality | Shading | Food inputs to streams | In-stream biodiv. | Terrest. biodiv. | Conn. T/H | Bank stability |
| East Victorian Uplands | Forestry<br>Water production<br>Ag - grazing (sheep & cattle)<br>Ag - dairy | Flow disruption (impoundments)<br>Turbidity / sedimentation | Habitat loss<br>Invasive species<br>Fire | ✓ | | | ✓ | ✓ | ✓$_H$ | ✓ |
| West / South Victorian Uplands | Ag - grazing (sheep & cattle)<br>Mining - gold<br>Forestry<br>Urban | Flow regulation<br>Loss of riparian vegetation<br>Erosion / sedimentation<br>Salinity | Loss of vegetation (fragmentation)<br>Invasive species<br>Fire | ✓ | ✓ | ✓ | ✓ | ✓ | $^T$✓$_H$ | ✓ |
| Murray Basin Plains<br>- Riverine Plain | Ag - cropping<br>Ag - grazing<br>Ag - irrigation | Salinity (GW)<br>Excess nutrient inputs<br>Flow regulation erosion | Loss of vegetation (fragmentation)<br>Loss of biodiversity<br>Invasive species | ✓ | | | ✓ | ✓ | $^T$✓$_H$ | ✓ |

Abbreviations: Ag Agriculture, biodiv. biodiversity, Conn. connectivity (terrestrial, T, or hydrological, H), GW groundwater

| Physiographic region | Dominant land uses | Major waterway issues | Major terrestrial issues | Management objective most likely to predominate | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Water quality | Shading | Food inputs to streams | In-stream biodiv. | Terrest. biodiv. | Conn. T/H | Bank stability |
| Murray Basin Plains<br>- Mallee Dunefield<br>- Wimmera Plain | Ag - grazing (livestock)<br>Ag - cropping<br>Ag - irrigation | Flow regulation<br>Salinity | Erosion<br>Loss of vegetation (fragmentation) | | | | ✓ | ✓ | $^{T}\checkmark_{H}$ | ✓ |
| West Victorian Volcanic Plains | Ag - grazing (sheep & cattle) | Catchment hydrology<br>Salinity | Loss of vegetation (fragmentation)<br>Invasive species | ✓ | ✓ | ✓ | ✓ | ✓ | $^{T}\checkmark_{H}$ | ✓ |
| South Victorian Coastal Plains | Ag - grazing (sheep & cattle)<br>Plantations (hard / softwood)<br>Centre-pivot irrigation | Excess nutrient & chemical inputs<br>Erosion<br>Salinity | Invasive species<br>loss of vegetation (fragmentation) | ✓ | | | ✓ | ✓ | $^{T}\checkmark$ | ✓ |
| South Victorian Riverine Plains | Ag - dairy (sheep & beef)<br>Mining - coal<br>Plantations (hard / softwood)<br>Urban | Eutrophication & excess nutrient inputs<br>Flow regulation<br>Rising GW<br>Loss of riparian vegetation | Loss of vegetation (fragmentation)<br>Invasive species | ✓ | ✓ | ✓ | ✓ | ✓ | $^{T}\checkmark_{H}$ | |

Abbreviations: Ag Agriculture, biodiv. biodiversity, Conn. connectivity (terrestrial, T, or hydrological, H), GW groundwater

Information in table assembled using the D.S.E. Victorian Resources Online Bioregion of Victoria website (http://www.dpi.vic.gov.au/DPI/Vro/vrosite.nsf/pages/biodiversity_bioregions_vic) and the Assessment of River Condition (Norris *et al.*, 2001)

## 1.4 Riparian ecosystems in Australia

**What information relevant to riparian widths is available from Australian studies?**

Information pertaining to riparian zone widths in Australia for different management objectives is generally poor (see also Campbell, 1993). Few studies are specifically aimed at collecting data on the relationship between riparian width and ecological function. Instead, most research has focused on specific aspects of riparian function and the interactions between the riparian and aquatic environments. Studies are often limited to specific landscape settings including forestry (Davies and Nelson, 1994, Bren, 2000, Dignan and Bren, 2003, Lloyd *et al.*, 2006), tropical systems especially regions of Queensland where waterways experience predictable cycles of wet and dry (Catterall *et al.*, 2001, Pusey and Arthington, 2003, Rutherford *et al.*, 2004, Rassam *et al.*, 2006) and southern Western Australia (McKergow *et al.*, 2003, Rutherford *et al.*, 2004, Doupé *et al.*, 2006, McKergow *et al.*, 2006a, McKergow *et al.*, 2006b, Ocampo *et al.*, 2006, Callow and Smettem, 2007). A number of riparian research projects (e.g. Webb and Erskine, 2001, McKergow *et al.*, 2003, Williams *et al.*, 2008b) have used restoration works as the basis of their investigations.

Riparian restoration is proceeding rapidly in Australia and is the dominant form of restoration in central Victoria, constituting nearly half of management works across four catchment management authorities (Brooks and Lake, 2007). These works tend to focus on objectives relating to improving bank stability and in-stream habitat, but are frequently undertaken with little sound planning, guidance and virtually no post-works monitoring (Brooks and Lake, 2007). While riparian restoration will have benefits for the re-establishment of ecological processes in catchments (Davies and Bunn, 1999), the extent, longevity and trajectories of those benefits is not clear. As a result of the paucity of pre- and post-restoration works monitoring data, riparian width recommendations for new restoration projects are still based primarily on best professional judgement and inferred based on information provided by related research, or negotiated on the basis of non-ecological considerations (e.g. landholder agreements).

Research relating to riparian zones is heavily focused on issues in the Murray-Darling Basin for the obvious environmental, economic and social implications of river regulation and water extractions there. Information pertaining to the effects of flow regulation includes floodplain hydrology and salinity (Lamontagne *et al.*, 2005, Holland *et al.*, 2006), and changes in floodplain biodiversity (Kingsford, 2000, Siebentritt *et al.*, 2004). However, few of these studies are directly translatable to the problem of delineating riparian zone widths as this is not usually the aim of the study nor is it directly relevant to the ecological patterns being described. The most relevant are those that have been able to quantify the lateral extent of surface-groundwater interactions, which is information useful in determining the effective floodplain width.

In drier climatic regions of Victoria (western and central), where restoration efforts are targeting massively degraded waterways, data on food inputs (terrestrial subsidies to aquatic food webs) and organic matter dynamics (Boulton and Lake, 1992, Campbell *et al.*, 1992, Ballinger and Lake, 2006, Reid *et al.*, 2008a, Reid *et al.*, 2008b) have been collected. These data provide evidence for the importance of riparian vegetation extent in terrestrial-aquatic trophic subsidies. In this vein, functions relating to wood and detritus inputs have received attention across different climatic regions of Australia (McKie and Cranston, 2001, Mac Nally *et al.*, 2002, Brooks *et al.*, 2004, Lester and Boulton, 2008), although the data generated from these sources suffers from the same lack of transferability as hydrology and salinity research because quantification of riparian widths is rarely an objective of the study.

In Victoria, those headwater streams that have received the majority of research attention occur in forested catchments of the Central Highlands of Victoria (Campbell *et al.*, 1992, Greenwood *et al.*, 2004, Hopmans and Bren, 2007, Mac Nally *et al.*, 2008). The study by Mac Nally *et al.*, (2008) is one of the few Victorian headwater studies to provide riparian zone width information and does so for a specific riparian function (plant biodiversity) that differs to the functions usually considered in forestry-riparian studies (e.g. moderating water temperature).

In other regions of Australia, there are various studies on different riparian functions and their importance in the catchment. In south-east Queensland, terrestrial avian assemblage diversity is characterised by riparian- and upslope-specialist species, but their distinction is not necessarily straightforward, especially from a landscape-planning perspective (Catterall *et al.*, 2001, Martin *et al.*, 2006). Variable use of riparian buffers and upslope wooded habitats by bats in sub-tropical forests of NSW (Lloyd *et al.*, 2006) also highlights the difficulties in distinguishing riparian-dependent from more generalist species, information that might translate to width requirements for a specific management objective, e.g. increasing riparian vertebrate biodiversity.

There have been a number of reviews of stream ecosystems in the Australian context that address issues pertaining to riparian zones (Bunn, 1993, Barling and Moore, 1994, Davis *et al.*, 1998, Kingsford, 2000, Harris, 2001, Martin, 2003, Pusey and Arthington, 2003, Drewry *et al.*, 2006, Lester and Boulton, 2008). These collectively discuss a range of issues relating to riparian zones and their functions, some of which provide useful summaries relating to riparian zone widths. Information relating to Australian riparian zone studies, recommendations for management and relevant legislation is summarised in Appendix 1.

Overall, there is a substantial body of information relating to riparian ecosystems in Australia, but much of it is in a form not readily accessible to managers and is difficult to translate to management guidelines for width recommendations. Nevertheless, evidence for the importance of riparian zone management in Australian contexts is growing and, when used in combination with international research findings, will be important for setting objectives and priorities for riparian management in Victoria.

## 1.5 Riparian ecosystems overseas

**How relevant is international research on riparian zone widths to Australian systems?**

The bulk of riparian research stems from North America where the majority of studies into improving catchment water quality have been conducted. While nitrogen and phosphorus removal dominate the literature, there is also a large body of research devoted to erosion control, provision of wood and other detrital inputs from the riparian zone to the stream, and riparian zones as terrestrial habitat and movement corridors. Similarly in New Zealand, studies on nutrient and sediment inputs to streams are common, as are those that quantify the effects of shading on aquatic function (see review by Parkyn, 2004). Importantly, riparian research from overseas is increasingly placed within a broader framework of whole catchment management and highlights the importance of understanding the influence of landscape context on the strength of the mediation function of the riparian zone. As a good example, Craig *et al*., (2008) provide a framework for identifying and rehabilitating waterways with high nitrogen loads, but emphasise the need to couple in-stream mitigation works with land-based management strategies for identification of major N input localities and reducing catchment N export.

Prior to 1994, most research on vegetation performance in buffer strips had been carried out in North America and was not considered directly transferable to semiarid environments like those occurring in Australia (Barling and Moore, 1994). While, much of the theory related to buffer performance is relevant in any watershed setting, the dominant mechanisms of nutrient, sediment and non-point source pollution removal may vary considerably in Victoria compared with North America owing to different soils, climate and hydrology (Harris, 2001). For example, buffers for sediment entrapment and reducing surface flows are often reported as ineffectively performing their function (eg. Dillaha *et al*., 1989) or, in exceptional cases, concentrating nutrients in buffer outflows (Jordan *et al*., 1993). The applicability of these findings to other systems will necessary be landscape context-specific (regardless of country, climate or physiography) and therefore, while the principles are probably generalisable to Victorian systems, the specifics will require local and regional assessments.


Tributary of Nantes. Bretagne.

Extensive research has been conducted in Chesapeake Bay Watersheds in the State of Maryland, (in the United State of America), where the Chesapeake Executive Council has set 2010 targets for the protection and restoration of riparian zones, especially with respect to water quality (Lowrance *et al*., 1997, Lowrance, 1998). Physiographic province (regions characterised according to lithography, soils and geomorphology) was used to categorise the hydrological and geomorphic aspects of the catchment in the context of riparian function. Land use, slope and soils were found to strongly influence the delivery of water via surface and subsurface flows into waterways. Similar detailed information for Victorian bioregions could potentially be assembled from existing databases in Australia. This information could then be used to prioritise locations where agricultural intensity is high and groundwater delivered to streams can be effectively intercepted by wide riparian buffers, thus maximising the opportunity for retention.

### *1.5.1 The riparian forest buffer system*

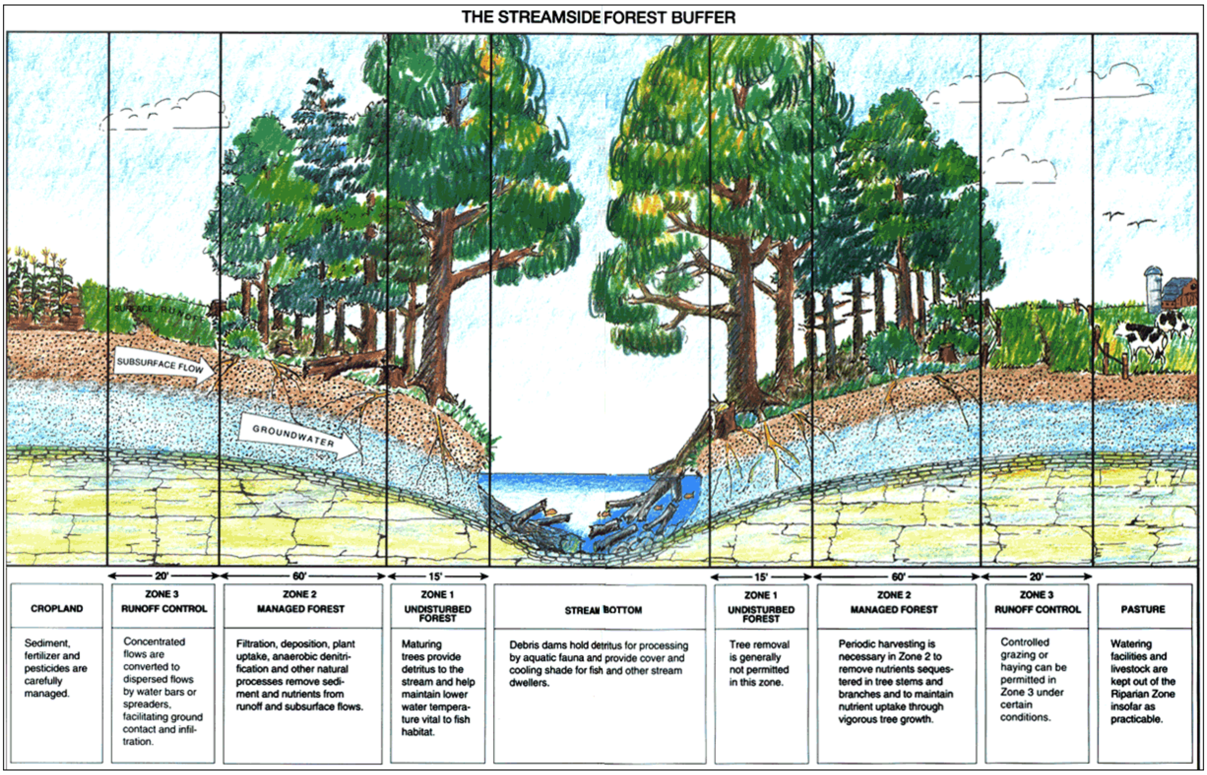
### *Is this useful for Victorian catchments?*

In response to the problem of variability in buffer effectiveness and the need to protect waterways, Welsch (1991) proposed a three zone riparian forest buffer system (RFBS) for agricultural land of eastern United States. The three zones are designed to simultaneously meet one or more management objectives.

Zone One has a designated width 15 feet (or ~5m) beginning at the top of bank and comprises either unmodified mature native vegetation (trees and shrubs) or is restored with equivalent native plantings. This zone provides shading and controls stream temperature, prevents streambank erosion, provides inputs of woody debris and provides food and energy inputs (organic debris) to the waterway. Stock and any other modifying activities should be excluded from this zone.

Zone Two should have a minimum width of 60 feet (~20m) beginning at the end of zone 1. This width may need to be adjusted upward depending on site conditions and management objectives relevant to the site. This zone provides a nutrient filtering, uptake and assimilation environment as well as slowing the flow of runoff into zone 1. Predominant vegetation type is native which may be selectively harvested while still maintaining filtering and soil stabilising capacity. Stock exclusions still apply in this zone.

Zone Three is a grassy strip beginning at the end of zone 2 and extending for a minimum of 20 feet (~6 m). This filters sediment and acts by converting concentrated flow to uniform flow. It should be mowed and grazed (but usually not intensively) to maintain vigorous growth. Soil capability class should be used to determine the combined zone 1 / zone 2 buffer width, which can extend up to 150 feet (~50m) depending on class on-site. However, the performance of grass filter strips in southern Australia remains to be tested under Victorian field conditions, especially in those regions where quality and extent of ground cover is reduced by drought and grazing pressures.




The Streamside Forest Buffer (Welsch, 1991). Image courtesy of United States Department of Agriculture Forestry Service.

In North America, the RFBS is frequently advocated as best riparian management practice (Lowrance *et al*., 1997, Fischer and Fischenich, 2000, Hawes and Smith, 2005). Some organisations in Australia have used this a template for their own guidelines and recommendations, the most notable being the Department of Infrastructure, Planning and Natural Resources in NSW with their Riparian Corridor Management Study, prepared for Wollongong City Council (DIPNR, 2004). In Victoria, a similar system may also be successful in meeting multiple management objectives by simultaneously acting as a buffer from disturbance and providing suitable habitat. A RFBS may also address issues relating to invasive plant species, as the cultivation of an outer grassy zone (once fencing, weed removal and tubestock planting is complete) may hinder re-establishment of weeds once the riparian forest buffer is established. However, the use of zones will require active management and ongoing monitoring and therefore, where management involves only fencing for stock exclusion their usefulness is probably very limited.

Riparian zone buffer widths for different functions, reported in international studies, are summarised in Appendix 2.

### *1.5.2 How much international data can be extrapolated to Victorian catchments?*

Ultimately, all the information that derives from international studies will be useful, to varying degrees, for determining minimum riparian zone widths in Victorian catchments. It will also be necessary to use this information where possible, as little comparable data for Australia exists. General physical processes are likely to be similar in both North America and Australia, but many of the biotic processes are unlikely to be comparable. For example, sediment interception by the riparian zone will occur via similar mechanical processes, but the biological processes governing nutrient assimilation by plants may differ depending on the dominant vegetation type in the riparian zone. On face value, width recommendations from North America for removal of non-point source pollutants may be adequate or even generous for Australia, where agricultural intensity on average tends to be lower (Drewry *et al.*, 2006), but as many Australian native plants may use less nutrients than their overseas counterparts, these recommendations may actually prove inadequate to buffer the stream where nutrient exports from the catchment are high.

There are some examples where extrapolation of international data to Victoria would be clearly flawed. Carbon inputs and shading provided by conifer forests to North American streams will have little relevance to Victorian catchments where eucalypts are the predominant overstorey species. Litterfall studies from deciduous forested riparian zones are only partially informative in Australia, where peak litterfall periods occur during summer and are less pronounced than autumn litterfall in the Northern hemisphere (Lake *et al.*, 1985).The use of intact riparian zones as migratory pathways in the Americas, where large mammals are present and where a much larger proportion of birds undergo seasonal neo-tropical migration, will have only some relevance to Australia where there are virtually no large migratory native mammals, and relatively fewer woodland-dependent bird species that undergo predictable migrations (owing to the dispersed nature of resources in south-east Australia).

These considerations are critical to deciding the confidence with which we can extrapolate international research findings to Victoria in the absence of comparative data. As riparian zones are inherently variable and spatially diffuse, regardless of country or landscape setting, any set of rules developed using data from different systems is always going to be overly broad and potentially inadequate in some locations. Moreover, the amount of data that would be required to quantify widths for all landscape contexts is prohibitive and some level of uncertainty is unavoidable when attempting to develop a set of broadly-applicable rules. Where information from overseas is used to guide prioritisation of riparian restoration management objectives in Victoria, it is important that targeted pre- and post-works monitoring is undertaken to ensure that implemented widths are adequate for long-term maintenance of riparian function.

## 1.6 Consequences of below-minimum width riparian zones

**What are the consequences of riparian zone widths that are too narrow to meet a specified management objective?**

Riparian zones in their minimal state for stream protection need to be sufficiently wide and longitudinally continuous to mitigate against impacts and disturbances within the catchment that have arisen as a result of land use modifications. Where that width is unachievable (due to social or economic constraints), the functional benefits of the riparian zone are significantly reduced and there is a risk that works efforts will be mostly ineffectual over a long time frame. Furthermore, there is the additional risk that the benefits accrued by restoration works will be compromised by invasive species. Nevertheless, as riparian zones are severely degraded across much of Victoria and consequently, as waterway health has been significantly compromised, intact riparian zones of any width will have greater long-term ecological benefits than modified and degraded riparian zones.

As the riparian zone reduces in width, the perimeter to area ratio increases. The increase in riparian perimeter relative to riparian habitat area may introduce problems associated with edge effects. The most obvious of these is weed invasion and their subsequent proliferation in the absence of grazing pressure. To experimentally address this, it is necessary to have data that explicitly compare narrow fenced riparian zones to both wider and unfenced riparian zones. To undertake such a comparison, what constitutes "narrow" needs to be determined in the context of a certain restoration goal. To date, there are no empirical studies that specifically address this.

Modelling studies in Australia have demonstrated that stock exclusion can lead to changes in exotics in fenced compared with unfenced plots (Lunt *et al.*, 2007b). In the event that a narrow degraded riparian zone was clearly defined, the benefits of stock removal from the riparian zone may outweigh the disadvantages of weed invasion. The presence of weeds may improve water quality by reducing inputs of sediment and excess nutrients to the stream. Furthermore, rehabilitation of in-stream habitat can be attempted once stock is excluded from the channel, potentially improving aquatic biodiversity. Subsequent weed-control can then be undertaken.

What constitutes “narrow” is going to be highly case-sensitive as well as landscape-specific, and will depend on what the dominant restoration goals are and which management objectives are considered most important. It is clear that, at this time, there is little research that has attempted to quantify the potential negative impacts of riparian zones that are too narrow.


Riparian plantings. Back Creek.

# SECTION 2. RIPARIAN LITERATURE REVIEW

## 2.1 Introduction

A vast amount of research has been amassed over the previous two decades that highlights the ecological importance of riparian zones (Gregory *et al.*, 1991, Castelle *et al.*, 1994, Naiman and Décamps, 1997). The degree to which riparian zones influence waterbodies and their catchments depends on a range of biophysical properties including the type, amount and extent of vegetation present, soils and geology, hydrology, climate and topography. The role of the riparian zone will also differ depending on the position in the catchment and the extent of lateral and longitudinal connectivity (Naiman and Décamps, 1997, Ward *et al.*, 2002, Naiman *et al.*, 2005, Rodriguez-Iturbe *et al.*, 2009). This research should underpin riparian management and policy.

## 2.2 Riparian zones and their functional extent

The definition of what constitutes the riparian zone is important for managing riparian land to produce beneficial ecological outcomes. The riparian zone may be defined as the ecotone or interface between a waterway and the upslope environment (Gregory *et al.*, 1991, Naiman and Rogers, 1997). Riparian zones facilitate the flow of energy, and physical and biotic vectors between aquatic and terrestrial environments (Lake, 2005, Naiman *et al.*, 2005). Consequently, they are environments of often, exceptionally high diversity.

In a natural system without flow regulation, the riparian zone can conceivably encompass the entire extent of the floodplain. This not only includes the immediate streamside vegetation, but can also include adjacent plant communities, which influence the waterway especially during and after flood events (Knutson and Naef, 1997, Correll, 2005). A good example of this in Victoria is the river red gum / black box floodplain vegetation community that occurs in the western Murray-Darling Basin (Roberts, 2004). In this example, the effective riparian zone is both the red gum and black box vegetation. This floodplain community is up to 10km wide in some sections (Roberts, 2004). Similarly, the riparian zone can be considerably wider than expected in upland stream sections where the plant community directly adjacent to the stream is indistinguishable from that found in the surrounding gullies (Mac Nally *et al.*, 2008).

Floodplains are connected laterally to the waterway both structurally, through terrestrial vegetation, and hydrologically, through flooding, subsurface flows and groundwater. The lateral boundary of hydrological limits may be indistinct and highly variable, resulting in lateral zonation of vegetation communities from the stream edge to the valley slopes (Ward *et al.*, 2002). These vegetation communities will differ depending on soils characteristics (moisture and oxygenation), sediment deposition, the frequency and duration of inundation events and the erosive action of floods (Ward *et al.*, 2002). The delineation of these zones may not be straightforward (neither is defining their role in waterway function) and therefore, they should be included in the effective riparian zone (or riparian habitat area). This will also provide the maximum protection from floods and maximum storage capacity of wetlands (Wenger, 1999).

Hydrologic connectivity with the waterway may be maintained with floodplain components like billabongs and anabranches (both of which have their own riparian zone), and potentially with paleo-meanders through periodic flooding (Ward *et al.*, 2002), but also with seasonal changes in groundwater levels (Lowrance *et al.*, 1997, Ward *et al.*, 2002, Fisher *et al.*, 2004, Vidon and Hill, 2004a, Holland *et al.*, 2006, Ocampo *et al.*, 2006). These differing levels of connectivity are mediated by the extent of flooding and the topography of the floodplain. In a comprehensive review of riparian zones in eastern America, Knutson and Naef (1997) provided a set of width recommendations based upon stream size and permanency of flows. They noted that widths should extend to the 1 in 100 year flood level, in the event that the recommended buffer width is narrower.

Lastly, the effective riparian zone (in terms of a given function) will vary spatially depending on landscape characteristics like slope and topography, soil type, vegetation community and dominant hydrological flow paths, but it will also vary temporally as channels meander in response to flooding and fluvial processes (Latterell *et al.*, 2006). The extent of the riparian zone will be inherently difficult to define due to this variability, which will occur both within and between watercourses, and therefore the ‘width’ will depend on the management objectives or impacts that are considered most important.

## 2.3 Functions of the riparian zone and their importance to river catchments

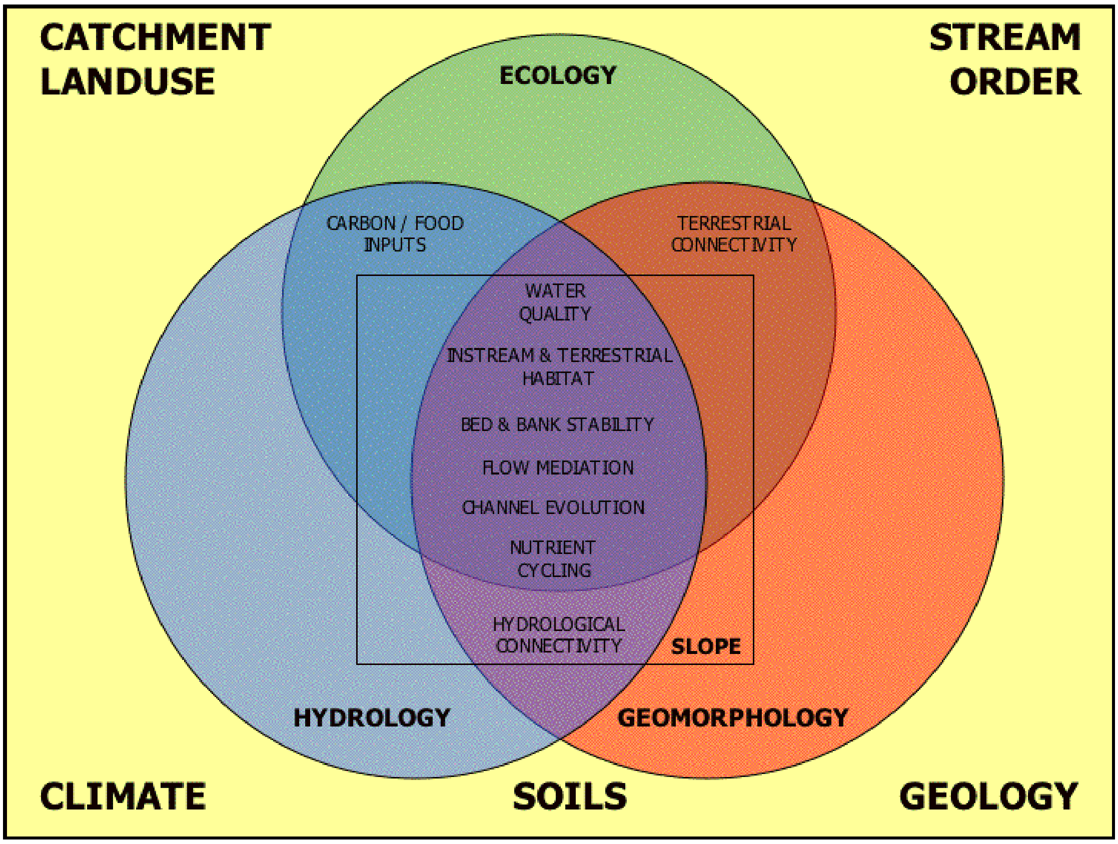
The ecosystem functions of the riparian zone may be divided into three broad, inter-related categories:

1. Ecology. These functions include water quality maintenance and nutrient processing, shading and water temperature control, food (carbon) inputs and subsidies, in-stream and terrestrial habitat (which contribute to increased biodiversity), and connectivity (movement and dispersal corridors).
2. Geomorphology. These functions include bed and bank stability, lateral channel migration (channel evolution), flow regulation and flood mediation (accumulation / transport of sediments).
3. Hydrology. These functions relate largely to hydraulics and the mediation of discharge (not separable from geomorphic function). The riparian zone facilitates longitudinal and lateral hydrological connectivity, and maintains hydrologic condition (modifying storage capacity and aquifer recharge).

Figure 1 illustrates the relationships of each riparian function.

It is important to note that the riparian functions belonging to each of the three categories are not mutually exclusive (linked in some way). In addition, all functions are influenced by stream and catchment conditions. While it may seem convenient to treat each separately for the purpose of defining management objectives, all functions are inter-related and changes in one can impact on many of the others. Ultimately, to understand the interaction between riparian ecosystem properties and function, attention should be given to the entire ecosystem, including transitional areas beyond hydrological limits (Brosofske *et al.*, 1997).

Some riparian functions are not necessarily directly related to width recommendations (e.g. maintenance of hydrologic condition) and functions like flow regulation are influenced by the same characteristics of the riparian zone that also influence in-stream biodiversity. Therefore, we focus discussions primarily on width-related functions. These are improving water quality and nutrient processing, shading and temperature control, food (carbon) inputs, in-stream habitat, terrestrial habitat, erosion control and connectivity. In defining these, important management objectives are identified.




Riparian functions and their inter-dependencies. All functions are influenced by catchment conditions (land use, climate, soils, geology (lithology) and stream placement in the drainage network). Slope is the catchment sub-feature exerting the greatest influence on the majority of functions and is, in itself, influenced by each catchment condition.

### 2.3.1 Improving water quality and nutrient cycling

Key points

- Riparian zones act as filters, sinks, processors and exporters of nutrients
- Nitrogen removal is most effective where shallow groundwater flow passes through root zone
- Sediment and sediment-bound phosphorus retention is most effective with grassy, continuous buffers that convert channelised flow to uniform sheet flow
- Riparian zones can act as phosphorus sinks and therefore, need to be wider where excess phosphorus is a dominant management issue. Periodic removal of riparian vegetation may be necessary
- Dominant hydrological flow paths affect riparian buffering efficiency
- Nutrient removal and processing is most effectively achieved in headwater streams
- Wetlands are good nutrient sinks and sediment traps
- Riparian widths necessary for excess nutrient removal are typically >50m, depending on nutrient type, buffer type, soil type, slope and dominant landuse

Riparian zones act as filters, sinks, processors and exporters of nutrients. The efficacy of riparian nutrient retention and processing is strongly influenced by characteristics of the soil, including soil carbon (Osborne and Kovacic, 1993, Dosskey *et al.*, 2006) and also by hydrological connectivity (Naiman *et al.*, 2005). Nutrient and sediment transport from upland zones to riparian zones occurs via surface or overland flows, subsurface and groundwater flows (Drewry *et al.*, 2006). Nutrients and other contaminants may be transported either as solutes or bound to sediment. Nutrient and sediment control in the riparian zone is achieved by:

- filtering (deposition and erosion, infiltration, dilution and adsorption/ desorption)
- sediment trapping (deposition)
- nutrient (especially nitrogen and phosphorus) uptake, assimilation and removal
- nutrient cycling and transformation (e.g. denitrification) in the soil

*The role of riparian zones in nutrient processing*

Both riparian and in-stream ecosystems are processing stations for incoming nutrients, especially nitrogen and carbon (Peterson *et al.*, 2001, Fisher *et al.*, 2004, Bernhardt *et al.*, 2005). Upslope zones may be sources of nitrates and other nutrients, participating in their downslope transport, whilst riparian zones are responsible for their depletion or export (Ocampo *et al.*, 2006). Bi-directional fluxes of nutrients occur between the riparian zone and the stream, and the retention of nutrients in the riparian zone occurs via biotic processes (e.g. assimilation) and abiotic processes (eg. adsorption) (Naiman *et al.*, 2005). The retention and recycling of nutrients and energy resources from the surrounding watershed dictates the productivity and persistence of stream ecosystems (Newbold *et al.*, 1982).

Nutrients like nitrogen (N) and phosphorus (P) need to be transformed to make them available for sequestration by plants and animals. Bioavailability depends on molecular form. Nitrogen is only available as ammonium ($NH_4^+$) or nitrate ($NO_3^-$) (Naiman *et al*., 2005). Phosphorus is available to plants predominantly in the form of orthophosphate ($PO_4^{3-}$) (Naiman *et al.,* 2005). Microbial transformation of nutrients relies on the presence of bioavailable carbon in the system (which may be soil carbon or plant material).

***Nitrogen processing:*** Microbial reduction-oxidisation in the soil is largely responsible for the flux of nitrogen (plus other compounds) and this process is linked to the cycling of carbon and other elements. Bacteria in the soil transform organic nitrogen to ammonium (mineralisation) and to nitrate (nitrification). Ammonium is stable under anaerobic conditions and is adsorbed or stored by biotic assimilation (Naiman *et al*., 2005). Under aerobic conditions, ammonium is oxidised to nitrate, which is subsequently assimilated by plants or else transformed through denitrification to gaseous forms $N_2$, $N_2O$ (greenhouse gas) and NO (Naiman *et al.,* 2005). Denitrification is maximised in presence of plentiful carbon (C) (eg. wetlands and riparian soils rich in organic matter) and anoxic conditions (Parkyn, 2004). Soil denitrification is sustainable over long time periods dependent on the availability of C (Lowrance, 1998) with denitrification potentials being positively correlated with background levels of soil nitrate (Fellows *et al*., 2007).

The effectiveness of plant uptake (to remove N) will depend upon subsurface / groundwater flow paths, evapo-transpiration rates and water availability (Naiman and Décamps, 1997, Lowrance, 1998). In different parts of Australia, denitrification potential in the riparian zone is similar when either woody versus non-woody forms are present (Fellows *et al*., 2007) suggesting that both forms can supply bioavailable C. However, regional differences exist that relate to woody vegetation cover (which may be a function of soil moisture and the presence of nitrogen-fixing species like *Acacias*), such that Victorian riparian zones that are well treed tend to have higher denitrification potential than sparsely treed ones (Fellows *et al.*, 2007).

Processes that occur within the stream ecosystem may have a major role in catchment N export. Following a disturbance event, streams and their catchments can recover along very different trajectories. For example, in the Hubbard Brook Experimental Forest (Likens *et al.*, 1978), monitoring of small headwater streams found that stream ecosystems may retain nutrients as forest ecosystems lose them, and that this was largely a function of retention within the stream by debris dams and other geomorphic obstructions (Bernhardt *et al.*, 2005). Importantly, nitrogen uptake rates are highest in small streams and thus exert the greatest control over catchment nitrogen export (Peterson *et al.*, 2001).

***Phosphorus processing:*** Less is known about P processing (and processing of other nutrients like sulphur S) compared with N processing (Naiman *et al*., 2005). Orthophosphate ($PO_4^{3-}$) is taken up and assimilated by plants but only occurs in low concentrations as P strongly adsorbs to other compounds. Sediment-bound P may contribute over 70% of the total P export from riparian zones into waterways (Muscutt *et al.*, 1993). In-stream P processing involves adsorption by stream sediments and periphyton and utilisation by aquatic plants (Storey and Cowley, 1997). The efficacy of the riparian or aquatic zones to sequester P is therefore heavily reliant on the retention of sediment.

Distinct import and export pulses affect both the nature and rate of internal nutrient-cycling processes on agricultural watersheds (Lowrance, 1998). This is especially true in Victorian catchments where rainfall is highly variable, meaning that delivery of nutrients to riparian zones is not constant. Indeed, episodic rainfall was found to be responsible for the majority of phosphorus loss from Australian catchments (Davis *et al.*, 1998).

***The role of carbon in nutrient processing:*** The presence of carbon is strongly related to nutrient cycling and the retentive capacity of the terrestrial-aquatic ecosystem is important to nutrient dynamics and ultimately, aquatic heterotrophy (Battin *et al.*, 2008). The cycling of carbon relies upon soil type and moisture, watershed hydrology and subsurface biogeochemistry. Organic matter / carbon availability is closely linked to nitrogen processing in both terrestrial and aquatic zones (Bernhardt and Likens, 2002, Craig *et al.*, 2008). Experimental additions of dissolved organic carbon to small streams have been shown to result in reductions of nitrate concentrations and increases in metabolism, as a result of increased assimilation of nitrogen by bacteria (Bernhardt and Likens, 2002). Increasing carbon availability to, and storage in, streams can be used as a strategy to reduce nitrate and ammonium levels (Craig *et al.*, 2008).

***In-stream solute and particle retention:*** Nutrient spiralling length is a measure of the retentiveness of the system for particular resources (Quinn *et al.*, 1993, see also Elwood et al 1983). Riparian zones exert important influences on in-stream nutrient spiralling by influencing the retention of particles and solutes (Quinn *et al.*, 1993). In-stream retentiveness relies on riparian inputs and woody debris to maintain channel complexity which in turn slows flow velocities (Gregory *et al.*, 1991). For example, phosphorus spiralling lengths may be reduced by increases in riparian leaf litter inputs (Gregory *et al.*, 1991). Sheldon and Thoms (2006) demonstrated the importance of organic matter retention to food webs in sections of the Barwon-Darling that have high geomorphic complexity. Studies in New Zealand have also shown that stock exclusion allows proliferation of macrophytes, which decrease nutrient spiralling lengths (Quinn *et al.*, 1993). In contrast, shading out of periphyton through rehabilitation of riparian vegetation can increase spiralling lengths (Quinn *et al.*, 1993).

*The role of riparian zones in improving water quality*

The majority of data on the benefits of greater riparian widths relates to improving water quality and the processing of nutrients. Research pertaining to control of excess nutrients / non-point source pollution (which includes sediment) is probably the most extensive of all riparian studies. This is due, in part, to the widespread nature of agricultural land use and therefore, the major goal of restoration in these areas is nutrient reduction from these sources (Osborne and Kovacic, 1993, Parkyn, 2004).

Sediment and sediment-bound pollutants are removed in the riparian zone primarily via mechanical retention of sediments in surface runoff, adsorption of soluble nutrients by organic and inorganic soil particles, and immobilisation of soluble nutrients by vegetation and microbes (Osborne and Kovacic, 1993). The extent to which sediments and contaminants are filtered depends on the type of riparian filter and the type of surface flow (uniform sheet versus channelised) (Dillaha *et al.*, 1989, Muscutt *et al.*, 1993, Osborne and Kovacic, 1993). Furthermore, it is well established that reduction of non-point source pollutants (especially nitrates) is most effectively achieved in headwater riparian systems (Lowe and Likens, 2005, Craig *et al.*, 2008).

***The influence of hydrology on nutrient removal:*** Hydrology exerts a strong influence on the effectiveness of riparian zones in reducing input of nutrients to streams (Vidon and Hill, 2004b, Rassam *et al.*, 2006). The highest levels of nitrate removal are typically found in areas with high water tables where shallow groundwater flow to streams occurs near or through carbon-rich root zones (Peterjohn and Correll, 1984, Jordan *et al.*, 1993, Lowrance, 1998, Naiman *et al.*, 2005, Dosskey *et al.*, 2006, Rassam *et al.*, 2006). When highly conductive (hydrologically) sediments are present (which equates to efficient transmission of nutrients), riparian zone widths of 40-60m may be necessary for any significant nitrate removal to occur (Vidon and Hill, 2004b). Where groundwater flow by-passes the riparian root zone and surface soil layers, reduction in nitrate exports by buffers is minimal (Lowrance, 1998, Mayer *et al.*, 2005). Based on the meta-analysis of Mayer *et al*., (2005), buffers of 3m, 28m and 112m were effective at removing 50%, 75% and 90% of total nitrogen, respectively, averaged over all vegetation types and flow paths. However, when re-analysed averaging over only surface flow paths, these values increased to 34m, 118m and 247m. Details of riparian buffer widths from overseas studies are given in Appendix 2.

The dominant pathway for removal of nutrients in some agricultural catchments will be overland flow and in others, it may be groundwater discharge (Fisher *et al.*, 2004, Drewry *et al.*, 2006). If the dominant flow path is directly down to the aquifer, then the riparian zone may have little influence on uptake; this is the case in some physiographic regions within Chesapeake Bay watersheds (Lowrance, 1998, Craig *et al.*, 2008). In New Zealand streams where pasture retirement is used in riparian restoration, re-vegetation did not reduce in-stream nitrate loads because groundwater bypassed the riparian zone and entered the stream bed through springs (Quinn *et al.*, 1993). Deep-rooted vegetation is recommended in restoration strategies to enhance nitrogen removal in these cases. However, it was noted in a comprehensive review of riparian management for New Zealand waterways that riparian carbon inputs to streams may increase the potential for stream bed denitrification, which will be important when groundwater flows bypass the riparian zone or where there is tile drainage (Parkyn, 2004). Therefore, even when the groundwater is too deep for flows to intercept the roots of most plants, the riparian zone will still provide an important although indirect contribution to nitrate removal in the form of organic matter inputs.

***The effectiveness of riparian zones for removal of excess nutrients and sediment:*** In general terms, wider filter strips reduce water and contaminant runoff better than narrower ones (Schmitt *et al.*, 1999, Dosskey *et al.*, 2006). However, there is considerable variability associated with both landscape attributes (soil, vegetation and topography) and hydrology. Riparian zones have been shown to be effective in removing sediment-bound pollutants from surface flows, but they are often less effective in removing dissolved pollutants (Dosskey *et al.*, 2006). Sediment removal (and sediment-bound P) relies upon on continuous groundcover (grass or litter) to reduce flow velocity and allow deposition (Barling and Moore, 1994) and is therefore be strongly related to the type, extent and width of groundcover, and the rate of saturation of the buffer. However, removal of dissolved nutrient and contaminants relies on vegetation uptake and denitrification. As uptake and assimilation are also affected by soil type and permeability, and the dominant flow paths (Muscutt *et al.*, 1993), removal of non-point source pollutants may not necessarily be tightly correlated with buffer width (Wenger, 1999).

Many Australian streams are eutrophic with resulting persistent algal blooms, owing to excess bioavailable P, the majority of which is sediment bound to particles from erosion and diffuse sources (Wallbrink *et al.*, 2001). The efficacy of riparian zones in P removal depends on their ability to retain sediments (McDowell *et al.*, 2004); therefore, control of erosion, especially in headwater streams, will be effective in reducing P export to waterways.

Fencing riparian zones in a sub-catchment near Albany, WA, reduced suspended sediment, probably as a result of reductions in streambank erosion, but had little impact on P and N exports (McKergow *et al.*, 2003). The low effectiveness of the riparian zone in pollutant uptake was attributed to the sandy low P-binding soils in the catchment. In this particular study, the range in riparian widths was not reported and it is possible that the riparian zone was not wide enough to allow sufficient water residence time for the uptake of N and P. This was found to be true in their later study of *Eucalyptus globulus* riparian buffers (also in southern WA) where subsurface flows were the dominant flow path, but short residence times reduced the opportunity for plant uptake, denitrification and chemical transformation (McKergow *et al.*, 2006a, McKergow *et al.*, 2006b). In their assessment of the same buffers for improving water quality, they found that B-horizon subsurface flows were the dominant flow paths (in both buffer types) for nutrient transport and carried contaminant loads nearly three times greater than surface flows (McKergow *et al.*, 2006b).

Several overseas studies have reported that riparian zones under 50m in width were not effective at reducing P export (Wenger, 1999). However, Wenger (1999) also noted that saturated riparian zones may still regulate flow of P from land to stream by reducing extreme pulse events and preventing direct runoff of P into streams during storm runoff. He recommended a minimum of 15-30m, which should be increased with slope and landscape contexts like concentrated animal feeding operations (especially swine and chickens) upslope application of fertilisers and proximity of septic systems.

Dillaha and others (1989) found that vegetative filter strips of 4.6m and 9.1m were effective in removing between 50 and 85% of incoming sediment, total N and total P, but that soluble components were often more concentrated in outputs due to filter saturation. Wenger (1999) recommended a minimum width of 30m for sediment control, but stressed that this should be coupled with longitudinal preservation of buffers. Importantly, the presence of gaps along the riparian zone influences its capacity to effectively intercept surface flows and trap sediment. When riparian zones are narrow, convergent overland flow paths entering the buffer zone punctuate it with gaps that efficiently transport sediment and nutrient to the steam with little opportunity for interception by riparian vegetation (Weller *et al.*, 1998). To mitigate the effects of gaps, riparian zones may need to be wider than average recommendations, which are usually based upon uniform buffer strip performance with no micro-topographic convergence points. Consistent with these findings, a meta-analysis by Mayer *et al.* (2005) determined that a minimum native vegetated buffer width of 50m is required for consistent effective reduction of subsurface nutrients.

The accumulation of nutrients over time may reduce the efficiency of a buffer to remove these from surface and subsurface flows (Osborne and Kovacic, 1993, Lowrance, 1998). Nutrients retained in the riparian zone accumulate in vegetation over differing timeframes (short for non-woody, long for woody) but P cannot be removed by transformation as N is by denitrification. The ability of riparian zones to immobilise nutrients in woody biomass may also decline as the plants mature (Naiman and Décamps, 1997, Lowrance, 1998). Thus, plant immobilisation of excess nutrients (especially P) may be counter-balanced by senescence, litter-fall and decomposition (Muscutt *et al.*, 1993, Lowrance, 1998, McDowell *et al.*, 2004). Selective harvesting of woody vegetation, or fruits and nuts from riparian zone will facilitate permanent removal of P (Cooper *et al.*, 1995, Parkyn, 2004). Low intensity grazing of riparian zones may also facilitate removal of P in non-woody vegetation and may have the added benefit of reducing weeds (Burrows and Butler, 2001), but stock access to waterways increases direct nutrient inputs via manure.

***Removal of excess nutrients by wetlands:*** Wetlands are particularly good sinks for nitrogen owing to their hydric (poorly drained), highly organic soils and anoxic soil conditions, which all promote significant denitrification (Simmons *et al.*, 1992, Parkyn, 2004). While wetlands are an important source of nitrogen removal via denitrification (Vellidis *et al.*, 2003), they are also sinks for sediment and phosphorus (Barling and Moore, 1994). Barling and Moore (1994) report the results of a study, using $^{137}Cs$ test deposition in floodplain environments, where it was found that 50% of sediment was deposited in first 100m above the floodplain swamp (Cooper *et al.*, 1987). Vellidis *et al*. (2003) reported higher nitrogen-removal efficiencies than phosphorus-removal in a wetland riparian forest, due mainly to high denitrification rates. The retention of sediment by wetlands facilitates P removal, as does the uptake by aquatic plants, although this retentiveness decreases over time due to accumulation of organic solids (McDowell *et al.*, 2004). Mayer *et al*., (2005) have reported large variability in wetland buffer performance in reducing nutrient inputs, ranging from 1 m to 200 m (depending on flow path).

A remnant channel (billabong) of Arthurs Creek.

The Land and Water Fact Sheet (Price *et al.*, 2005) makes recommendations for riparian widths around wetlands, based upon legislative requirements from Western Australia, of 100 to 2000 m for the maintenance of water quality (including groundwater), and reduction of pollutant inputs. In Canada, recent research into the critical distance at which land use impacts degrade wetland water quality found significantly larger distances than those recommended by Australian agencies: water N and P was negatively correlated with forest cover up to 2250 m and sediment P levels were negatively correlated up to 4000 m (Houlahan and Findlay, 2004). As data from wetland systems in Australia relating to buffer widths are lacking, most recommendations will necessarily be based upon data from overseas studies and are clearly in need of targeted investigation. The importance of wetlands in nutrient cycling and improving water quality should not be understated, especially for dry regions of Victoria with highly variable rainfall.

Saline wetland. Murray Sunset rangelands

### *2.3.2 Increased shading and water temperature control*

Key points

- Riparian vegetation along small streams (order 1-3) exerts a strong influence on stream water temperature and primary productivity
- The slope of the riparian zone will alter the amount of shading provided by vegetation
- Riparian shading influences terrestrial microclimate over greater distances than it influences stream temperature (typically >45m)
- Riparian zone widths required to provide stream shading are typically 10-30m (slope dependent)

In headwater / low order streams (typically order 1-3) intact riparian zones are critical for regulating stream water temperature and in-stream primary productivity. Vegetated riparian zones are also important for maintaining terrestrial microclimatic conditions and soil temperatures.

The three characteristics of riparian zones that have the strongest influence on temperature are:

- vegetation extent (type, height and age, canopy cover);
- topography (slope); and
- aspect.

In-stream primary production is influenced by the amount of shading, and this varies with stream size. Small narrow streams receive relatively little direct insolation and thus, in-stream energy sources are reliant on allochthonous inputs from riparian vegetation. In larger, mid-order streams, riparian vegetation shading has lesser impact on stream temperatures and autochthonous primary productivity combined with organic matter imports from upstream is the dominant energy source (Vannote *et al.*, 1980). A recent meta-analyses by Battin *et al.*, (2008) does however, suggest that even in open stream sections, dissolved organic carbon (DOC) imported from upstream may strongly influence community production. The retentiveness of the floodplain and in-stream geomorphic features (especially woody riparian inputs) for imported DOC and the strength of the role of DOC in community production is still poorly understood (but see Gawne *et al.*, 2007).

The presence and longitudinal connectedness of intact riparian vegetation influences stream water temperature. Where streams flow through riparian zones with low / no shade to zones with high shade, substantial decreases in water temperature may be observed (Storey and Cowley, 1997, Rutherford *et al.*, 2004, DeWalle, 2008). Conversely, higher stream temperatures and greater temperature fluctuations are observed when riparian vegetation is removed or where streams move through pasture compared with forest (Quinn *et al.*, 1993, Quinn *et al.*, 1997). Spatial continuity is particularly important in maintaining water temperature, and rehabilitation measures will have limited downstream effect if they are spatially patchy (Pusey and Arthington, 2003). This is certainly true in Australian streams in both temperate and tropical regions, where water temperatures are found to be high where riparian vegetation has been removed and significantly lower where vegetation is intact (Rutherford *et al.*, 2004).


Algal growth resulting from full sunlight. Gnarkeet Creek.

Aquatic organisms may be highly temperature sensitive. Elevated in-stream temperatures directly affect aquatic biota through ecosystem respiration, which reduces dissolved oxygen availability and pH, (Davies *et al.*, 2004, Rutherford *et al.*, 2004). Some taxa are extremely sensitive to elevated temperatures, for example, mayfly larvae have upper lethal limits of around 22$^{o}$C (Davies *et al.*, 2004) and NZ stoneflies are unable to acclimatise to stream temperatures above 19$^{o}$C (Quinn *et al.*, 1994). Reductions in dissolved oxygen affect basal metabolic rate, and consequently, fitness parameters like growth and reproduction. Changes in thermal regime can impact fish reproduction and increased temperatures can also reduce their tolerance to other toxicants, e.g. ammonia (Pusey and Arthington, 2003).

Loss of riparian vegetation results in changes to in-stream autotrophy, which has subsequent indirect impacts on in-stream fauna and aquatic biodiversity. For example, in forested streams in New Zealand shade effects on algal biomass were the major cause of lower abundance of some invertebrates, notably midge larvae (Parkyn, 2004). Increased light levels also promote macrophyte growth, which can affect benthic habitat and invertebrate communities (Storey and Cowley, 1997, Parkyn, 2004). Microhabitat use by fish is influenced by changes in water temperature (Pusey and Arthington, 2003).

Both slope and aspect will vary the shading provided by the riparian zone; for instance, vegetation on steep slopes will provide more shading than gentle slopes (DeWalle, 2008). Steeply incised canyons may provide partial shading even in the absence of riparian vegetation (Vannote *et al.*, 1980, DeWalle, 2008). Some management guidelines include slope modifiers to their recommended buffer widths (Cummins, 1993, Wenger, 1999, Schwartz, 2006) and some studies report the effects of increasing slope on shading and other riparian functions (Dillaha *et al.*, 1989, Vidon and Hill, 2004a). Barling and Moore (1994) report the use of the equation riparian width (m) = 8 + 0.6 × slope (%), after Trimble and Sartz (1957), by soil conservation officers in Victoria. The Forestry Code of Practice designates a minimum buffer width of 30m for rivers having a high water quality risk and slope of 0-20$^{o}$, and 40m where the slope is 21-30$^{o}$ (DSE, 2007). In New Zealand, riparian buffers greater than 50m wide, and containing plantings older than 25 years, provided adequate canopy closure to improve invertebrate communities (Parkyn, 2004). In the US, a 30m buffer in forestry operations maintained temperatures within 1$^{o}$C of their former average (see Lynch *et al.*, 1985) and generally provides the same level of shading as old-growth forest (see Beschta *et al.*, 1987). The minimum width recommendation for the provision of adequate stream shading, summarised from the American literature, is 10m (Osborne and Kovacic, 1993, Wenger, 1999). Recent modelling work (in America) on riparian shading demonstrated that vegetation height: stream width ratios of 1.4 to 2.3 provided 75% (or more, depending on overhang angle) shading to streams at latitude 40$^{o}$ (DeWalle, 2008).

In addition to stream water temperatures, intact riparian vegetation also affects microclimatic variables like humidity and surface and soil moisture (Naiman and Décamps, 1997), which affects the amount of moisture available for plant growth and microbial processes like denitrification. In their work on riparian buffers in the West Tarago River catchment in SE Victoria, Dignan and Bren (2003) found significant light attenuation at around 10m from the stream edge, dependent on stream aspect. There was no significant effect detected on south-facing edges, but there were significant effects detected beyond 80m on north-facing edges. This will be relevant when considering minimum riparian zone widths, as a width of, for example, 10m may provide enough shading for in-stream processes, but a larger width may also regulate the riparian forest microclimate (hence soil and surface temperature, and evapotranspiration; Naiman and Décamps, 1997), which relates to riparian plant diversity and consequently, terrestrial faunal diversity. This was found to be the case in a study in western Washington, where riparian buffers needed at least 45m wide (on moderate to steep slopes) to maintain natural microclimatic conditions (Brosofske *et al.*, 1997).

### *2.3.3 Carbon and prey inputs/outputs*

Key points

- Organic matter inputs (from the riparian zone) are important to in-stream productivity
- Single (mature) tree riparian widths may provide some carbon inputs to small streams but are subject to damage and / or loss due to windthrow
- Standing stocks of POM and DOC in floodplains are mobilised during flood events and may make significant contributions to in-stream productivity
- Long-term retention of carbon by floodplains between flood pulses is not well quantified and may be related to riparian extent
- Widths for provision of food inputs vary between 5 and 30m

Riparian areas are the dominant contributor to aquatic food webs (Cummins, 1974, Gregory *et al.*, 1991, Knutson and Naef, 1997) in streams. Riparian vegetation is an important source of particulate organic matter (especially carbon) inputs to streams, as well as controlling inputs of dissolved and particulate organic matter from upslope environments (Quinn *et al.*, 1993). Organic matter inputs from the riparian zone include leaves, twigs, fruits, flowers and invertebrates (especially insects). These inputs contribute to:

- allochthonous carbon and prey subsidies to stream food webs
- facilitation of in-stream nutrient cycling

Organic carbon, generated principally from plant matter growing in the riparian zone, is crucial to in-stream nutrient cycling and retention (carbon availability dictates bioavailability of N and P), and represents an essential basal resource for many stream food webs. Carbon can enter aquatic ecosystems as dissolved organic carbon (DOC) or particulate organic carbon (POC), with the former making the largest contribution to terrestrial-aquatic carbon fluxes (Battin *et al.*, 2008). DOC is an important source of C for stream heterotrophs and, in many systems, bacteria and fungi may be carbon limited (Bernhardt and Likens, 2002).

Carbon inputs from upstream reaches (which are predominantly allochthonous) subsidise higher order downstream reaches, where the majority of organic carbon is metabolised (Naiman et al 1987). Consequently, the relative importance of coarse particulate organic matter (CPOM) inputs to community consumption is theorised to decrease from low order to higher order streams (Vannote *et al.*, 1980). In larger waterways, where shading exerts less influence on stream temperature, there is a shift from heterotrophy to autotrophy (primary production) and CPOM has been processed to fine particulate organic matter (FPOM) (Vannote *et al.*, 1980). Testing of this concept along free-flowing lowland sections of the Murray River ($8^{th}$ order stream at this point) revealed shifts between heterotrophy and autotrophy influenced by seasonal riparian inputs in different reach sections and by flooding (Gawne *et al.*, 2007). Seasonal riparian inputs and flooding potentially contribute significant inputs of DOC and unprocessed POM to community productivity (Gawne *et al.*, 2007). Flood pulses facilitate lateral transactions of OM between the river and its fringing floodplains (Flood Pulse Concept: Junk *et al.*, 1989) which results in long-term retention by the floodplain relative to in-stream storage (Battin *et al.*, 2008). In Australian systems, the storage capacity of intact riparian floodplain vegetation between flood pulses is poorly quantified.

In the northern hemisphere, stream invertebrates that consume riparian litter (shredders) are closely tied to the timing of litterfall and to the conditioning process by microbes and leaching (Cummins *et al.*, 1989). Shredders (which include amphipods, stoneflies, and some caddisflies, dipterans and mayflies) convert CPOM to FPOM, which subsidises other feeding guilds (e.g. collectors) or is exported downstream (Vannote *et al.*, 1980, Cummins *et al.*, 1989).

In Australia, leaf litter inputs experience peaks in summer in contrast to northern hemisphere where peaks occur in autumn (Boulton and Lake, 1992, Reid *et al.*, 2008a). However, Australian summer inputs are less pronounced than Northern Hemisphere autumnal inputs (Reid *et al.*, 2008a). In some Victorian streams there is a distinct peak in benthic detritivores, collectors-gatherer and shredder densities that coincides with summer peaks in standing stocks of benthic organic matter (BOM) and seasonal cessation in discharge in temporary streams (e.g. Boulton and Lake, 1992). Where Victorian streams drain pasture catchments instead of forested catchments, litter accession to the stream is much lower (Campbell *et al.*, 1992). The abundance of CPOM and shredders is more closely correlated in New Zealand streams that drain indigenous forest than those draining tussock grassland (Quinn *et al.*, 1993) emphasising the importance of riparian detrital inputs to macroinvertebrates.

Riparian production substantially subsidises aquatic food webs (Baxter *et al.*, 2005, Ballinger and Lake, 2006). Nakano and Murakami (2001), Baxter *et al*., (2005) and others have shown that stream food webs can be dramatically altered if prey in the form of terrestrial invertebrates is limiting. Equally as strong influences occur in the other direction with many studies showing how riparian spiders, birds, invertebrates and bats benefit from prey derived from aquatic sources such as adult macroinvertebrates (examples in Baxter *et al*., 2005; see also Sabo and Power, 2002, Burdon and Harding, 2008). Reciprocal subsidies will be particularly important where one habitat is depauperate in resources compared with the adjacent habitat (Polis *et al.*, 1997). This may vary seasonally (for example, emergent aquatic insects provide a food source for birds) and with flooding events (Ballinger and Lake, 2006). In the case of the latter, transferral of aquatic-terrestrial subsidies will rely on the spatial extent of the receiving riparian zone.

Few management recommendations for riparian widths necessary to provide adequate food inputs have been made for Australian streams. Land and Water Australia recommends a minimum of 5 to 30m for food inputs and shading (combined), however they advocate increasing those widths to ensure the longevity of restoration efforts (Price *et al.*, 2005). Management recommendations from US studies of food inputs have minimum widths of around 10m (Naiman and Décamps, 1997, Fischer and Fischenich, 2000).

In Victoria, tree removal has resulted in significant reductions in benthic detritus available to in-stream biota (Reid *et al.*, 2008a). A minimum canopy cover along these streams of 50% provided a reliable supply of labile terrestrial detritus, as well as providing shading to streams and control of water temperature (Davies and Bunn, 1999, Reid *et al.*, 2008a). Where the majority of wooded riparian vegetation consists of large spreading trees (e.g. river red gum *Eucalyptus camalduensis*, Reid *et al*., 2008), the minimum number of mature trees required to provide 50% canopy cover or more may be at least one tree on each bank. However, single trees may be prone to collapse and extensive damage from weather in the absence of adjacent vegetation (Lindenmayer *et al.*, 1990, Welty *et al.*, 2002). Clearance of upslope vegetation can result in wind speeds over an order of magnitude higher at riparian buffer edges (Brosofske *et al.*, 1997), which will exacerbate degenerating processes on old streamside trees, especially in the absence of recruitment. Therefore, in the red gum example, a minimum width consisting of two-three mature trees might exceed 50m.


Faithful Creek. Photo: P. Reich

### *2.3.4 In-stream habitat*

Key points

- Inputs of wood and wood fragments to streams, especially small-medium sized streams, are important for flow mediation and sediment deposition
- Variable flow and retentive structures (tree roots, branches and wood) provide microhabitat heterogeneity
- Riparian zones need to be 30m or larger to provide sufficient wood inputs to streams

Aquatic biodiversity is dependent on the provision of suitable in-stream habitat. Contributions of coarse wood from the riparian zone maintains channel geomorphological complexity, mediates flow and disturbance regimes, and retains sediment and organic matter in transit from upstream, all of which improve habitat heterogeneity and facilitate biochemical processes. Major habitat components contributed by the riparian zone are:

- wood and woody fragments from riparian vegetation
- tree roots and branches of vegetation on the stream bank

Wood fragments, tree roots, branches and whole trees are major structural components in streams and rivers (Campbell 1993, Naiman *et al*., 2005). By providing disruptions to flow, woody structures create variable flow conditions and in doing so, create variable microhabitats (that is, increased habitat complexity including pool-riffles and scour pools). They also provide other functions including inducing deposition of sediments (which facilitates nutrient cycling by increasing retention time), maintenance of bank stability (which also provides habitat for aquatic organisms), channel migration through aggradation / degradation and stable surfaces for important biofilm growth (Rounick and Winterbourn, 1983, Gregory *et al.*, 1991, Cummins, 1993, Naiman and Décamps, 1997, Pusey and Arthington, 2003, Battin *et al.*, 2008). Importantly, the retention of sediments and organic matter influences water chemistry, which affects carbon, oxygen and other elemental bioavailability (Lester and Boulton, 2008).

The accumulation of wood fragments in channels (debris dams) retains sediment and organic matter, which creates pools and areas of low flow and shelter for fish and invertebrates (Campbell 1993). The addition of wood to floodplain lagoons of the Normanby River (in the

Australian wet tropics) provided refuge for barramundi and fork-tailed catfish, which altered overall assemblage composition (Pusey and Arthington, 2003). On Murray River floodplains, coarse (large) wood is important for the retention of CPOM and other forms of finer debris, increasing microhabitat complexity as well as providing in-stream refuges when the floodplain in inundated (Mac Nally *et al.*, 2002).

Tree branches and root systems act in a similar fashion to wood fragments by increasing the variability in current and the complexity of microhabitats. Woody structures are also important for fish spawning and larval habitat (Pusey and Arthington, 2003). Coarse wood creates debris dams, pool habitats and pathways for movement of native fish in undisturbed, sand-bed, forest streams in East Gippsland (Webb and Erskine, 2001). A proportion of coarse wood at one location was contributed by living plant material, in the form of *Tristaniopsis laurina* trees within the channel. Debris dams also provide habitat for riparian-obligate mammal species like platypus (Menkhorst, 1995). Freshwater mussels in the Hawkesbury-Nepean Rivers most commonly occurred in silt areas stabilised by boulders, tree roots and the bank profile (Brainwood *et al.*, 2006). Tree root masses tend to be associated with undercut banks, which are used by fish species like gudgeons, catfish, grunters and eels (Pusey and Arthington, 2003) and provides protection from avian predators and flood events (Hughes *et al.*, 2007).

Wood is especially important where the channel bed is silty or sandy, as it will provide sites suitable for retention of benthic organic matter and development of biofilms and thus, attract invertebrate consumers and sustains macroinvertebrate communities (Campbell, 1993, Pusey and Arthington, 2003, Lester and Boulton, 2008, Lyon *et al.*, 2009). In sandy river systems in south-west WA, addition of coarse wood had a positive impact on native fish and macroinvertebrate biodiversity during low flows (Till *et al.*, 2001).

Land and Water Australia recommends riparian zone widths of 5-10m for providing food inputs and aquatic habitat (Price *et al.*, 2005). In the US, a review of studies into riparian wood inputs found that the majority was recruited from forest growing within 45m of the stream (Knutson and Naef, 1997). Management guidelines from the State of Georgia recommended riparian buffer zones of at least 15m for maintenance of large wood inputs (Wenger, 1999). Other studies investigating coarse wood inputs from riparian zones for the provision of in-stream habitat have found widths varying between 30 and 87m adequate (Erman *et al.*, 1977, Murphy and Koski, 1989, Van Sickle and Gregory, 1990) (May 2000). See Appendix 2 for more details.

Davies and Nelson (1994) in their studies on riparian buffer widths in logging coupes in Tasmania stated that small buffer widths (<10m) were not adequate to protect a stream from the impacts of canopy modification and the consequent changes in algal, macroinvertebrate and fish biomass and diversity. Growns and Davis (1991) found buffers of 100m along streams in logged catchments in south-western WA were sufficient to maintain macroinvertebrate assemblages, and questioned the value of narrower buffers. Similar work by Newbold *et al*., (1980) in Canadian forest streams found buffers greater than 30m resulted in significantly higher macroinvertebrate diversity compared with steams without buffers.


Bendigo Creek. Photo: P. Reich

### *2.3.5 Terrestrial habitat*

Key points

- Intact riparian zones provide refuge, foraging and breeding habitat, and migratory pathways for riparian-obligate and generalist taxa
- Intact riparian zones maintain soil moisture and humidity, and facilitate interactions between groundwater, surface flows and subsurface flows
- Riparian zones experience high levels of disturbance from flow regimes and flood events, which continually reset vegetation communities and create highly heterogeneous riparian floristic structure
- Establishment of minimum widths for generic biodiversity outcomes risks under-protection of multiple landscape elements important for the persistence of populations of different animal taxa during different life history stages (e.g. widths for adult amphibians may be too small to accommodate dispersing juveniles)
- Typical riparian widths for the provision of avian habitat in North America vary from 75-300m, and for reptiles and amphibians, from 30-400m
- Riparian avian communities may extend up to 1 km into adjacent uplands
- Data for riparian use by Australian terrestrial fauna are lacking (especially for mammals)

Riparian zones are frequently noted for their higher terrestrial biodiversity value than the surrounding landscape. This may be attributed to the generally greater availability of water (Catterall, 1993). Water availability influences habitat complexity by promoting a mosaic of different vegetation communities in multi-aged stands, which subsequently promotes diversification in other terrestrial communities. Furthermore, the relatively high disturbance environment of fluvial systems contributes to the production of diverse plant communities containing species ranging from flood-tolerant to flood-intolerant. This also creates variable habitats for biota, driving niche specialisation and ultimately increasing regional species diversity (Sabo *et al.*, 2005).

Riparian zones maintain terrestrial biodiversity by:

- providing refuge, foraging and breeding habitat, plus movement corridors for riparian-obligate and generalist taxa
- maintaining soil moisture and humidity
- interactions with groundwater, surface flows and subsurface flows

Intact riparian vegetation also facilitates microbial nutrient cycling via its influence on soil and surface microclimate (Cooper *et al.*, 1995, Brosofske *et al.*, 1997).

As one moves upslope, the vegetation community changes, reflecting the decreasing impacts of disturbance regimes from flooding. Flooding can reset plant communities by removing existing, disrupting soils, dispersing propagules (Ward *et al.*, 2002, Siebentritt *et al.*, 2004) and initiating the germination of soil stored seed banks (Capon, 2007). Flood waters shape geomorphic patterns of the riverine corridor (Naiman and Décamps, 1997). Old floodplain terraces and levees increase riparian soil and microclimate heterogeneity promoting bio-diversification (Gregory *et al.*, 1991, Ward *et al.*, 2002).

The availability of water is critical to riparian plant diversity, and variability in precipitation and flow, especially during dry spells and droughts, determines the broad-scale patterns of floodplain forest development (Ward *et al*., 2002). The relatively constant supply of water in riparian compared to upslope zones allows proliferation of a greater array of plant types (Naiman *et al*., 2005). These include species that invade following disturbance events, those that either endure or resist flooding and those that are flood-intolerant (Naiman and Décamps, 1997). This creates highly heterogeneous vegetation communities, which contributes to the generally higher levels of local and regional diversity in riparian zones.

Intact riparian zones harbour different faunal species pools ($\beta$-diversity) compared with upslope zones and therefore contribute significantly to increased species richness ($\gamma$-diversity) in the catchment (Knopf and Samson, 1994, Catterall *et al.*, 2001, Sabo *et al.*, 2005, Johnson *et al.*, 2007, Clarke *et al.*, 2008). They are important for faunal diversity, in terms of habitat for obligate riparian species, for species seeking edge habitats and for species associated with early successional stage vegetation (Catterall, 1993). The degree of use by residents, breeders, visitors and transients will depend on the resources the riparian zone provides, the seasonal (or climatic) variation in those resources and the landscape context of the riparian zone (intact, partially modified or cleared).

Riparian areas tend to provide a greater variety of specific food resources (e.g. greater insect abundances) and higher primary and secondary productivity (due to greater availability of water and nutrients) than upslope areas (Catterall, 1993). The provision of resources for other taxa not only contributes to local and regional biodiversity, but also provides ecosystem services via pollination, insectivory, provision of vectors (for movement of propagules and other material), trophic subsidies and refuges for threatened species. Furthermore, by promoting diverse vegetation communities containing species that presumably have different nutrient retention capabilities, riparian nutrient interception and processing efficiency may be higher.

*Birds*

Birds are important to any ecosystem, and riparian zones are no exception. By virtue of their mobility and prevalence in all landscape types, birds provide ecosystem services to riparia including pollination, dispersal and insectivory. Riparian-obligate avifauna is not common in Victoria, and the use of riparian zones tends to be in the form of visitation for food and water resources (and nesting, although this is not restricted to riparian zones) and by migratory, transient or irruptive species. In tropical regions of Australia, generalist, forest resident and forest seasonal migratory species will tend to occur in greater numbers in riparian zones compared with non-riparian bushland or pastoral zones (Bentley and Catterall, 1997). Some waterfowl species (e.g. wood ducks) will use wooded riparian zones as breeding sites, but the majority of waterbirds are associated with wetlands and flood-tolerant wetland vegetation. Thus, maintenance of off-stream waterbodies containing intact wetland and wetland-riparian vegetation is critical for reproductive success of waterbirds. Both wetland vegetation and waterbird breeding are tied closely to flooding regimes. However, as most waterbirds are transient to some extent, their dependence on local riparian and wetland condition may not be as great as for other less-mobile species (e.g. frogs and salamanders).

Red-kneed Dotterel. Hattah Lakes

Bird assemblages may vary greatly between riparian and upland zones, depending on catchment climate. This is especially true in the Americas where riparian zones, which constitute around 1% of the landscape, harbour up to 80% of resident breeding avifauna (Knopf and Samson, 1994). While North American riparian zones were found to contain distinct avian assemblages compared to adjacent uplands, riparian arid-zone avian communities were found to extend up to 0.6 - 1.0 km into uplands from the stream edge (Szaro and Jakle, 1985). Bird assemblages in forest riparian mosaics of south-east Australia harbour significantly greater species richness and abundance than adjacent non-riparian sites (Palmer and Bennett, 2006). In the massively-altered agricultural landscapes of central Victoria, riparian vegetation is a key element for avian diversity and contributes to increased $\gamma$-diversity (Johnson *et al.*, 2007).

Only a small number of Australian studies have been conducted that relate avian riparian use to riparian zone width, but the widths reported are similar in magnitude to those from overseas studies (i.e. usually large). Wide fenced riparian zones (51-220 m) were found to contain greater species diversity than narrow fenced zones (8-50 m) in Queensland tropical savannas (Bengsen and Pearson, 2006). Recommendations for protecting riparian zone widths for bird (and other wildlife) communities in south-east Queensland are up to 100m (Catterall, 1993). In southern and eastern Australia, avian diversity is negatively influenced by the presence of noisy miners (Martin *et al.*, 2006), and wide riparian zones (300m or more) may be required to maintain diverse avian communities when noisy miners are present (Clarke and Oldland, 2007).

In North America, various studies have attempted to quantify riparian zone widths necessary to support breeding birds (usually water fowl, raptors, kingfishers and neotropical migratory passerines). These widths tend to be quite large, varying from 75m up to 300m (summarised in Knutson and Naef, 1997; see Appendix 2 for details of these studies).

### *Reptiles and amphibians*

Reptiles and amphibians exhibit variable dependence on riparian zones and local hot spots of high herpeto-diversity may coincide with specific riparian habitat characteristics (Wenger, 1999). In northern Italy, forest cover, road density and hydrographic network were found to have an additive influence on three amphibian species, but at different spatial scales and for different functions (Ficetola *et al.*, 2008). Suitable terrestrial habitat for adults required intact riparian zones extending between 100 and 400m from the wetland, but for the maintenance of meta-population structure that allowed the dispersal of juveniles, intact landscapes needed to extend up to 1500m from the wetland edge. This study highlights the importance of considering multiple landscape elements when defining riparian zone limits for different taxa or life history stages within taxa, in this case, for buffering amphibians from the modifying impacts within the catchment.

Reciprocal subsidies are important for energy transfer between aquatic and terrestrial systems, and are influenced by the quality and extent of habitat in each. In Californian streams with cobble bars between the water and the riparian vegetation, emergent aquatic invertebrates are an important food source for riparian lizards and subsidise terrestrial arthropods like spiders (Sabo and Power, 2002). Exclusion of aquatic invertebrates from riparian zones was found to impact upon lizard growth rates in early summer. Furthermore, the reduction in availability of aquatic invertebrates resulted in an increase in predation by the lizards on terrestrial invertebrates (Sabo and Power, 2002).

Microclimatic conditions in riparian vegetation may influence the distribution and abundance of amphibian and reptile taxa. For example, in south-east Queensland, riparian floristics and elevation were found to significantly influence the composition of frog assemblages, and sufficient stream water retention time was required for tadpoles to develop to metamorphosis (Parris and McCarthy, 1999). Burrowing frogs produce a semi-pervious cocoon which protects them from dehydration during floodplain dry periods (Lee and Mercer, 1967). Soil moisture is important to preventing gradual evaporation from cocoons and is presumably dependent upon subsurface floodplain hydrology. Several other animal taxa are also adapted to specific microclimate variables such as cooler temperatures, higher humidity and reduced wind velocity, humidity and cooler air (Brosofske *et al.*, 1997), which are influenced by riparian vegetation. Brosofske *et al*., (1997) found microclimate influences up to 45m from the stream edge in North America, and significant changes in microclimatic variables up to 300m away. In other forested ecosystems in North America, edge effects persisted for 95 to 160m into the forest interior (Harris, 1984, Franklin and Forman, 1987, Chen *et al.*, 1992).

Studies from North America have determined riparian widths of 30m are adequate for the provision of habitat for terrestrial and stream invertebrates (Erman *et al.*, 1977, Newbold *et al.*, 1980, Gregory *et al.*, 1987) and of 30-95m for reptiles and amphibians (Rudolph and Dickson, 1990).

### *Mammals*

Australian mammals tend to be visitors or transients to riparia, primarily for access to water and riparian food resources, rather than being obligate residents as is the case in many other countries. The most notable exceptions are the platypus *Ornithorhynchus anatinus*, the water rat *Hydromys chrysogaster*, and the large-footed myotis *Myotis adversus* (Menkhorst, 1995). In addition, alluvial floodplains of the Murray River may be critical to the continued presence of the paucident planigale *Planigale gilesi* in north-western Victoria, where it is found to coincide with cracking clay soils that have not been trampled by stock (Menkhorst, 1995).

The lack of ecological information about floodplain-obligate vertebrates like reptiles and *Hydromys* (Kingsford, 2000) hinders assessment of their importance in floodplain function. In sub-tropical forests in NSW where logging operations are conducted, riparian bat activity is influenced by the presence of buffers (Lloyd *et al.*, 2006). Arboreal and scansorial mammals will make use of suitable nest trees in riparian zones where they exist, but hollow-nesting species are not restricted to these environments.

Wildlife exerts an important influence on riparian zones including biophysical and habitat modifications, through activities like herbivory and burrowing, which may convert habitat from macro- to meso-patches (Naiman and Rogers, 1997). For example, in North America beavers are important ecosystem engineers: by building debris dams they contribute to retention of nutrients, nutrient cycling and provision in-stream habitat features (Naiman and Rogers, 1997).

In Australia, the decline and extinction of small mammals has been implicated in the reduction in soil quality, coincident with increases in hard hoofed animals (Martin, 2003). Through their action in the soils (burrowing, digging, and other forms of soil disturbance) mammals increase topsoil formation and infiltration, as well as moving seeds and mycorrhizal fungi (Martin, 2003). In Australia, the role mammals play in riparian form and function is largely overlooked and may contribute to soil seed bank maintenance and dispersal of plant propagules. Conversely, the declines or absence of small scansorial and soil-fossicking mammals from modified dry regions of Victoria (Menkhorst, 1995, Lada and Mac Nally, 2008) may be related to impoverished soil seed banks (Siebentritt *et al.*, 2004) or to altered patterns of dispersal and germination (Williams *et al.*, 2008b). Therefore, the maintenance of suitable riparian vegetation, as well as connecting remnant patches, for small mammal habitat should be considered when designating riparian zone widths.

### *Aquatic organisms*

Riparian vegetation is also important to aquatic animals, especially during periods of flooding and high flows. Stream invertebrates use riparia as breeding habitat when they emerge from the stream as adults (Quinn *et al.*, 1993, Wenger, 1999). Some stonefly species use food resources from within riparian zones (e.g. nectar) and may play a role in pollinating riparian plants (Smith and Collier, 2000). Dispersal distance travelled by adult aquatic insects can be considerable (>100m) (Collier and Smith, 1998) and is influenced by vegetation cover. Riparian zones influence longevity of adults of some taxa by regulating temperature and humidity (Collier and Smith, 2000). Psephenid beetles, which have aquatic larvae, reside in the riparian zone as adults and leptocerid caddisflies use the riparian zone to breed (Towns, 1983). Despite the importance of riparian zones to aquatic animals, there is relatively little information available to determine the width of riparian zones necessary to maintain these species/taxa, especially in Australia.

### *2.3.6 Bank stability and erosion control*

Key points

- Intact riparian zones are required to maintain bed and bank stability via structural reinforcement of soils
- Loss of riparian vegetation can result in excessive mobilisation of sediments
- Stock access to riparian zones exacerbates sedimentation
- Existing Australian guidelines set a minimum riparian buffer width of 5m for erosion control, which is modified by adding the height of the bank plus the time taken for vegetation to mature (likely to be 100 years or more for species like river red gum) adjusted by the erosion rate
- International studies recommend wider buffer widths for controlling erosion, varying from 10m in New Zealand to 30m in North America
- Riparian zone widths of between 15 and 55 m are necessary to provide woody inputs for in-stream sediment retention

Intact riparian zones are critical to maintaining bed and bank stability, and mediating erosion. This is achieved through structural reinforcement by vegetation roots, maintaining moisture in soils (preventing drying out and failure), providing groundcover which protects soils from sub-aerial erosion (from rainfall or wind) and by decreasing overland flow velocity (Gregory *et al.*, 1991, Nguyen *et al.*, 1998, Abernethy and Rutherfurd, 1999, Prosser *et al.*, 2001). Erosion and subsequent sedimentation result in:

- increased bed sediment loads, smothering benthic habitats
- increased turbidity, altering nutrient processing and primary productivity
- altered hydrology

Tree root masses bind soils, which helps to prevent slumping and maintain the structural integrity of the bank. Inputs of wood also maintain bank stability as well as in-channel heterogeneity, and loss of woody debris through de-snagging and reduced terrestrial inputs from riparian vegetation may result in bank incision, stream expansion and homogenisation of channel morphology (Campbell, 1993, Brooks *et al.*, 2004). Removal of riparian vegetation can increase bank erosion by up to 30 times (Naiman and Décamps, 1997).

In Australia, extensive river improvement works were conducted in the early-mid 20$^{th}$ century, which involved removal of snags, removal of native vegetation and channel straightening (Zelman, 1977, Erskine, 2001, Brooks *et al.*, 2004). To address ensuing erosion problems, thousands of exotic willows were planted to stabilise banks (Webb and Erskine, 2003, Brooks *et al.*, 2004). This has ultimately doubled the difficulties faced by stream managers: willows also have several negative environmental effects which has led them to become a declared environmental weed (Holland-Clift and Davies, 2007) and has prompted their removal, which must be coupled with native plantings and short-term bank stabilisation works.

Erosion in headwater areas makes a disproportionately high contribution to waterway sedimentation and elevated nutrient levels (Lowe and Likens, 2005, Naiman *et al.*, 2005). Ephemeral streams also contribute large amounts sediment and nutrients that are mobilised during storm events (Wenger, 1999, Fisher *et al.*, 2004). As noted by Runge (1977), local erosion control works carried out where the majority of silt is delivered from the catchment upstream have been a costly and pointless exercise.


Severe erosion. Back Creek. Photo: P. Reich

Exposed and compacted soils are highly susceptible to erosion by overland flow (Nguyen *et al.*, 1998). Stock access to riparian zones causes soil compaction and damages riparian vegetation, causing destabilisation of the stream bank (Nguyen *et al.*, 1998, Parkyn, 2004) and reducing the retention of sediment during overland flows. Channelised flows are proliferated by the lack of groundcover vegetation (which convert concentrated flow to sheet flow when groundcover is continuous), thus increasing delivery of sediment to the stream. Grazing in forested catchments of Gippsland with grassy valley floors has caused massive incision of valleys due to gully erosion (Prosser *et al.*, 2001). In New Zealand, riparian zones 10-13m wide are recommended for sediment removal from channelised flows (through retired pasture) (Parkyn, 2004).

Given the biodiversity implications of degraded riparian zones (Section 2.3.5) in addition to the need to stabilise streambanks, erosion control is best achieved by restoring indigenous vegetation to the riparian zone. The exclusion of livestock is critical to protect seedlings and saplings, and allow regeneration. Abernethy and Rutherfurd (1999) recommend a basic setback width of 5m in addition to two modifiers: one for height of bank and another for establishment of plantings (age to maturity of plantings adjusted by the erosion rate). Land and Water Australia's recommendations for reducing streambank erosion, following Abernethy and Rutherfurd (1999), are 5-10m (Price *et al.*, 2005). In North America, riparian widths required to control bank erosion (in the context of habitat for salmon) vary between 30-38m (Knutson and Naef, 1997). An analysis of riparian buffer width guidelines from different jurisdictions in North America showed that width recommendations typically ranged between 15 and 60m (slope dependent) to control sedimentation (Lee *et al.*, 2004). An extensive literature review by Wenger (1999) produced an overall minimum width recommendation of 30m for the purposes of erosion control. The difference in width recommendations from North America compared to Australia lies in the management basis for those recommendations, which in America are more broadly focussed on delivering waterway quality outcomes rather than defining and addressing only single objectives.

All channels will naturally erode and migrate, even if waterways and riparian zones are unmodified. On this basis, Wenger (1999) recommends that the riparian buffer zone should extend at least to the edge of the active (100-year) floodplain to best achieve long-term bank stability (Wenger, 1999). Historic erosion (from first clearance of the floodplain in the early 1800s to commencement of river training works in the mid 20$^{th}$ century) along Williams River (NSW) has resulted on the retreat of the stream bank by 120m (Erskine, 2001). This clearly demonstrates the need to incorporate greater riparian widths than many of the minimum recommendations outlined above if lateral channel movement is to be accommodated over long time periods.

### *2.3.7 Connectivity*

Key points

- Hydrological flow paths are influenced by riparian vegetation, which in turn, influence riparian zone function through efficient delivery of water, energy and propagules
- Lateral hydrological connectivity is provided by flows but is mediated by vegetation
- Longitudinal hydrological connectivity is related to discharge, but is regulated by unmodified headwater catchments
- Structural and functional connectivity between fragmented populations of non-mobile taxa may be strongly influenced by the presence of intact and continuous riparian zones
- Riparian connectivity with vegetation in the surrounding hinterland may be necessary for taxa that use riparian zones on a transient basis or during particular life history stages
- Riparian corridors for North American migratory species (usually birds and mammals) are typically between 100 and 200m
- The role of riparian zones in providing movement corridors in unmodified Australian landscapes is poorly quantified

Connectivity can be defined as pertaining both to hydrology (flow paths of water and water-borne energy and matter) and to terrestrial contiguity of vegetation and populations of fauna. Indeed, hydrological and terrestrial flow paths (e.g. dispersal of biota) may be correlated (Fisher *et al.*, 2004). Riparian terrestrial connectivity may be defined by the amount and configuration of vegetation in the landscape, but may also be defined by the connectivity of faunal populations that are linked to those vegetation communities. Hydrological connectivity will be maintained by natural flow regimes and cycles of flooding.

*Hydrological connectivity*

Hydrological connectivity is critical to sustaining riverine landscape diversity (Vannote *et al.*, 1980, Junk *et al.*, 1989, Ward *et al.*, 2002, Fisher *et al.*, 2004). Riparian vegetation influences hydrological connectivity primarily through its mediation of flow paths, namely:

- overland and subsurface flows

- flood attenuation
- bankfull discharge
- groundwater discharge and recharge
- catchment discharge

The riparian zone facilitates transactions of water and its dissolved load to and from the stream and the uplands (Naiman *et al.*, 2005). Its interaction with incoming water is important not only to nutrient removal and processing, but also to the attenuation of flooding and subsequent runoff during flood recession. The riparian zone, by virtue of its width to the geomorphic floodplain extent, is the best means of flood attenuation (Ward *et al.*, 2002, Horn and Richards, 2007).

Longitudinal hydrological connectivity is provided by the frequency, timing and duration of flow events and is moderated by channel bedform and woody inputs from an intact riparian zone. The presence of vegetation alters in-stream hydraulic effects on channel morphology, including lateral and longitudinal channel migration. Wood plays a major role in shaping the geomorphic features of floodplains and the different channel forms (straight, meandering, braided and anastomosed) are mediated by vegetation (Gurnell *et al.*, 2002, Ward *et al.*, 2002, Anderson *et al.*, 2006, Opperman *et al.*, 2008). Flow velocity is altered by the presence of woody structures like tree roots and branches (Gregory *et al.*, 1991, Anderson *et al.*, 2006). Experimental removal of wood was found to homogenise stream flow (Campbell, 1993), which thus modifies the bed profile through changes to sediment transport.

Intact vegetation in headwaters regulates catchment discharge. By moderating surface flow velocities and retaining water in soil layers, riparian zones regulate the baseflow component of streamflow as well as controlling catchment storm response (Bren and Turner, 1980, Ocampo *et al.*, 2006, Renöfält and Nilsson, 2007). In Susannah Brook catchment (WA), the interaction of the riparian and upslope aquifers is responsible for seasonal variation of stream baseflow (Ocampo *et al.*, 2006).

Hydrological connectivity (both longitudinal and lateral) is important in the dispersal of vegetative propagules, and riparian regeneration often requires the delivery of propagules from upstream source populations (Johansson *et al.*, 1996, Boedeltje *et al.*, 2004). Lateral hydrological connectivity delivers propagules onto the floodplain and may therefore be important for the re-establishment of impoverished or locally extinct populations, as is the case along degraded European rivers (see Francis and Gurnell, 2006).

In addition to physically influencing the successional dynamics of vegetation communities, lateral hydrological connectivity maintains streamside vegetation through the delivery of surface and subsurface water. This is not limited only to riparian vegetation, but will extend to vegetation communities beyond the limits of streamside zone. Spatial and temporal variations in riparian-upslope hydrological connections are important in the exchange of nutrients (especially nitrate: Ocampo *et al.*, 2006) and may be mediated by the presence of intact vegetation. Lateral surface and subsurface hydrological flow paths are influenced by riparian vegetation through plant interactions with soils, (e.g. by tree root channels) (Cooper *et al.*, 1995, Bramley *et al.*, 2003, Holland *et al.*, 2006). Removal or degradation of vegetation may impact the waterway-riparian-upslope bi-directional movement of water, which will have flow-on effects to nutrient and sediment transport and biogeochemical reactions performed by organisms (see Naiman *et al.*, 2005).

Information directly linking riparian zone widths to changes in hydrology is sparse (Lockington, 1992). Riparian width recommendations for sediment and nutrient control, and woody debris inputs are most relevant to hydrological considerations. As catchment hydrology influences riparian zone function, it is difficult to identify the cause and effect relationship between the two in the absence of specific studies that quantify the parameters important to groundwater-stream-riparian interactions (Lockington, 1992). In general terms, geomorphic and hydrologic functions are both performed by the same structural characteristics of riparia, for example, flow mediation and flood attenuation are maintained by the hydraulic resistance of wood and other riparian inputs.

A riparian "corridor" in a massively altered landscape. Photo: P. Reich

*Terrestrial connectivity*

Terrestrial connectivity may be either structural (continuous vegetation cover) or functional (gene flow between populations). The extent to which riparian zones provide for biological and ecological pathways that sustain plant and animal species throughout a region may be used as a measure of structural and functional connectivity (Fischer and Fischenich, 2000). Here, we explore more closely the role that intact riparian zones play in terms of maintaining terrestrial connectivity, whilst also noting that terrestrial and hydrological connectivity are closely related as they frequently fulfil the same function. Longitudinally connected riparian vegetation has been demonstrated to provide:

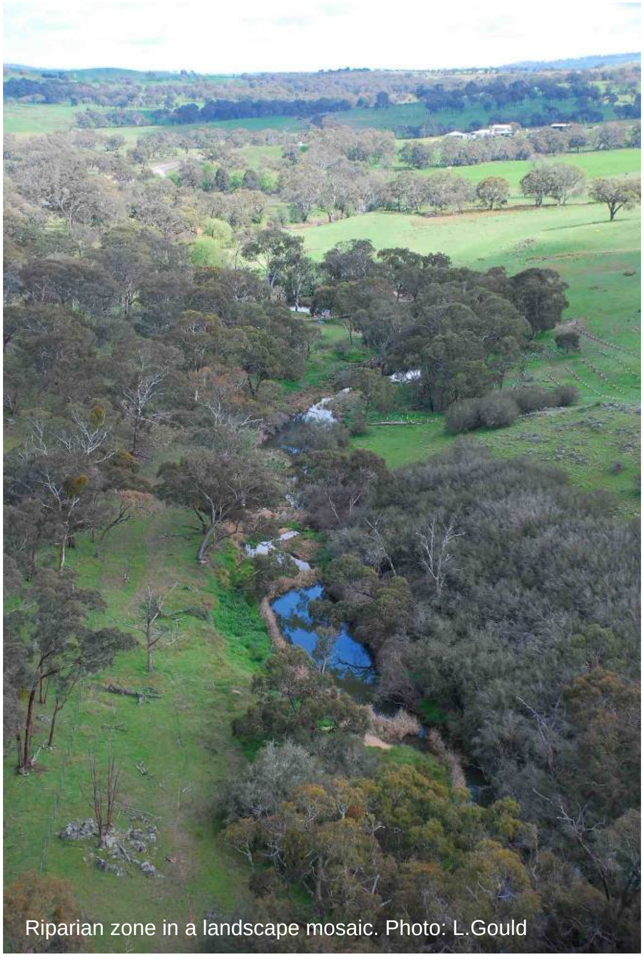
- migratory pathways
- connection between refugia and areas depauperate in biodiversity
- sources of dispersers including vegetative fragments and seeds (propagules), terrestrial invertebrates and vertebrates

Longitudinally intact riparian habitat may provide pathways for movement of wildlife. In North America they are used extensively by migratory species like birds (Lock and Naiman, 1998). Suitable habitat for movement generally requires very wide riparian zones with laterally-contiguous vegetation that extends beyond the immediate bounds of the streamside zone. In Australian forestry operations, riparian zones that are designated for the provision of wildlife corridors need to be 100 m wide (Dignan and Bren, 2003). Most studies conducted in North America have demonstrated that neotropical migrant birds, breeding water birds and breeding raptors, require very wide riparian zones, typically over 100m and up to 300m (Knutson and Naef, 1997, Fischer and Fischenich, 2000).

Where intact riparian zones exist upstream, they may provide an important source of plant propagules for downstream regeneration. The dominant flow paths for dispersal of propagules are either uni-directional via wind and water (hence, hydrological connectivity), or multi-directional via animal vectors (Johansson *et al.*, 1996, Boedeltje *et al.*, 2004). Regeneration may occur from patches of intact vegetation located in close proximity, especially if they are located upwind, upslope or upstream and contain an adequate soil seed bank (Naiman and Décamps, 1997, Boedeltje *et al.*, 2004). Where there is inadequate remnant vegetation located in close proximity, where the local soil bank is impoverished, as is the case along sections of the Murray River floodplain (Siebentritt *et al.*, 2004), and where propagule-delivering flows are reduced through river regulation, then it is insufficient to rely natural recruitment for re-establishment of riparian function. In this situation, native riparian vegetation may fail to self-recruit despite fencing for stock exclusion, and active management will be required to reinstate major parts of the plant community (Williams *et al.*, 2008b). Maintenance of vegetative structural connectivity will also facilitate zoochory (dispersal of propagules by animals).

In modified landscapes, structurally intact riparian zones may connect refugial animal populations and maintain gene flow (movement resulting in successful breeding) at levels sustaining locally isolated populations (Vignieri, 2005, Lada and Mac Nally, 2008). For highly mobile species like birds, re-connecting patches of vegetation via riparian restoration may be beneficial in some landscapes (Jansen, 2005). In the catchment of Western Port, roadsides and stream frontages are considered a priority for protection due to their role in maintaining movement corridors for vertebrate fauna in the modified agricultural and urban landscapes (Andrew *et al.*, 1984). In the United States, riparian zone widths necessary to achieve a corridor function (mostly for birds) varied between 46m to 183m (Freel, 1991, Knutson and Naef, 1997).

The degree to which riparian zones facilitate movement in un-modified landscapes is poorly quantified as few such landscapes exist and, where they do, data to support their role in landscape connectivity are lacking. It is tempting to assume that structural contiguity of vegetation is equivalent to functional connectivity between plant and animal populations (Arthington *et al.*, 1992), but the data providing widespread support for this notion are equivocal (refer to Labonne *et al.*, 2008). Species with low mobility may still exhibit population differentiation regardless of vegetation contiguity (Vignieri, 2005) and behavioural traits can also regulate population genetic structure (Pope, 1992, Dobson *et al.*, 1998) such that continuous habitat does not correlate with changes in population differentiation.



Riparian zone in a landscape mosaic. Photo: L.Gould

## 2.4 Major physical factors influencing riparian function

The geomorphic and hydrologic processes that shape the catchment (climate, soils, topography and flow regimes) form a physical template upon which riparian zones are constructed. Integral to this construction is riparian vegetation, which is the major regulator of riparian zone function. The origin (native versus non-native), habit (woody versus grassy), height, extent (width and length) and stand structure (single age versus mixed, young versus mature) of vegetation determines most of the functions that riparian zones perform. Consequently, physical factors that influence these characteristics dictate the effective width of the riparian zone.

### *2.4.1 Climate*

Climatic conditions are instrumental in the formation and function of riparian zones. Precipitation dictates catchment hydrology, the delivery of water to riparian ecosystems, erosion and consequent evolution of river systems (Gregory *et al*., 1991, Ward *et al*., 2002, Naiman *et al*., 2005). Australia has a highly variable climate, experiencing periods of drought and occasional flooding, which may transport high sediment and nutrient loads (Drewry *et al.*, 2006). Australian dryland rivers (receiving 500mm rainfall per annum or less) including many of those in the Murray-Darling system, have some of the most variable flow patterns in the world (Sheldon and Thoms, 2006). The variability of precipitation and discharge in high rainfall areas is much greater in Australia compared with many other parts of the world (Lake 1995, Drewry *et al*., 2006).

Dominant flow paths will vary between different regions with different rainfall. In dry (xeric) environments, overland flow is the dominant flow path for precipitation to the stream channel and groundwater recharge through the hyporheic zone (Rassam *et al.*, 2006). Water levels in larger streams are maintained by groundwater and lateral bank discharge rather than surface flows. Small streams experience drying periods that reduce surface water to small pools or remove it completely. In these environments, riparian vegetation (e.g. river red gums) may make use of infiltrating rainwater only opportunistically and tend to rely more on groundwater than stream water where the latter varies in its availability (Busch *et al.*, 1992, Mensforth *et al.*, 1994, Lamontagne *et al.*, 2005). In the case of river red gums on the

Chowilla floodplain, trees growing more than 15m from the stream did not use stream water, and instead accessed predominantly groundwater (Mensforth *et al.*, 1994).

In wet (mesic) environments, where precipitation is greater, the dominant flow paths are subsurface: overland flow is less common (Rassam *et al.*, 2006). Groundwater is shallower and hydrological connectivity between the riparian and upland zones is more frequent. It is conceivable that water use by vegetation may be predominantly interception of precipitation and infiltrating surface water, rather than by accessing deeper groundwater (as might be expected in drier climates where water availability is less reliable: see Naiman *et al.*, 2005, for further discussion about plant water sources).

The broad impact of climate on riparian functions may require climate to be considered when prioritising management objectives where dominant flow paths influence restoration efforts. For example, where rainfall in agricultural catchments (with substantial N and P exports) is high enough to result in frequent overland flows, riparian zones may need to be increased to allow for efficient sediment-trapping. The landscape setting and dominant management objective on-site will determine what adjustments for climate will be required.

### *2.4.2 Soils*

Soils exert a strong influence on riparian function. Hydrologic flow paths are influenced by soil structure, which subsequently influences nutrient processing, non-point source pollutant removal and post-flood soil salt-leaching (Bramley *et al.*, 2003, Drewry *et al.*, 2006). The substrate characteristics that influence riparian zone function are:

- soil particle size, nutrient adsorption, permeability
- surface and subsurface biogeochemistry
- underlying geologic materials (regolith, bedrock)

Nutrient cycling and microbial processes depend on soil moisture content, which is in turn, influenced by physical characteristics of the soil such as pore space and particle surface, each of which dictate flow paths and soil-nutrient interactions (Naiman *et al.*, 2005). The permeability of the substrate will influence water retention and therefore the opportunity for nutrient interception (Vidon and Hill, 2004b, Rassam *et al.*, 2006) and microbial interaction with water-born organic matter (Cooper *et al.*, 1995). Denitrification is highest in saturated, anoxic, fine particle soils, which limit pore size and reduce drainage (Mayer *et al.*, 2005). In sandy soils, hydraulic conductivity is higher and water residence time relatively short. In clay soils, where water retention is much higher, soil particles readily adsorb P and ammonium, making clay soils a more effective nutrient sink than sandy soils (McDowell *et al.*, 2004, Craig *et al.*, 2008).

The extent to which soil type and permeability is used to modify riparian zone widths will depend on restoration goals. If the goal is to improve water quality, and soils contain predominantly sand, riparian zones will need to be very wide to ensure adsorption of excess P (see McKergow *et al.*, 2003). Similarly, if the goal of restoration is to increase riparian microbial processing of excess nitrogen then soil organic matter and moisture will be important, and where they are insufficient, strategies to increase carbon and water retention time will need to be implemented, either by increasing the riparian zone width and / or planting deep-rooted, perennial vegetation.

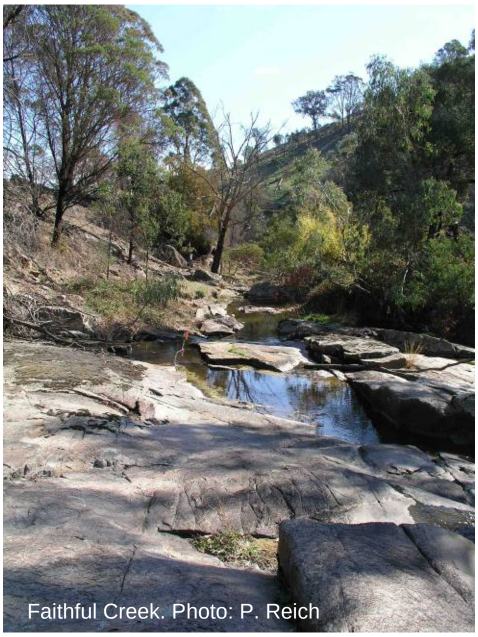
### *2.4.3 Topography and slope*

The topography (especially slope) and drainage area influences the hydrologic loading of the catchment, and thus, the delivery of sediment to the riparian zone via groundwater, subsurface and surface flow paths (Bren, 2000, Vidon and Hill, 2004b).

For the purpose of flow interception (especially in steep catchments), riparian zones need to be wider as slope increases to maintain the same protection to the waterway because faster flowing water is able to transport more sediment (Herron and Hairsine, 1998). As slope increases, concentrated runoff may also increase, which can inundate grassy riparian vegetation and reduce its capacity for filtration (Barling and Moore, 1994). Parkyn (2004) reported that buffer widths for New Zealand systems needed to be increased as slope length and clay content increase and soil drainage decreases. Large-scale research characterising Chesapeake Bay watersheds, in north-eastern USA, showed that in all physiographic settings, the slope of riparian forested buffer strips was the main factor limiting the effectiveness of sediment removal function (Lowrance *et al.*, 1997).

The topographic setting of a waterway also exerts a strong influence on groundwater-surface water-riparian zone interactions (Vidon and Hill, 2004b). The flow rate of groundwater is proportional to the magnitude of gradients in force potential and the hydraulic conductivity of the substrate, or permeability (Lockington, 1992). The rate and magnitude of exchanges between water and its dissolved load with the riparian and regional aquifers will therefore be dependent on valley form (Naiman *et al*., 2005).

Along a given river reach, the upslope drainage area will rarely be a planar slope. It is more likely to be punctuated with small drainage lines, depressions and gullies that all increase channelised overland flow (see Bren, 2000). Where topographic variations occur, riparian buffers may need to be extended into adjoining land to entrap sediment in channelised runoff (Weller *et al*., 1998, Parkyn, 2004). Simulation studies have determined that the amount of soil moisture and the degree of topographic convergence may exert a stronger influence on buffer width predictions than the magnitude of rainfall events (Herron and Hairsine, 1998). Therefore, the slope of the riparian zone, the drainage topography and the drainage area will influence the riparian width necessary to slow surface runoff, direct sub-surface flows and retain sediment.


Faithful Creek. Photo: P. Reich

It is interesting to note that in North America, jurisdictions with riparian buffer width guidelines that have slope modifiers had, on average, narrower baseline widths than those without slope incorporated in their guidelines (Lee *et al*., 2004). While slope clearly has an important influence on riparian buffering performance, a lack of slope should not be used as a justification to reduce riparian zone widths as the width decision should be guided by other factors in conjunction with slope.

### *2.4.4 Flow and disturbance regimes*

Flow and disturbance regimes control the pattern of channel evolution and floral community structure and composition in riparian zones (Naiman and Décamps, 1997). These hydrological processes drive the continual geomorphic change of rivers and the discharge regime causes aggradation and degradation, shaping channel features. By the mobilisation, transport and deposition of sediment, stream channels meander laterally and down stream (Naiman and Décamps, 1997) simultaneously re-shaping riparian zones. In addition to baseflow discharge, the frequency and extent of flooding dictate the rate at which channel evolution occurs. Flow regimes also exert a strong influence on in-stream biogeochemical processes by affecting nutrient processing rates and organic matter transfer.

High-energy flow events re-configure vegetation in the riparian zone by modifying and re-setting plant communities (Ward *et al*., 2002), promoting diverse faunal communities that utilise the greater array of botanical species and life history stages. The increase in flow regulation and water abstraction in Australian riverine systems has resulted in reduced riparian habitat complexity and loss of local biodiversity (Erskine *et al*., 1999, Mac Nally *et al*., 2002, Lester and Boulton, 2008). Weir operations along the Murray River cause fluctuations in water levels downstream (diminishing with distance), which has strongly influenced the littoral community (i.e. the shore-line community; a subset of the riparian zone) (Walker, 1993). The major challenge for waterway managers is to restore and maintain riparian and aquatic ecosystems in the absence of riverine-landscaping provided by natural flow regimes and flooding.

Rubicon River in flood. Photo: P. Reich

## 2.5 The influence of invasive species on riparian function

Invasive flora and fauna are of considerable concern to both waterway managers and farmers. Victoria has serious problems with a large number of introduced plant and animal species, and the extent to which passive restoration results in further proliferation of these remains to be fully quantified. Plant species like willows (Reed *et al.*, 1994, Greenwood *et al.*, 2004, Clift *et al.*, in prep), reed sweet grass (*Glyceria*: Loo *et al.*, 2009), phalaris (Williams *et al.*, 2008a), and blackberry (Douglas, 1977), among others, are serious invaders of riparian zones, and rehabilitation or restoration programs need to incorporate active management techniques to control their spread.

Willows are well-established, highly invasive weeds in riparian zones in Australia. They cause significant negative changes to terrestrial riparian invertebrate assemblages compared with native riparian vegetation (Greenwood *et al.*, 2004). Furthermore, they affect reciprocal subsidies across the terrestrial-aquatic interface, thus impacting food web structure (Greenwood *et al.*, 2004, Clift *et al.*, in prep). Other noxious species that receive far less exposure, but are just as problematic, are those like phalaris: a highly valued hardy pasture grass, but serious impediment to the success of riparian restoration programs (Williams *et al.*, 2008a). The extent to which these species will inhibit restoration efforts will depend on site conditions and the deployment of active management.

Fencing of riparian zones that have little or no woody vegetation, for exclusion of livestock, may assist the subsequent spread of some invasive species like willows and reed sweet grass (Loo *et al.*, 2009) and phalaris (Williams *et al.*, 2008a). When serious infestations of invasive plant species are present, landscape context is extremely important in the determining the best restoration strategy for degraded riparian zones. Clearly, there


Willows and other invasive plants in riparian zone. Campaspe River.

will be cases where fencing out livestock will need to be accompanied by additional management strategies for weed control. However, even where exotics proliferate this may not preclude the effectiveness of some riparian functions (e.g. improving water quality) with only minimal additional management intervention.

Along the Murrumbidgee River, riparian condition assessments of private land has found that, even at sites where stock has been excluded for over 50 years, there are still significant problems with exotic plants (Jansen and Robertson, 2001a). Various strategies are proposed to deal with this, the main one being ongoing weed control by the owner supported by the government. Increasing buffer widths to allow for edge effects may provide an alternative to active management of riparian zones (see Webb and Erskine, 2003), depending on the proximity to and composition of on-site soil seed banks (Williams *et al*., 2008a) and upstream remnants. In this context, river flow management at the catchment scale is acknowledged as being important for tree recruitment (Jansen and Robertson, 2001, see also EPA 1997).

The effects of invasive species are mediated by flow regimes. Flood suppression due to the Snowy Mountains Hydro-Electric Scheme has seen a reduction in disturbance by floods on contracted downstream reaches and a resultant increase in invasion of exotic plant species in riparian zones (Erskine *et al*., 1999). Therefore, the spread of invasive plant species may occur whether or not fencing for stock exclusion is undertaken.

There is much debate about the potential negative consequences of ecological corridors as access points, protection and breeding grounds for invasive animal species (e.g. foxes and cats). It cannot be debated that where intact vegetation occurs, some species will take advantage of its presence for the purpose of cover or residency. However, the surpassing negative impacts of corridors in terms of facilitation of invasive spread versus the maintenance of native biodiversity and gene flow in largely fragmented landscapes has not been unequivocally demonstrated in Australia. Furthermore, as highly invasive species like foxes and cats occur in many regions of the country and are one of the most significant ecological problems facing native fauna, the potential for fenced riparian zones to increase their impact is negligible.

It is important to note that, while invasive plant species may have detrimental consequences to riparian zones (e.g. to some taxa and to local biodiversity), there are still management objectives that can be met in their presence. Water quality and bank stability may both be achieved with exotic riparian plants, and is likely to be a better outcome for waterways than allowing river beds and banks to be trampled and eroded by livestock. Therefore, under no management scenario is it probable that no riparian zone protection is better than limited protection.

*Edge effects*

Edge effects may occur due to encroachment or invasion by feral and exotic species or changes in microclimate at interfaces (e.g. clearings). The configuration of the riparian zone dictates the magnitude of edges and the influence of edge effects on riparian communities. Edge effects are known to have a significant impact on breeding birds in some landscape contexts, for example, nesting success may be impacted from 15m and up to 50m from forest edges (Catterall *et al.*, 2001, Paton, 2004); although neither of these specifically refer to riparian landscapes. Similarly, noisy miners may have severe detrimental impacts on avifauna diversity for distances of 150-300 m into woodland blocks (Clarke and Oldland, 2007, Taylor *et al.*, 2008). The influence edge effects have on riparian zones may be significant where invasive species can penetrate well into the riparian zone, as may be the case with long, narrow riparian plantings. Webb and Erskine (2003) report on trial riparian plantings (15-30m) in the Hunter Valley, which resulted in edge effects that reduced regeneration of planted species. This was attributed to increased competition of weeds with native vegetation and large spacings between plantings allowing invasion. They concluded that edge-effects will be reduced with larger widths and that 15-30m was too narrow.

Re-plantings. Curdies River

## 2.6 The influence of landscape context on riparian buffering efficiency

### *2.6.1 Land Use and Land Use Intensity*

Land use changes in the catchment have significant and long-lasting impacts on riparian and waterway function. Riparian research both in Australia and overseas frequently draws the same over-arching conclusion, that restoration and management efforts need to focus on the entire catchment, especially given the disproportionate contribution that headwater streams make to overall catchment function (Osborne and Kovacic, 1993, Brosofske *et al.,* 1997, Knutson and Naef, 1997, Lowrance *et al*., 1997, Naiman and Décamps, 1997, Wenger, 1999, Peterson *et al*., 2001, Lee *et al*., 2004, Parkyn, 2004, Lake, 2005, Lowe and Likens, 2005, Mayer, 2005, Rassam *et al*., 2006). To focus on riparian zones or waterways alone risks ignoring potentially larger issues within the catchment, which may be the major contributors to riparian deterioration.

Severely degraded riparian zone. Photo: P.Reich

The whole-catchment approach to riparian management should be implicitly obvious as processes occurring upstream (and upslope) have significant impacts on downstream stream reaches, the fundamental premise of the River Continuum Concept (Vannote *et al*., 1980). Furthermore, as the riparian zone mediates transactions of energy, nutrients, sediments, and biota between the stream and its hinterland (Lake, 2005), both will be subject to impacts occurring in the other. Thus, changes in the catchment will affect restoration efforts at the reach scale and must therefore be part of any decision-making process regarding riparian zones (Craig *et al*., 2008).

Headwater streams are disproportionately important for removal of non-point source pollutants and nutrient processing (Lowrance *et al*., 1997, Naiman and Décamps, 1997, Peterson *et al.,* 2001), as well as maintaining high levels of habitat and species diversity (both in-stream and terrestrial) (Lowe and Likens, 2005, Clarke *et al*., 2008). Most N removal occurs in small streams (Peterson *et al.*, 2001, Craig *et al.*, 2008, Valett *et al.*, 2008). This removal occurs not only in the riparian zone but also within the waterway itself, especially where retention by debris dams and organic matter build-up is high (Bernhardt *et al.*, 2005). Upstream restoration, like riparian re-vegetation, may improve downstream conditions and increase the effectiveness of downstream restoration (Lake *et al.*, 2007). Therefore, establishing riparian buffers along smaller streams is more likely to counter-balance the impacts of catchment land use than buffers located along downstream reaches. Furthermore, protection of headwater stream networks may provide more catchment-wide ecological benefits if buffers are continuous and of unspecified width, rather than intermittent and wide (Correll, 2005).

Discontinuous riparian zones result in substantially reduced buffer performance (relative to the area they occupy), whereby the benefits accrued by an intact riparian zone at one location are off-set by gaps at another. Thus, the efficiency of the riparian system at mitigation of catchment disturbance effects is greatly reduced and nutrient flow pathways are disrupted or compromised. This is not restricted to just riparian buffering capacity but also extends to considerations of habitat continuity and suitability of riparian zones for maintaining populations of biota. A similar principle applies to riparian zones on opposite sides of the waterway. For both small and large streams, it is important to have continuous buffers on both sides (Correll, 2005). As activities on either bank may differ, and the impact of these activities will also depend on land uses in the rest of the catchment, narrowing the buffer on one side could negate the beneficial effects of the wide one. Furthermore, high intensity land uses may increase (non-point source) leakage rates from catchments well above natural levels and thus, to protect streams, riparian zones may need to be widened above what is considered natural levels.

Parkyn (2004) reports on a conceptual modelling exercise that assessed the trade-off between shading and water quality benefits of upstream riparian rehabilitation, and found that headwater buffer strips out-performed those along higher order reaches. This exercise highlighted the problems associated with implementing riparian tree planting programmes in a piecemeal fashion (and/or in random parts of the catchment) and concluded that planting should commence in the headwaters and progress downstream to avoid nutrient yield increases (Parkyn, 2004). The same may be true for improving both aquatic and terrestrial biodiversity, in that restoration of habitat starting upstream and progressing downstream will substantially increase regional ($\gamma$) species diversity through increases in $\beta$-diversity across the upper parts of the catchment.

Impacts on the waterway vary depending on the intensity of modifying activities and the ability of the riparian zone to mediate those influences. Land uses that have significant impacts on riparian zones include:

- agriculture (cropping and horticulture) - type and intensity (e.g. fertilizer application contributing non-point source pollution, irrigation altering groundwater, intensive soil tillage, application of herbicides and pesticides)
- agriculture (dairy) - grazing of dairy livestock has more intense impacts on water quality through pasture improvement and irrigation, substantially increasing sediment and nutrient loads (through both fertilisers and manure) to streams, and antibiotics, hormones and other veterinary chemicals
- agriculture (grazing) - cattle, deer, horses, sheep and other hard-hoofed animals increase sedimentation through impacts on soils and loss of ground cover, and destroy aquatic habitat through trampling or wallowing
- agriculture (concentrated animal feeding operations) - swine and poultry farms generate excessive point source nutrient loads
- roads - impervious surfaces that increase channelised runoff and sediment delivery to streams
- plantation forestry - primarily radiata pine (but also monocultures of native hardwoods) alters surface flows and nutrient availability, affecting sub-catchment hydrology due to increased evapotranspiration
- mining - contributes excessive contaminant inputs to streams and groundwater, increases sedimentation and runoff generation, and alters catchment hydrology and local geomorphology
- salinity
- urban - this activity is covered elsewhere in detail (see for example Walsh *et al*., 2005) and is therefore not included in these discussions

These land use activities are discussed in more detail below.

*Agriculture*

Agricultural activities constitute around 60% of Australia's land use (Lester and Boulton, 2008). The two most significant impacts of agriculture on riparian zones and waterways are the loss and/or alteration of riparian habitat through clearing, and the excessive supply of nutrients and other non-point source pollutants, including sediment (Osborne and Kovacic, 1993, Knutson and Naef, 1997). Sedimentation is considered to be one of the most serious issues affecting waterways in Victoria (Norris *et al.*, 2001); refer to Section 2.3.6 for discussion of sediment inputs to streams.

Removal of riparian vegetation to allow agricultural activity to the waterway edge has direct consequences on many functions performed by the riparian zone. Deforestation and conversion to agriculture results in bank destabilisation (Runge, 1977, Parkyn, 2004). In the cane fields of Queensland, riparian vegetation often cleared right up to the edge of the bank resulting in increasing the erosion of streambanks and reducing floodplain resistance (Barling and Moore, 1994). In south-eastern Australia, conversion of native vegetation to pastures and croplands has reduced invertebrate biomass and shading in upland streams (Reed *et al.*, 1994).

Application of fertiliser and other agrochemicals produces excessive nutrient loading and delivery to riparian zones predominantly as total nitrogen and total phosphorus (Peterjohn and Correll, 1984, Harris, 2001, McDowell *et al.*, 2004). Inputs from upslope can substantially exceed the filtering and assimilation capacity of riparian vegetation, especially where that vegetation has been removed or degraded in quality and extent. The deterioration of water quality in agricultural catchments is irrefutably linked to the intensification of agricultural practices (Peterjohn and Correll, 1984, Muscutt *et al.*, 1993, Quinn *et al.*, 1997, Carpenter *et al.*, 1998, Parkyn, 2004).

Erosion risk may be magnified by agricultural activities on different soil types, for example, where soils are loosely aggregated and planted with shallow-rooted crops (Cooper *et al.*, 1995, Bird *et al.*, 2004, Lowrance *et al.*, 2007). Cultivation of soils increases sediment in surface runoff especially when they are bare and exposed to rain (Muscutt *et al.*, 1993, Parkyn, 2004). There is no information concerning the relative contribution of wind erosion to sediment inputs to streams. Cotton farming and other forms of row cropping also substantially increase sediment in runoff (Wenger, 1999). In the United States, erosion from croplands accounts for 40-50% of sediment in waterways (Knutson and Naef, 1997). The delivery of sediment to streams is further exacerbated by irrigation of crops and pastures.

***Irrigation and drainage:*** Agricultural activities frequently result in alterations to drainage from upslope. Channelisation to improve pasture drainage can have serious indirect effects on stream stability by exposing non-cohesive (and unstable) substrates (Quinn *et al*., 1993). In agricultural regions overseas, tile drainage is used to reduce waterlogging and this causes flows to bypass the riparian zone and empty directly into the waterway, significantly reducing the opportunities for soil-water interactions. Surface flow and rill irrigation carry significant amounts of fine sediment to streams systems (Knutson and Naef, 1997). Periods of peak irrigation and the start of the irrigation season were found to correspond to high sediment loads in the Yakima River in the US (Knutson and Naef 1997). Within the Goulburn-Broken catchment as well as other parts of Victoria, the first irrigation after intensive fertiliser applications to pastures causes over 50% of the annual phosphorus export via surface flows (Davis *et al.*, 1998, Drewry *et al.*, 2006). Some irrigation practices (e.g. using subsurface drip irrigation) have also been found to contribute to salinity problems.

The replacement of native vegetation with annual crops and pastures, and the subsequent irrigation of these crops, increases groundwater recharge (deep drainage), resulting in shallow water tables and land surface salinization (Doupé *et al.*, 2006). The use of centre pivot irrigation has increased over the last 24 years in Western Victoria and has resulted in increases in deep drainage (Maron and Fitzsimons, 2007, Qassim *et al.*, 2008). The extent to which this results in rising groundwater levels and increased salinity problems depends on the permeability of soils and timing of rainfall events (Biggs *et al.*, 2006).

***Grazing and dairy:*** Livestock access to riparian zones has a multitude of detrimental impacts, all of which are ameliorated to varying degrees by exclusion through fencing. Exclusion of stock from riparian zones may partially or fully address virtually all management objectives for Victorian catchments. This is because grazing and stock access to riparian zones reduces water quality, reduces terrestrial and in-stream habitat extent and function (and thus, biodiversity), and increases erosion (Sovell *et al.*, 2000, Jansen and Robertson, 2001a, Dorrough *et al.*, 2004, Fellows *et al.*, 2007, Lunt *et al.*, 2007b, Lester and Boulton, 2008). These impacts occur due to:

- soil compaction
- increased surface flows during high rainfall events
- mobilised sediments
- increased nutrient input to streams

- trampling of the channel bed and bank
- destruction of riparian and aquatic vegetation
- introduction and spread of invasive plant species

The effects of grazing on riparian zones and waterways may be both direct and indirect. Direct effects are the result of stock access to the waterway. Stock access to riparian zones impacts on waterways through degradation of riparian vegetation (and concomitant increases in stream water temperature due to loss of canopy cover), increased sediment inputs to the waterway and destruction of in-stream habitat through trampling and wallowing (Bell and Priestley, 1999, Parkyn, 2004).


Deposition of faecal material into stream or onto bank has direct impacts on the waterway when it is subsequently washed in by overland flow (Parkyn, 2004). Indirect effects include increased surface flows and nutrient runoff, substantially increased sedimentation in-stream and decreased sediment trapping and infiltration ability of the riparian zone due to damaged riparian vegetation (Parkyn, 2004). As rates of denitrification are highest in riparian surface soils, soil disturbance through grazing can reduce denitrification potential by reducing levels of bio-available C (Fellows *et al.*, 2007)

In Australia, grazing by introduced ungulates constitutes the majority of agricultural practices (Jansen and Robertson, 2001). Surveys of riparian condition along the Murrumbidgee River in NSW found only 7% of sites were in good condition and that all of these experienced little to no grazing (Jansen and Robertson, 2001). In heavily grazed habitats, poor riparian condition was associated with the absence of suitable ground terrestrial habitat, reduction of organic matter inputs to streams, and insufficient interception of materials in overland flows. Furthermore, red gum recruitment was limited, contributing to fragmentation of riparian habitats.

Drewry *et al*., (2006) found that in Australia, nutrient exports from beef and sheep grazing are lower than from dairy, but that both are higher than for native riparian forest (facilitated by leaching and overland flow). They commented that the rates from beef and sheep grazing were considerably higher than had been reported in other studies. In the state of Washington (North America) grazing is quoted as having the most destructive impacts upon riparian ecosystems (Knutson and Naef, 1997). In the U.S.A. in the mid-late 1990s, 83% of riparian zones were in an unsatisfactory condition as a result of grazing (Knutson and Naef, 1997). Minimum riparian habitat area widths recommended to counter these impacts are 46m for narrow streams (<1.5m) and 61m for wider streams (Knutson and Naef, 1997). In New Zealand, where agricultural grazing constitutes over 50% of the land use, increases in flow variability, maximum stream temperatures, baseflow nutrient concentration and periphyton biomass have been correlated with increasing catchment development as 'improved pasture' (Quinn *et al*., 1993). A minimum width of 10-20m was recommended for Auckland Regional Council to address related water quality issues (Parkyn, 2004).


Cattle-grazed riparian zone. Curdies River.

***Animal feeding operations:*** Concentrated animal feeding operations (CAFO), for example, swine and poultry farms, are significant and damaging sources of nutrient-rich (nitrogen- and phosphorus-dominated) waste to waterways, as well as being potential sources of biological diseases (Knutson and Naef, 1997, Davis *et al*., 1998, Wenger, 1999). Decaying animal wastes deplete oxygen, increase nitrate levels, and increase acidity, which harms or kills fish and other aquatic organisms (Knutson and Naef, 1997). In America, CAFO qualify as point-source polluters and require special permits (Wenger, 1999). They should not be located anywhere near a waterway, which in the State of Georgia (US) is considered to be a minimum of 100 feet (~30m) or outside the 100-year floodplain level (Wenger, 1999). The same is true for sewer pipes and septic drain fields. Ideally buffers should extend as far as possible where these operations occur upslope, to compensate for inevitable buffer saturation from high incoming nutrients loads.

*Roads*

Road networks are impervious surfaces that contribute substantial runoff from the catchment. Roads of virtually all types and locations have significant impacts on riparian zones and waterways through their alteration to watershed drainage and removal of native vegetation, which results in the mobilisation of soils and erosion (Knutson and Naef, 1997, Wenger, 1999, Parkyn, 2004). Roads effectively increase the waterway network length by altering drainage through ditches and culverts, and creating gully erosion through increased runoff, resulting in increased delivery of sediment loads to waterways (Montgomery, 1994, Bren, 2000). Even wheel tracks may substantially increase sediment delivery to streams by damaging surfaces and exposing underlying soils, especially where these are located in crop fields with regular irrigation (Lowrance *et al.*, 2007). Hydrological linkages between roads and streams in NSW forests have been found to negate the effects of riparian buffers for sediment / nutrient removal (Mockler and Croke, 1999). In forestry in Tasmania, unlogged streams had riparian zones >50m wide (Davies and Nelson, 1994) and roads located within this distance significantly increased delivery of sediment to waterways. Roads are also sources of contaminants to waterways, including heavy metals like zinc.


Access road. Barwon River.

*Plantations*

In Victoria, *Pinus radiata* plantation forestry is widespread, which potentially has significant local impacts on waterways. Pine plantations established in north-east Victoria in 1975 with a 30m riparian buffer were found to increase water yields (especially after storm-flow events) compared with paired unmodified catchments. However, a native riparian buffer helped maintain water quality within the range of pre-plantation levels (Hopmans and Bren, 2007). Pine plantations have little to no understorey, and the opportunity for riparian interception of nutrient and sediment-bearing overland flow is much reduced (Quinn 1993), hence the need for intact riparian zones of suitable width. Conifer canopy cover may be much greater than native vegetation, which will influence water temperatures through shading, and therefore, primary productivity. Macroinvertebrate assemblages may respond differently to exotic riparian vegetation and some specialist feeding groups (wood gougers and algal grazers) prefer native riparian inputs (McKie and Cranston, 2001). Denitrification potential of plantations may be reduced compared with unmodified native forest due to increased evapotranspiration and decreased streamflow (Vink *et al.*, 2007). Hardwood timber plantations may have lesser impacts in terms of stream shading and riparian inputs, but the extent to which hardwood monocultures impact other processes occurring at the terrestrial-aquatic interface requires investigation.

**Private sugar gum plantation adjoining an eroded drainage line, Heathcote**

Production forestry results in increased sediment delivery after harvesting (Parkyn, 2004) and native forest buffers of 30m in pine plantations have been found to be an effective filter (Hopmans and Bren, 2007). It is therefore of some concern that plantations on private land appear to be exempt from the riparian buffer specifications that are applied to other timber production activities (*Code of Practice for Timber Production*, DSE 2007). While timber harvesting activities in native forest (public and private) require the retention of buffers varying from 10m (drainage lines and temporary streams) to a maximum of 40m (permanent streams on slopes exceeding 20$^o$), operations within plantations on private land are merely encouraged to apply the same buffer widths and activities up to the top of bank are still allowable. Stricter specifications may be prudent for plantation forestry on private land until more information about their effects on water quality and delivery to waterways is available.

*Mining*

Mining has severe consequences for all landscapes through changes to hydrology, geomorphology and topography, destruction of vegetation, inputs of toxic substances and other pollutants, increased surface runoff, and increased sedimentation. Data relating to the effects of mining on riparian zones is uncommon (but see Wenger 1999, Pond et al 2008). Given that the impacts of mining should be considered as part of any Environmental Impact Assessment and that those impacts will be site-specific and dependent on the type of mining being conducted, mining is not addressed in this report.

*Salinity*

The removal of vegetation from the landscape has altered surface-groundwater interactions, resulting in widespread stream, irrigation and dryland salinity problems. Salinity problems and mitigation have, and continue to receive substantial management and research attention, and are therefore not discussed in detail here. Despite salinity being an important issue for many of Victoria's waterways and floodplains, data on stream salinity are not directly transferable to riparian zone width recommendations (Norris *et al.*, 2001, Holland *et al.*, 2006). The catchment-scale nature of salinity problems means that finding solutions relevant to riparian management will require catchment-scale protection or restoration of riparian zones. In addition, information on the cumulative effect of salinity in production landscapes on riparian zone function is required to relate salinity to riparian buffer widths.

### *2.6.2 Landscape connectivity*

We have covered the role of connectivity when discussing functions of the riparian zone (Section 2.3.7). It is worth re-emphasizing that the ability of a riparian zone to maintain natural levels of terrestrial biodiversity will be influenced by patch size and degree of isolation (see Johnson *et al.*, 2007). Therefore, the functional width of the riparian zone (in terms of providing pathways for movement of biota) at any given site will be influenced by the proximity of remnant patches. Where remnant patches are located within some threshold distance for dispersal, the greatest biodiversity benefits in that part of the catchment may be provided by the lateral extension of riparian zones to incorporate these patches (riparian or woodland patches). The information required to determine species and assemblage dispersal capability is still lacking for the majority of mobile and sessile organisms (e.g. plants and soil invertebrates, microbes).

Management for long, continuous riparian zones may well be a higher priority over fragmented but wider strips (Weller *et al.*, 1998, Fischer and Fischenich, 2000). The landscape context for making this choice is important. If riparian zones are not continuous (perhaps because they are punctuated by cadastral boundaries) and catchment land use is an intensive form of agriculture that has severely modified the water quality and in-stream biota, then the management objective should therefore be focused less on how wide, as width may provide few water quality and biodiversity benefits, and instead focus on buffer length. Unfortunately, the effects of fragmentation of riparian zones are poorly understood and should therefore be a major area of rigorous research.

### *2.6.3 Stream size (placement within the catchment)*

The position of the stream in the drainage network may dictate the width of the stream and the riparian zone, hydrological connectivity between the waterway, the riparian aquifer and the regional aquifer, the ratio of gross primary productivity to community respiration and the mobilisation or deposition of sediment. The stream-riparian interactions change along different sections of the drainage network and the functions the riparian zone performs alter from the headwaters to the lowland floodplains.

The River Continuum Concept (RCC) (Vannote *et al*., 1980) provides a useful framework for determining how stream size and order may influence the functions of the riparian zone as one moves from the headwaters to lowland floodplains. However, in many cases these general concepts may not apply, especially in Australia as the RCC was developed on the basis of North American drainage basins (Lake *et al.*, 1985). It also fails to consider the processes facilitated and controlled by flooding, which form the basis for the Flood Pulse Concept (Junk *et al.*, 1989). It will therefore be the responsibility of any field assessor to determine what aspects of stream placement in the catchment are most meaningful for determining riparian zone widths (e.g. export of sediment from low order streams, versus floodplain retention along high order rivers).

In small streams (order 1-3) sediments are eroded and mobilised, riparian zones contribute large amounts of allochthonous (CPOM) inputs, in-stream primary productivity is suppressed by shading and the stream is heterotrophic (Vannote *et al*., 1980, Naiman *et al*., 2005). In these small stream systems, riparian canopy cover and organic inputs from the riparian zone are critical to maintaining community respiration, and gross primary productivity makes a minimal contribution to ecosystem metabolism. Thus, riparian zones need to be wide enough to contribute inputs of organic matter and woody debris, process nutrients, to provide adequate stream shading and for sediment control.

As streams increase in size (order 4-6) the reduced influence of riparian shading coincides with shifts  from heterotrophy to autotrophy (Vannote *et al*., 1980). The importance of allocthonous inputs is reduced and autochthonous organic matter production alters the ratio of gross primary productivity to community respiration (Vannote *et al*., 1980). Sediments eroded in the headwaters are selectively deposited and re-mobilised as water moves downstream, a process which is influenced by in-stream structures like debris dams (Gregory *et al*., 1991). Riparian wood inputs will be important, as will live structural reinforcements like tree roots and branches, to maintain heterogeneity of the stream channel (Ward *et al*., 2001).

In larger rivers (order 7 and above) inputs of FPOM from upstream facilitate the proliferation of invertebrate collectors, which shifts the stream to an equilibrium between gross primary productivity and community respiration (Vannote *et al*., 1980). FPOM processed upstream may be the dominant carbon import to lowland stream systems; CPOM inputs and shading are thought to be relatively insignificant. However, the relative importance of floodplain carbon to nutrient cycling is still poorly understood and may have a greater role in lowland production than previously thought (Junk *et al.*, 1989). Sediments transported from upstream are gradually deposited in lowland systems (Naiman *et al*., 2005), creating extensive alluvial floodplains and increasing the lateral hydrological extent. The spreading out of floodwaters result in substantially laterally-extended riparian zones in terraces, representing former floodplain levels and containing different water- and disturbance-tolerant vegetation classes

(Ward *et al*., 2002). Wide riparian zones may be required to enable effective transactions of water and vegetative propagules between the floodplain and the waterway.

### *2.6.4 Dams and off-stream water storages*

In-stream impoundments (dams) effectively inundate riparian land, but the deleterious impacts on the riparian zone will vary depending on the topography and extent of flooding at a given site (Knutson and Naef, 1997, Bombino *et al.*, 2008). Apart from their obvious downstream impact on flow regimes and flooding extent, in-stream dams (especially where they occur on small streams) may affect minimum daily water temperatures through cooling of bottom water layers and release of this colder water into the stream from bottom-release dams (Rutherford *et al*., 2004). Top release dams will do the opposite by contributing surface water that has been warmed. Check dams in the Mediterranean have been found to influence downstream sediment size and deposition, as well as vegetation canopy cover (Bombino *et al.*, 2008).

Off-stream dam. Stewart Ponds.

Off-stream (farm) dams alter catchment hydrology by storing water that would otherwise contribute to down-stream flow (Beavis and Lewis, 2001). Farm dams are a widespread feature of south-eastern Australia agricultural landscapes, and the frequency of their occurrence may determine the focus of management efforts, for example, where sediment inputs to streams is a dominant environmental issue. Upstream wetlands can assist in recovery of downstream sediment-impacted channels by acting as depositional zones. In a similar fashion dams may act as sediment traps, but they can also act as point-sources of nutrients (Beavis and Lewis, 2001). The retention or addition of contaminants to outflows will occur when surface soil is remobilised (Schmitt *et al.*, 1999) such as occurs in pulse events. Therefore, near-stream dams may be incorporated into buffer design to capitalise on their sediment-removal ability, but the stream should also be buffered from the dam to reduce the likelihood of high nutrient and/or stream inputs during pulse events.

# SECTION 3. WIDTH GUIDELINES AND RESEARCH PRIORITIES

## 3.1 Riparian zone width guidelines

Key points

- The greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications and disturbances
- In order to maximise functional efficiency, riparian zones should be longitudinally continuous as well as sufficiently wide, targeting first degraded headwaters and then proceeding downstream
- Based on a meta-analysis of >200 studies, riparian buffer widths of between 30 and 200 m are recommended, dependant on land use intensity and management objective
- Recommended widths apply to both banks
- Riparian width recommendations should be used in landscape forecasting - where land use changes are proposed, riparian zones need to be adjusted to account for potential increases in disturbance impacts

When making decisions about riparian zone widths, consideration should first be given to:

1. Hydrological regime (e.g. flow regulation, the frequency and magnitude of overbank flows).
2. The degree of fragmentation of the riparian zone (in terms of longitudinal connectivity of riparian vegetation)
3. The presence of invasive plant species (e.g. willows)

Where these factors are influential, *a priori* decisions need to made by a field assessor or land manager regarding what potential gains will be achieved by setting a riparian zone width in their presence.

Importantly, land use intensity (definitions given below) will govern the decision about what width is appropriate for a given location and management objective– the greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications and disturbances. Where best agricultural management practice is implemented (reducing impacts from farming on the waterway), the need for wider buffers will be reduced. Unless the catchment is unmodified (uncleared) on one side of the waterway, widths will apply to both banks.

Re-plantings on a single bank. Waurn Ponds Creek.

We identified 222 studies from Australia and overseas, that provided information relating to riparian zone widths based on one or more riparian function. An initial breakdown these studies revealed the majority of information to be related to improving water quality (reducing nitrogen, phosphorus and sediment delivery to waterways) and the provision of terrestrial habitat for fauna (See Table 2). In comparison, other riparian functions like delineation of riparian vegetation extent in different contexts, widths for the provision of stream shading, wood and other inputs to the aquatic environment and widths for reducing edge effects were minimally investigated. Studies relating to improving connectivity for fauna populations were highly context specific and had little relevance to Victorian ecosystems (for more detailed discussion on transferability of international findings in Section 1.5 and below).

We categorised each of the 222 studies into six major "function" groups (Table 2) relating to riparian functions as defined in section 2. We then conducted a simple meta-analysis by computing the median width and 25$^{th}$ percentile from the minimum values contained in these studies, in order to establish a quantitative width range for each function category (Table 2). Only in one case (off-stream waterbodies) were we able to make an additional distinction to function, i.e. landscape context. Most studies were not readily (or consistently) classifiable into land use intensities, which might otherwise reflect important distinctions between width recommendations from different landscape contexts.

**Table 2. Results of a meta-analysis on the minimum riparian zone width necessary to augment or initiate a particular function. Studies are categorised into "function" groups to reflect the purpose of that investigation (e.g. widths necessary to intercept nitrogen). The total number of studies, including the number of overseas and Australasian (AUS) studies contributing to the analysis is shown (original research, does not include reviews). All widths are in metres.**

| Function | Median width | $25^{th}$ percentile | Width range | Total no. studies | North American studies | AUS studies | Other studies |
|---|---|---|---|---|---|---|---|
| Connectivity for fauna | **100** | 87 | 46-183 | **4** | 4 | - | - |
| Edge effects on fauna | **160** | 100 | 55-670 | **9** | 7 | 2 | - |
| Inputs for aquatic fauna | **45** | 30 | 15-100 | **24** | 17 | 3 | 4 |
| Riparian vegetation extent & shading | **37** | 30 | 5-109 | **29** | 16 | 7 | 6 |
| Terrestrial habitat for fauna | **100** | 50 | 23-900 | **63** | 55 | 1 | 7 |
| Improving WQ | **30** | 15 | 1-190 | **89** | 61 | 9 | 19 |
| Improving WQ - offstream waterbodies (& wetlands) only | **120** | 38 | 30-2250 | **4** | 2 | - | 2 |

For details of these studies, refer to Appendix 2.

Finally, the median values in Table 2 were used as a basis for making width recommendations for Victorian systems. Values were applied to a subset of the seven management objectives outlined in section 1.3:

- Improving water quality (combining nutrient and sediment interception)
- Increase shading and moderate stream temperatures
- Provide food and other resources to the aquatic environment (includes facilitating reciprocal subsidies)
- Improve in-stream biodiversity
- Improve terrestrial biodiversity

It can be seen above that we treat the capture and/or uptake of all non-point source pollutants (i.e. nitrogen, phosphorus and sediment) under the more general objective of improving water quality. Furthermore, as increasing riparian width does not necessarily relate to improving structural or hydrological connectivity, we do not attempt to develop width recommendations for connectivity-related management objectives.

Table 3 provides a matrix of width recommendations for each of the five management objectives for a set of important landscape contexts (discussed below). In each case, the width recommendation for a single management objective was set by the median value, and was increased by an amount corresponding to the 25$^{th}$ percentile for each increase in land use intensity (see below for definitions). This was done to reflect the need for wider riparian buffers to mitigate against greater impacts and disturbances originating from the catchment. For simplicity, these numbers are rounded to the nearest 5m where applicable. In some contexts (e.g. steep catchment/low order streams) there was inadequate information contained across the relevant studies to make this distinction in the meta-analysis. In these situations, expert opinion has been used to modify the width recommendation.

Where more than one context applies, the most appropriate width will be the greatest. This is necessary to reduce the impacts of the most intensive land-use practice on the waterway.


Native Hut Creek.

**Table 3. Minimum width recommendations for Victorian riparian zones based upon available scientific literature and adjusted using expert opinion, where appropriate, to account for known differences between Victorian and international systems. Colours indicate the level of scientific certainty for each recommendation and are explained below. All widths are in metres.**

| Landscape context / Management Objective | Land Use Intensity High | Land Use Intensity Moderate | Land Use Intensity Low | Wetland/ lowland floodplain/ off-stream water bodies | Steep catchments/ cleared hillslopes/ low order streams |
|---|---|---|---|---|---|
| Improve water quality | 60 | 45 | 30 | 120 | 40 |
| Moderate stream temperatures | 95 | 65 | 35 | 40 | 35 |
| Provide food and resources | 95 | 65 | 35 | 40 | 35 |
| Improve in-stream biodiversity | 100 | 70 | 40 | Variable * | 40 |
| Improve terrestrial biodiversity | 200 | 150 | 100 | Variable * | 200 |

* Variability in width is related to the lateral extent of hydrological connectivity and thus, any recommendation will be site specific.

Below are listed the definitions of land use intensity used in Table 3. The practice of irrigating will generally increase intensity, and thus many distinctions are based upon irrigation versus non-irrigation:

| | |
|---|---|
| **HIGH** | dairy (high stocking rates >10 DSE/ha/annum [1,2])<br>irrigated dairy<br>dryland cropping (e.g. canola, wheat)<br>high intensity grazing (high stocking rates - beef, horses, deer, etc.)<br>swine and poultry (CAFO)<br>market gardens (where crops are irrigated)<br>high fertilizer application rates (>15kg P/Ha/yr [3])<br>sealed roads within 30m |
| **MODERATE** | dairy (all other stocking rates ≤ 10 DSE/ha/annum)<br>grazing (medium stocking rates 5-15 DSE/ha/annum)<br>other forms of dryland cropping (e.g. lucerne) where irrigation is not used<br>orchards (including citrus)<br>other production crops including vines hops olives<br>medium-low fertilizer application rates (<15 kg P/Ha/yr)<br>high-medium intensity sheep grazing<br>unsealed roads within 30m |
| **LOW** | grazing (low stocking rates <5 DSE/ha/annum all stock)<br>pasture cropping<br>timber plantations<br>forestry operations<br>pesticide application (e.g. Endosulfan-containing insecticides, glyphosate, organophosphates, etc. [4]) |

Sources used for determining stocking rate (DSE = dry sheep equivalents) and fertiliser application thresholds are:
[1] adapted from Jansen and Robertson (2001a)
[2] adapted from Ridley *et al*., (2003)
[3] adapted from Johnston *et al*., (1993)
[4] refer to Radcliffe (2002) for more information on pesticide use in Australia

It was not possible to make landscape context distinctions among water quality-related studies, despite the relatively large number of studies relating to this objective (93). Of the 93 water quality studies, only 34 could be placed into one of the three land use categories: low (n=8), moderate (n=5) and high (n=17). The median width value for high and low intensity land uses were identical (25m) and the median for moderate intensity land use was lower than these (12m), reflecting the lack of consistency between these studies. All other studies were highly variable in terms of other landscape variables including stream size, slope, multiple land uses in one study, and soil type (among others). This lack of consistency, in terms of experimental design and data collection, reflects the common difficulty faced when conducting any meta-analysis. As a result, many comparisons are difficult or impossible to make.

The majority of riparian research is from North American systems (Table 2) and while general physical processes are likely to be similar in both continents, many of the biotic processes are unlikely to be comparable. For example, stream shading may be achieved by continuous riparian canopy cover regardless of tree type, but litter accession from streamside coniferous vegetation will differ markedly to that from deciduous riparian vegetation which, in turn, will differ significantly from eucalypt leaf litter. Considerations such as these are critical to deciding the confidence with which we can extrapolate international research findings to Victoria in the absence of comparative data.

On this basis, we have assigned three levels of scientific certainty (confidence) to data summarised from the literature (see below). These levels were used to describe the level of confidence (in terms of the availability, rigour and relevance of scientific evidence) of each width recommendation. These confidence levels are illustrated in Table 3 using three colours:

| | |
|---|---|
| **High = green** | Many overseas studies applicable to temperate Australian systems; several studies conducted in temperate Australia in different contexts; general principles should be largely transferable to Victorian systems. |
| **Moderate = yellow** | Some overseas studies transferable to temperate Australian systems; very limited evidence from Australian systems (usually only 1 or 2 studies done in similar or the same context); general principles may not necessarily apply in many Victorian systems. |
| **Low = red** | Overseas studies are not applicable to Victorian systems; no data from Australian studies; general principles are unlikely to apply in Victorian systems. |

## 3.2 Key Knowledge Gaps and Research Priorities

Key points

- Targeted monitoring of ecological responses to riparian restoration is generally very poorly done in Australia.
- Science that should underpin the assumptions of effective riparian management has not progressed substantially in the last two decades as information from earlier successes or failures has not been adequately documented
- Applicability of international research findings to Australian systems is mostly uncertain
- Effects of fragmentation of riparian zones (both longitudinal and lateral) on the dispersal capability of riparian biota is poorly understood

Riparian zone widths should at their minimum provide [ecologically] sustained support for the aquatic environment (Welsch, 1991, Lowrance, 1998). However, the information required to determine what "sustained" represents in Australia is inadequate and thus hinders development of meaningful management guidelines for maintaining or restoring aquatic-terrestrial ecosystems.

Not only is the state of knowledge in Australia insufficient to create meaningful management guidelines, the opportunities to gain new information from existing management programs are frequently overlooked. It is unfortunate that, despite the large number of restoration projects undertaken in Australia, monitoring and reporting of restoration outcomes is still woefully inadequate: only 14% of restoration projects reported some form of post-works monitoring with few including an evaluation of effectiveness (Brooks and Lake, 2007). This information is urgently needed to inform the development of guidelines for effective riparian restoration and would provide better support for the determination of minimum riparian widths necessary to achieve particular management objectives. The collection of monitoring data, for a suite of key indicators and linked to clearly stated goals, should be an integral part of any restoration program (Palmer *et al.*, 1997).

In addition to the need for improved monitoring and reporting, there are many knowledge gaps that need addressing in order to improve our understanding of the role of riparian zone width in achieving management objectives. These knowledge gaps are outlined below under eight major themes.

Many of these knowledge gaps could be simultaneously addressed in a large-scale, long-term dedicated ecosystem experiment (at a similar scale to the Hubbard Brook Experimental Forest in North America), where data can be obtained on biotic, physical and chemical processes prior to, during and after disturbance and / or restoration (Likens *et al.*, 1978, Carpenter, 1998). Such an approach would require long-term planning for strategic acquisition of land within an entire catchment (or sub-catchment). Long-term ecological experimentation and monitoring has recently been advocated for Australia by Likens *et al*. (2009).


Upper catchment. Faithful Creek. Photo: P.Reich

| Theme | Knowledge gap | Description | Potential research / management approach | Outcomes |
|---|---|---|---|---|
| 1. Monitoring | Little information available on the effectiveness of restoration projects | Targeted monitoring, evaluation and reporting | Monitoring, evaluation and reporting with respect to a given set of management goals should be a compulsory part of any restoration activity | Information will be available to inform the guideline process and ensure its accuracy and applicability to Victorian systems |
| 2. Hydrology | The effects of flow regulation on riparian zone function | The role of hydrology in mediating riparian zone functions (including off-stream water bodies) and its relationship to riparian width is unclear | Compare riparian zone performance in achieving stated objectives (for example, improving terrestrial biodiversity) above and below impoundments in a variety of landscape contexts | The benefits of narrower or wider riparian zones can be assessed where flow regulation occurs |
| 3. Management objectives | Best approach for managing riparian zones to achieve multiple objectives | Collection of empirical data on augmenting or initiating multiple functions to riparian zones under different restoration strategies | Collect data before, during and after restoration works that relates to different objectives, e.g. N & P interception, riparian vegetation quality and lateral extent, and invertebrate and avian biodiversity | A clearer understanding of where riparian zones restored to a certain width for one management objective (e.g. to increase avian or mammalian diversity) will meet other management objectives (e.g. reduction of non-point source (NPS) pollutants to streams) |
| | The effectiveness of riparian management zones | The use of riparian management zones in North America (developed for Chesapeake Bay watersheds where excess N and sediment are having significant impacts on waterways) has potential application in Australia in areas of high land use intensity (Section 1.5.1) | Experimentally evaluate the effectiveness of riparian management zones in restoration where improving water quality is a primary objective | Targeted application of riparian management zones in areas of high N, P and sediment exports |
| 4. Landscape contexts | The relationship between stream size and riparian function | Information is lacking on how the role of riparian widths in mediating function alters with stream size/order, for factors like carbon inputs and terrestrial biodiversity | A long-term dedicated project across an entire catchment or sub-catchment which simultaneously assesses aquatic and terrestrial processes | This would provide a powerful knowledge base for making recommendations about restoration design, riparian/waterway management and ultimately, implementing policy for |

| Theme | Knowledge gap | Description | Potential research / management approach | Outcomes |
|---|---|---|---|---|
| | | | | catchment management |
| | NPS pollution control in different physiographic regions | The broad-scale classification of dominant mechanisms for removal of NPS pollutants by different physiographic region. | Characterise dominant flow paths in sub-catchments where excess nutrients and sedimentation are dominant environmental issues (*sensu* Lowrance et al 1997). | Identification and prioritisation of areas where delivery of nutrient and sediment to streams is most efficient and most effectively reduced by riparian restoration. This is also relevant to management of groundwater resources |
| 5. Riparian community persistence | An understanding of what constitutes a self-sustaining riparian zone | There is no management criterion for defining and qualifying riparian vegetation that is ecologically self-sustaining (self-recruiting). Furthermore, empirical data that attempts to quantify this in relation to width does not exist | Obtain a comprehensive understanding of the biology of target species and community ecology (potentially focussing on Ecological Vegetation Classes) before attempting to define thresholds for vegetation extent that equates to "self-sustaining". This can only be achieved through multidisciplinary research into natural history, ecology, population biology and quantitative genetic traits of key plant and faunal species | Potential capacity to determine the optimal configuration of plant communities to enables self-recruitment. Initially, this would be determined in the absence of disturbance but would subsequently be used to determine the nature and/or timing of necessary management interventions |
| 6. Data transferability | The applicability of international studies to Victorian systems | There is a need to further explore the applicability/relevance of riparian zone research from places like America to south-east Australia, especially in relation to terrestrial processes (but see Lake *et al.* 1986) | Assess the applicability of research data from other systems to Victorian catchments, either via new experimental comparisons or by analysing existing riparian data | Improved scientific certainty in extrapolating width recommendations from studies in non-Victorian systems |
| 7. Fragmentation and function of riparian habitat | The performance of fragmented riparian zones | The effects of riparian vegetation fragmentation (which is rarely defined clearly) is poorly understood and should be a major area of rigorous research | Use a combination of empirical and modelling approaches in different landscape contexts to elucidate the relationship between patterns of vegetation cover and extent and functions like N and P interception | Targeted restoration of stream sections in different parts of the drainage network |

| Theme | Knowledge gap | Description | Potential research / management approach | Outcomes |
|---|---|---|---|---|
| | The relationship between riparian vegetation width and length | Exploration of the relationship between riparian configuration (length versus area), its suitability as habitat for fauna (e.g. birds and minimum patch size) and its influence over nutrient retention and processing | Experimentally evaluate minimum patch sizes for riparian zones harbouring different vegetation classes and faunal assemblages | An clearer understanding of where and when to prioritise longitudinal riparian restoration over lateral (e.g. improving continuity of riparian zones rather than increasing their width) |
| | | Knowledge relating to the extent of riparian zone use by adult aquatic insects (for breeding and foraging), the distances they move into the riparian zone to mate and emerge, and the influence of vegetation cover on these movements is lacking in Australia | Experimentally assess terrestrial habitat use by aquatic invertebrate communities, especially where there is flow regulation and land use modifications | Improvement of ecological assessments (for example, ISC) and better translation of biotic indices into terrestrial habitat management for in-stream fauna<br>Targeted management of highly fragmented systems for rehabilitation of aquatic communities |
| | The influence of invasive species on riparian functions | The functionality of riparian zones dominated by invasives is not well understood and those which are maintained or lost in these 'novel ecosystems' are not known. | Expand the focus of riparian research beyond the impacts of willows to include the effects of other invasive species on key riparian functions in different landscape settings | The ability to make pragmatic trade-offs between the level of riparian function or performance and the level of management effort |
| | Habitat use by riparian obligate versus generalist species | The relative reliance of riparian-dependent versus generalist species on intact riparian zones in different landscape contexts requires investigation | Experimentally assess habitat use bf key terrestrial fauna of riparian zones in modified and unmodified landscapes. This should be conducted in both regulated and unregulated systems | This will provide better information relating terrestrial biodiversity management goals to riparian restoration design in different landscape contexts |
| 8. Nutrient cycling and subsidies | Riparian carbon contributions and DOC dynamics | The role of riparian vegetation in influencing carbon inputs, and the ecological role of DOC in-stream and soils is still poorly understood | Experimentally investigate floodplain plant-soil carbon dynamics in riparian restoration projects. Differences between regulated and unregulated systems should be explored | Improvement of riparian and in-stream carbon stocks for both biotic processes and climate change mitigation (through sequestration) |

| **Theme** | **Knowledge gap** | **Description** | **Potential research / management approach** | **Outcomes** |
|---|---|---|---|---|
| | The link between terrestrial and aquatic function | There is virtually no research on reciprocal subsidies and their relevance for terrestrial-aquatic linkages in Australian systems | Increase the focus of research on linking processes (e.g. exploration of the relationship between avian communities and aquatic invertebrate diversity) | Simultaneous improvement of aquatic and terrestrial biodiversity through targeted restoration (i.e. minimum widths required to restore certain vegetation communities as well as improve regional aquatic invertebrate diversity) |
| | Knowledge of N turnover / processing rates | Yet to be quantified for Australian systems | Increasing collaborative arrangements between primary industries and restoration ecology may provide new opportunities for acquisition of knowledge on nutrient processing and its benefits to the simultaneous maintenance of biodiversity and agricultural productivity | Characterisation and spatial delineation of riparian zones that make the most efficient contribution to nutrient retention |

## REFERENCES

Abernethy, B. & Rutherfurd, I.D. (1999) Guidelines for stabilising streambanks with riparian vegetation. Technical Report 99/10. Cooperative Research Centre for Catchment Hydrology. University of Melbourne, Parkville.

Allen, A.W. (1983) *Habitat suitability index models: beaver*, U.S. Fish and Wildlife Service, Washington, D.C.

Allen, A.W. (1986) *Habitat suitability index models: lesser scaup (breeding)*, U.S. Fish and Wildlife Service, Fort Collins, CO

Anderson, B.G., Rutherfurd, I.D. & Western, A.W. (2006) An analysis of the influence of riparian vegetation on the propagation of flood waves. *Ecological Modelling and Software,* **21,** 1290-1296.

Andrew, D.L., Lumsden, L.F. & Dixon, J.M. (1984) *Sites of Zoological Significance in the Westernport Region*, Department of Conservation Forests and Lands, Melbourne

Arthington, A.H., Bunn, S.E. & Catterall, C.P. (1992) The ecological roles of riparian vegetation. In: *The Role of Buffer Strips in the Management of Waterway Pollution from Diffuse Urban and Rural Sources.* (J. Woodfull & B. Finlayson & T. Mcmahon), pp. 93-102. Land and Water Resources Research and Development Corporation.

Bailey, C.E., Millar, R.G. & Miles, M. (2005) A proposed index of channel sensitivity to riparian disturbance. In: *Geomorphological Processes and Human Impacts in River Basins.* (R.J. Batalla & C. Garcia), pp. 223-230. Wallingford, Oxfordshire, UK.

Ballinger, A. & Lake, P.S. (2006) Energy and nutrient fluxes from rivers and streams into terrestrial food webs. *Marine and Freshwater Research,* **57,** 15-28.

Balmer, W.F., Williston, H.L., Dissmeyer, G.E. & Pierce, C. (1982) *Site preparation - why and how*, U.S. Department of Agriculture Forest Service, Atlanta, Georgia

Barling, R.D. & Moore, I.D. (1994) Role of Buffer Strips in Management of Waterway Pollution: A Review. *Environmental Management,* **18,** 543-558.

Battin, T.J., Kaplan, L.A., Findlay, S., Hopkinson, C.S., Martí, E., Packman, A.I., Newbold, J.D. & Sabater, F. (2008) Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience,* **1,** 95-100.

Baxter, C.V., Fausch, K.D. & Saunders, W.C. (2005) Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. *Freshwater Biology,* **50,** 201-220.

Beavis, S. & Lewis, B. (2001) The impact of farm dams on the management of water resources within the context of total catchment development. In: *Third Australian Stream Management Conference.* (I.D. Rutherfurd & F. Sheldon & G. Brierley & C. Kenyon), pp. 23-28. CRC for Catchment Hydrology.

Bell, I. & Priestley, T. (1999) Management Of Stock Access To The Riparian Zone. In: *Second Australian Stream Management Conference.* (I.D. Rutherfurd & R. Bartley), pp. 51-56. CRC for Catchment Hydrology.

Bengsen, A.J. & Pearson, R.G. (2006) Examination of factors potentially affecting riparian bird assemblages in a tropical Queensland savanna. *Ecological Management and Restoration,* **7,** 141-144.

Bennett, A., Brown, G., Lumsden, L., ☐Hespe, D., Krasna, S. & Silins, J. (1998) Fragments for the Future. Wildlife in the Victorian Riverina (the Northern Plains). Department of Natural Resources and Environment. East Melbourne.

Bennett, S.J. & Virtue, J.G. (2004) Salinity mitigation versus weed risk - can conflicts of interest in introducing new plants be resolved? *Australian Journal of Experimental Agriculture,* **44,** 1141-1156.

Bentley, J.M. & Catterall, C.P. (1997) The Use of Bushland, Corridors, and Linear Remnants by Birds in Southeastern Queensland, Australia. *Conservation Biology,* **11,** 1173-1189.

Bernhardt, E.S. & Likens, G.E. (2002) Dissolved Organic Carbon Enrichment Alters Nitrogen Dynamics in a Forest Stream. *Ecology,* **83,** 1689-1700.

Bernhardt, E.S., Likens, G.E., Hall Jr., R.O., Buso, D.C., Fisher, S.G., Burton, T.M., Meyer, J.L., Mcdowell, W.H., Mayer, M.S., Bowden, W.B., Findlay, S.E.G., Macneale, K.H., Stelzer, E.S. & Lowe, W.H. (2005) Can't See the Forest for the Stream? In-stream Processing and Terrestrial Nitrogen Exports. *BioScience,* **55,** 219-230.

Beschta, R.L., Bilby, R.E., Brown, G.W., Holtby, L.B. & Hofstra, T.D. (1987) Stream temperature and aquatic habitat: Fisheries and forestry interactions. In: *Streamside management: Forestry and Fishery Interactions.* (E.O. Salo & T.W. Cundy), pp. 191-232. University of Washington, Seattle, WA.

Biggs, A., Tolmie, P. & Silburn, D. (2006) *Deep Drainage: A problem or a asset?*, Department of Natural Resources and Water,

Bird, P.R., Jackson, T.T., Kearney, G.A., Saul, G.R., Waller, R.A. & Whipp, G. (2004) The effect of improved pastures and grazing management on soil water storage on a basaltic plains site in south-west Victoria. *Australian Journal of Experimental Agriculture,* **44,** 559-569.

Boedeltje, G., Bakker, J.P., Brinke, A.T., Van Groenendael, J.M. & Soesburgen, M. (2004) Dispersal phenology of hydrochorous plants in relation to discharge, seed release time and buoyancy of seeds: the flood pulse concept supported *Journal of Ecology,* **92,** 786-796.

Bombino, G., Gurnell, A.M., Tamburino, V., Zema, D.A. & Zimbone, S.M. (2008) Sediment size variation in torrents with check dams: Effects on riparian vegetation. *Ecological Engineering,* **32,** 166-177.

Borin, M. & Bigon, E. (2002) Abatement of NO3–N concentration in agricultural waters by narrow buffer strips. *Environmental Pollution,* **117,** 165-168.

Bottom, D.L., Howell, P.J. & Rodgers, J.D. (1983) Final report: fish research project Oregon salmonid habitat restoration. Oregon Department of Fish and Wildlife. Portland.

Boulton, A.J. & Lake, P.S. (1992) Benthic organic matter and detritivorous macroinvertebrates in two intermittent streams in south-eastern Australia. *Hydrobiologia,* **241,** 107-118.

Bowman, I. & Siderius, J. (1984) *Management guidelines for the protection of heronries in Ontario*, Wildlife Branch. Ontario Ministry of Natural Resources, Toronto

Brainwood, M., Burgin, S. & Byrne, M. (2006) Is the decline of freshwater mussel populations in a regulated coastal river in south-eastern Australia linked with human modification of habitat? *Aquatic Conservation: Marine and Freshwater Ecosystems,* **16,** 501-516.

Bramley, H., Hutson, J. & Tyerman, S.D. (2003) Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species Eucalyptus largiflorens. *Plant and Soil,* **253,** 275-286.

Brazier, J.R. & Brown, G.W. (1973) Buffer strips for stream temperature control. Research Paper 15. Forest Research Lab. Oregon State University, Corvallis, Or.

Bren, L.J. (2000) A case study in the use of threshold measures of hydrologic loading in the design of stream buffer strips. *Forest Ecology and Management,* **132,** 243-257.

Bren, L.J. & Turner, A.K. (1980) Hydrologic output of small forested catchments: implications for management. *Australian Forestry,* **43,** 111.

Brooks, A.P., Gehrke, P.C., Jansen, J.D. & Abbe, T.B. (2004) Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic amd ecological responses. *River Research and Applications,* **20,** 513-536.

Brooks, S.S. & Lake, P.S. (2007) River Restoration in Victoria, Australia: Change is in the Wind, and None too Soon. *Restoration Ecology,* **15,** 584-591.

Brosofske, K.B., Chen, J., Naiman, R.J. & Franklin, J.F. (1997) Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. *Ecological Applications,* **7,** 1188-1200.

Brown, E.R. & Krygier, J.T. (1970) Effects of clear-cutting on stream temperature. *Water Resources Research,* **6,** 1133-1139.

BrüSch, W. & Nilsson, B. (1993) Nitrate transformation and water movement in a wetland area. *Hydrobiologia,* **251,** 103-111.

Bunn, S.E. (1993) Riparian-stream linkages: research needs for the protection of in-stream values. *Australian Biologist,* **6,** 46-51.

Burdon, F.J. & Harding, J.S. (2008) The linkage between riparian predators and aquatic insects across a stream-resource spectrum. *Freshwater Biology,* **53,** 330-346.

Burns, D.A. & Nguyen, L. (2002) Nitrate movement and removal along a shallow groundwater flow path in a riparian wetland within a sheep-grazed pastoral catchment: results of a tracer study. *New Zealand Journal of Marine and Freshwater Research,* **36,** 371-385.

Burrows, D.W. & Butler, B. (2001) Managing livestock to protect the aquatic resources of the Burdekin catchment, North Queensland. In: *Third Australian Stream Management Conference.* (I.D. Rutherfurd & F. Sheldon & G. Brierley & C. Kenyon), pp. 95-102. CRC for Catchment Hydrology.

Busch, D.E., Ingraham, N.L. & Smith, S.D. (1992) Water Uptake in Woody Riparian Phreatophytes of the Southwestern United States: A Stable Isotope Study. *Ecological Applications,* **2,** 450.

Callow, J.N. & Smettem, K.R.J. (2007) Channel response to a new hydrological regime in southwester n Australia. *Geomorphology,* **84,** 254-276.

Campbell, I.C. (1993) Riparian Stream Linkages: an Australian Perspective on In-stream Issues. Ecology and Management of Riparian Zones in Australia. S.E. Bunn & B.J. Pusey & P. Price. Land and Water Resources Research and Development Corporation, Marcoola, Queensland. Occasional Paper Series No:05/93: Occasional Paper Series No:05/93.

Campbell, I.C., James, K.R., Hart, B.T. & Devereaux, A. (1992) Allochthonous coarse particulate organic material in forest and pasture reaches of two south-eastern Australian streams. I. Litter accession. *Freshwater Biology,* **27,** 341-352.

Capon, S.J. (2007) Effects of flooding on seedling emergence from the soil seed bank of a large desert floodplain. *Wetlands,* **27,** 904-914.

Carpenter, S.R. (1998) The Need for Large-Scale Experiments to Assess and Predict the Response of Ecosystems to Perturbation. In: *Successes, Limitations and Frontiers in Ecosystem Science.* (M.L. Pace & P.M. Groffman), pp. 287-312. Springer-Verlag, New York.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N. & Smith, V.H. (1998) Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications,* **8,** 559-568.

Cassirer, E.F. & Groves, C.R. (1990) Distribution, habitat use, and status of harlequin ducks in northern Idaho. Idaho Fish and Game, Boise.

Castelle, A.J., Conolly, C., Cooke, S., Emers, M., Erickson, T., E.D., M., Meyer, S., Mauermann, S. & Witter, M. (1992) *Wetland buffers: use and effectiveness*, Washington Department of Ecology, Olympia

Castelle, A.J., Johnson, A.W. & Conolly, C. (1994) Wetland and Steam Buffer Size Requirements - A Review. *Journal of Environmental Quality,* **23,** 878-882.

Catterall, C.P. (1993) The Importance of Riparian Zones to Terrestrial Wildlife. In: *Ecology and Management of Riparian Zones in Australia.* (S.E. Bunn & B.J. Pusey & P. Price), pp. 41-52. Land and Water Resources Research and Development Corporation.

Catterall, C.P., Piper, S.P., Bunn, S.E. & Arthur, M.J. (2001) Flora and fauna assemblages vary with local topography in a subtropical eucalypt forest. *Austral Ecology,* **26,** 56-69.

Cederholm, C.J. (1994) A suggested landscape approach for salmon and wildlife habitat protection in western Washington riparian ecosystem. In: *Washington forest landscape management project —progress report. Report No. 1.* (A.B. Carey & C. Elliott), pp. 78-90. Washington Department of Natural Resources, Olympia.

Cey, E.E., Rudolph, D.L., Aravena, R. & Parkin, G. (1999) Role of the riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in southern Ontario. *Journal of Contaminant Hydrology,* **37,** 45-67.

Chalmers, R.W. (1979) Erosion from snig-tracks on granite/ adamellite-derived soils. *Australian Forest Research Newsletter,* **6,** 142.

Chen, J., Franklin, J.F. & Spies, T.A. (1992) Vegetation responses to edge environments in old-growth Douglas-fir forests. *Ecological Applications,* **2,** 387-396.

Clarke, A., Mac Nally, R., Bond, N. & Lake, P.S. (2008) Macroinvertebrate diversity in headwater streams: a review. *Freshwater Biology,* **53,** 1707-1721.

Clarke, M.F. & Oldland, J.M. (2007) Penetration of remnant edges by noisy miners (*Manorina melanocephala*) and implications for habitat restoration. *Wildlife Research,* **34,** 253-261.

Clausen, J.C., Guillard, K., Sigmund, C.K. & Dors, K.M. (2000) Water quality changes from riparian buffer restoration in Connecticut. *Journal of Environmental Quality,* **29,** 1751-1761.

Clift, S.H., O'dowd, D.J. & Mac Nally, R. (in prep) Impacts of willow (*Salix* ξ *rubens*) invasion on riparian birds alont the Tarago River in West Gippsland, Victoria, Australia.

Clothier, R.R. (1955) Contribution to the life history of *Sorex vagrans* in Montana. *Journal of Mammalogy,* **36,** 214-221.

Collier, K.J. & Smith, B.J. (1998) Dispersal of adult caddisflies (Trichoptera) into forests alongside three New Zealand streams. *Hydrobiologia,* **361,** 53-65.

Collier, K.J. & Smith, B.J. (2000) Interactions of Adult Stoneflies (Plecoptera) with Riparian Zones I. Effects of Air Temperature and Humidity on Longevity. *Aquatic Insects,* **22,** 275-284.

Connor, R.N., Hooper, R.G., Crawford, H.S. & Mosby, H.S. (1975) Woodpecker nesting habitat in cut and uncut woodlands in Virginia. *Journal of Wildlife Management,* **39,** 144-150.

Cooper, A.B. (1990) Nitrate depletion in the riparian zone and stream channel of a small headwater catchment. *Hydrobiologia,* **202,** 13-26.

Cooper, A.B., Smith, C.M. & Smith, M.J. (1995) Effects of riparian set-aside on soil characteristics in an agricultural landscape: Implications for nutrient transport and retention. *Agriculture, Ecosystems and Environment,* **55,** 61-67.

Cooper, J.R., Gilliam, J.W., Daniels, R.B. & Robarge, W.P. (1987) Riparian Areas as Filters for Agricultural Sediment. *Soil Science Society of America Journal,* **51,** 416-420.

Corbett, E.S. & Lynch, J.A. (1985) Management of streamside zones on municipal watersheds. In: *Riparian ecosystems and their management: reconciling conflicting uses.* (R.R. Johnson & C.D. Ziebell & D.R. Patton & P.F. Ffolliott & R.H. Hamre), pp. 187-190. U.S. For. Serv. Gen. Tech. Rep. RM-120.

Corbett, E.S., Lynch, J.A. & Sopper, W.E. (1978) Timber Harvesting Practices and Water Quality in the Eastern United States. *Journal of Forestry,* **76,** 484-488.

Cormack, R.G.H. (1949) A study of trout streamside cover in logged-over and undisturbed virgin spruce woods. *Canadian Journal of Forest Research,* **27,** 78-95.

Cornish, P.M. (1975) The impact of forest operations on water quality. Forestry Commission of New South Wales, Sydney.

Correll, D.L. (2005) Principles of planning and establishment of buffer zones. *Ecological Engineering,* **24,** 433-439.

Craig, L.S., Palmer, M.A., Richardson, D.C., Filoso, S., Bernhardt, E.S., Bledsoe, B.P., Doyle, M.W., Groffman, P.M., Hassett, B.A., Kaushal, S.S., Mayer, P.M., Smith, S.M. & Wilcock, P.R. (2008) Stream restoration strategies for reducing river nitrogen loads. *Frontiers in Ecology and the Environment,* **6,** 529-538.

Croonquist, M.J. & Brooks, R.P. (1993) Effects of habitat disturbance on bird communities in riparian corridors. *Journal of Soil and Water Conservation,* **48,** 65-70.

Cross, S.P. (1985) Responses of small mammals to forest riparian perturbations. In: *Riparian ecosystems and their management: reconciling conflicting uses.* (R.R. Johnson & C.D. Ziebell & D.R. Patton & P.F. Ffolliott & R.H. Hamre), pp. 269-275. U.S. For. Serv. Gen. Tech. Rep. RM-120.

Cummins, K.W. (1974) Structure and Function of Stream Ecosystems. *BioScience,* **24,** 631-641.

Cummins, K.W. (1993) Riparian Stream Linkages: In-stream issues. In: *Ecology and Management of Riparian Zones in Australia.* (S.E. Bunn & B.J. Pusey & P. Price), pp. 5-20. Land and Water Resources Research and Development Corporation.

Cummins, K.W., Wilzbach, M.A., Gates, D.M., Perry, J.B. & Taliaferro, B. (1989) Shredders and Riparian Vegetation. *BioScience,* **39,** 24-30.

Davies, P., Cook, B., Rutherford, K. & Walshe, T. (2004) *Managing high in-stream temperatures using riparian vegetation*, River Management Technical Guideline, 5. Land and Water Australia, Canberra

Davies, P.E. & Nelson, M. (1994) Relationships between Riparian Buffer Widths and the Effects of Logging on Stream Habitat, Invertebrate Community Composition and Fish Abundance. *Australian Journal of Marine and Freshwater Research,* **45,** 1289-1305.

Davies, P.M. & Bunn, S.E. (1999) Restoring Fundamental Ecological Processes in Small, Forested Upland Streams: The Importance of Riparian Vegetation. In: *Second Australian Stream Management Conference.* (I.D. Rutherfurd & R. Bartley), pp. 193-198. CRC for Catchment Hydrology.

Davis, R., Hamblin, A., O'loughlin, E., Austin, N., Banens, R., Cornish, P., Cox, J., Hairsine, P.B., Mcculloch, M., Moody, P., Olley, J., Prove, B., Smalls, I. & Weaver, D.M. (1998) Phosphorus in the Landscape: Diffuse Sources to Surface Waters. C.R.C. for Soil and Land Management. L.W.R.R.D. Corporation,.

Department of Sustainability and Environment (2007) *Code of Practice for Timber Production*, Melbourne

Dewalle, D.R. (2008) Guidelines for Riparian Vegetative Shade Restoration Based Upon a Theoretical Shaded-Stream Model. *Journal of the American Water Resources Association,* **44,** 1373-1387.

Dickson, J.G. (1989) Streamside zones and wildlife in southern U.S. forests. In: *Practical approaches to riparian resource management: An educational workshop.* (R.G.

Gresswell & B.A. Barton & J.L. Kershner), pp. 131-133. U.S. Bureau of Land Management, Billings, MT.
Dickson, J.G., Williamson, J.H., Connor, R.N. & Ortego, B. (1995) Streamside Zones and Breeding Birds in Eastern Texas. *Wildlife Society Bulletin,* **23,** 750-755.
Dignan, B. & Bren, L. (2003) Modelling light penetration edge effects for stream buffer design in mountain ash forest in southeastern Australia. *Forest Ecology and Management,* **179,** 95-106.
Dillaha, T.A., Reneau, R.B., Mostaghimi, S. & Lee, D. (1989) Vegetative Filter Strips for Agricultural Nonpoint Source Pollution Control. *Transactions of the American Society of Agricultural Engineers,* **32,** 513-519.
Dillaha, T.A., Sherrad, J.H., Lee, D., Mostaghimi, S. & Shanholtz, V.O. (1988) Evaluation of vegetative filter strips as a best management practice for feed lots. *Journal of the Water Pollution Control Federation,* **60,** 1231-1238.
Dipnr (2004) Riparian Corridor Management Study. Department of Infrastructure Planning and Natural Resources. Wollongong.
Dobson, F.S., Chesser, R.K., Hoogland, J.L., Sugg, D.W. & Foltz, D.W. (1998) Breeding Groups and Gene Dynamics in a Socially Structured Population of Prairie Dogs. *Journal of Mammalogy,* **79,** 671-680.
Dorrough, J., Yen, A., Turner, V., Clark, S.G., Crosthwaite, J. & Hirth, J.R. (2004) Livestock grazing management and biodiversity conservation in Australian temperate grassy landscapes. *Australian Journal of Agrilcultural Research,* **55,** 279-295.
Dosskey, M.G., Helmers, M.J. & Eisenhauer, D.E. (2006) An approach for using soil surveys to guide the placement of water quality buffers. U.S.D.A. Forest Service – National Agroforestry Center. Lincoln.
Douglas, G.W. (1977) Vermin and noxious weeds on stream frontages. *Victoria's Resources,* **19,** 27-29.
Doupé, R.G., Lymbery, A.J. & Pettit, N.E. (2006) Stream salinization is associated with reduced taxonomic, but not functional diversity in a riparian plant community. *Austral Ecology,* **32,** 388-393.
Doyle, R.C., Stanton, C.G. & Wolf, D.C. (1977) Effectiveness of forest and grass buffer strips in improving the water quality of manure polluted runoff. ASAE Paper No. 77-2501, St Joseph, Mich.
Drewry, J.J., Newham, L.T.H., Greene, R.S.B., Jakeman, A.J. & Croke, B.F.W. (2006) A review of nitrogen and phosphorus export to waterways: context for catchment modelling. *Marine and Freshwater Research,* **57,** 757-774.
Dse (2007) *Code of Practice for Timber Production*, Department of Sustainability and Environment, Melbourne
Erman, D.C., Newbold, J.D. & Roby, K.B. (1977) Evaluation of streamside buffer strips for protecting aquatic organisms. Tech. Comp. Rep., Contrib. 16. California Water Resource Center. University of California-Davis, Davis, CA.
Erskine, W.D. (2001) Geomorphic evaluation of past river rehabilitation works on the Williams River,New South Wales. *Ecological Management and Restoration,* **2,** 116-128.
Erskine, W.D., Terrazzolo, N. & Warner, R.F. (1999) River rehabilitation from the hydrogeomorphic impacts of a large hydro-electric power project: Snowy River, Australia. *Regulated Rivers: Research and Management,* **15,** 3-24.
Fellows, C.S., Hunter, H. & Grace, M. (2007) Managing diffuse nitrogen loads: in-stream and riparian zone nitrate removal. Salt, Nutrient, Sediment and Interactions: Findings from the National River Contaminants Program. S. Lovett & P. Price & B. Edgar. Land and Water Australia, Canberra.

Femat (1993) *Forest Ecosystem Management: An Ecological, Economic, and Social Assessment*, C. U.S. Departments of Agriculture, and Interior, Portland, OR

Ficetola, G.F., Padoa-Schioppa, E. & De Bernardi, F. (2008) Influence of Landscape Elements in Riparian Buffers on the Conservation of Semiaquatic Amphibians. *Conservation Biology,* **23,** 114-123.

Fischer, R.A. & Fischenich, J.C. (2000) Design Recommendations for Riparian Corridors and Vegetated Buffer Strips. U.S. Army Engineer Research and Development Center,, Vicksburg, MS. ERDC TN-EMRRP-SR-24: ERDC TN-EMRRP-SR-24.

Fisher, S.G., Sponsellar, R. & Heffernan, J. (2004) Horizons in stream biogeochemistry: flowpaths to progress. *Ecology,* **85,** 2369-2379.

Francis, R.A. & Gurnell, A.M. (2006) Initial establishment of vegetative fragments within the active zone of a braided gravel-bed river (River Tagliamento, NE Italy). *Wetlands,* **26,** 641-648.

Franklin, J.F. & Forman, R.T. (1987) Creating landscape patterns by forest cutting: ecological consequences and principles. *Landscape Ecology,* **1,** 5-18.

Freel, M. (1991) *A literature review for management of the marten and fisher on national forests in California*, U.S. Forestry Service. Pacific Southwest Region, San Francisco, CA

Fustec, E., Mariotti, A., Grillo, X. & Sajus, J. (1991) Nitrate Removal by Denitrification in Alluvial Ground Water: Role of a Former Channel. *Journal of Hydrology,* **123,** 337-354.

Gabriel-Jones, D. (2008) A Review of the Management of Riparian Land in Victoria. Department of Sustainability and Environment, Melbourne.

Gaines, D. & Laymon, S.A. (1984) Decline, status and preservation of the yellow-billed cuckoo in California. *Western Birds,* **15,** 49-80.

Gates, J.E. & Giffen, N.R. (1991) Neotropical migrant birds and edge effects at a forest-stream ecotone. *Wilson Bulletin,* **103,** 204-217.

Gawne, B., Merrick, C., Williams, D.G., Rees, G., Oliver, R., Bowen, P.M., Treadwell, S., Beattie, G., Ellis, I., Frankenberg, J. & Lorenz, Z. (2007) Patterns of Primary and Heterotrophic Productivity in an Arid Lowland River. *River Research and Applications,* **23,** 1070-1087.

Ghaffarzadeh, M., Robinson, C.A. & Cruse, R.M. (1992) Vegetative filter strip effects on sediment deposition from overland flow. In: *Agronomy Abstracts.* (American Society of Agronomy, Madison, Wisconsin.

Gibney, L. (1977) The tenure of river frontages. *Victoria's Resources,* **19,** 2-3.

Gilmer, D.S., Ball, I.J., Cowardin, L.M., Mathisen, J.E. & Riechmann, J.H. (1978) Natural cavities used by wood duck in north-central Minnesota. *Journal of Wildlife Management,* **42,** 288-298.

Graynoth, E. (1979) Effects of logging on stream environments and faunas in Nelson. *New Zealand Journal of Marine and Freshwater Research,* **13,** 79-109.

Greenwood, H., O'dowd, D.J. & Lake, P.S. (2004) Willow (*Salix* × *rubens*) invasion of the riparian zone in south-eastern Australia: reduced abundance and altered composition of terrestrial arthropods. *Diversity and Distributions,* **10,** 485-492.

Gregory, S.V., Lamberti, G.A., Erman, D.C., Koski, K.V., Murphy, M.L. & Sedell, J.R. (1987) Influence of forest practices on aquatic production. In: *Streamside management: forestry and fishery interactions.* (E.O. Salo & T.W. Cundy), pp. 233-255. College of Forest Resources. University of Washington, Seattle.

Gregory, S.V., Swanson, F.J., Mckee, W.A. & Cummins, K.W. (1991) An Ecosystem Perspective of Riparian Zones. *BioScience,* **41,** 540-551.

Grice, D. & Rogers, J.P. (1965) The wood duck in Massachusetts. Massachusetts Division of Fish and Game. Final Rep. W-19-R.

Grismer, M.E. (1981) *Evaluating dairy waste management systems influence on fecal coliform concentration in runoff.* MSc, Oregon State University, Corvallis.

Growns, I.O. & Davis, J.A. (1991) Comparison of the Macroinvertebrate Communities in Streams in Logged and Undisturbed Catchments 8 Years after Harvesting. *Australian Journal of Marine and Freshwater Research,* **42,** 689-706.

Grubb, T.G. (1980) An evaluation of bald eagle nesting in Western Washington. In: *Washington bald eagle symposium.* (R.L. Knight & T.G. Allen & M.V. Stalmaster & C.W. Servheen), pp. 79-95.

Gurnell, A.M., Piégay, H., Swanson, F.J. & Gregory, S.V. (2002) Large wood and fluvial processes. *Freshwater Biology,* **47,** 601-619.

Hall, J.G. (1960) Willow and aspen in the ecology of beaver in Sagehen Creek, California. *Ecology,* **41,** 484-494.

Hannon, S.J., Paszkowski, C.A., Boutin, S., Degroot, J., Macdonald, S.E., Wheatley, M. & Eaton, B.R. (2002) Abundance and species composition of amphibians, small mammals, and songbirds in riparian forest buffer strips of varying widths in the boreal mixedwood of Alberta. *Canadian Journal of Forest Research,* **32,** 1784-1800.

Hanson, G.C., Groffman, P.M. & Gold, A.J. (1994) Symptoms of nitrogen saturation in a riparian wetland. *Ecological Applications,* **4,** 750-756.

Harris, G.P. (2001) Biogeochemistry of nitrogen and phosphorus in Australian catchments, rivers and estuaries: effects of land use and flow regulation and comparisons with global patterns. *Marine and Freshwater Research,* **52,** 139-149.

Harris, L.D. (1984) *The fragmented forest: island biogeography theory and the preservation of biotic diversity,* University of Chicago Press, Chicago, Illinois.

Haupt, H.F. (1959) Road and slope characteristics affecting sediment movement from logging roads. *Journal of Forestry,* **57,** 329-332.

Haupt, H.F. & Kidd, W.J. (1965) Good Logging Practices Reduce Sedimentation in Central Idaho. *Journal of Forestry,* **63,** 664-670.

Hawes, E. & Smith, M. (2005) Riparian Buffer Zones: Functions and Recommended Widths. Eightmile River Wild and Scenic Study Committee.

Haycock, N.E. & Burt, T.P. (1993) Role of Floodplain Sediments in Reducing the Nitrate Concentration of Subsurface Run-Off - a Case-Study in the Cotswolds, UK. *Hydrological Processes,* **7,** 287-295.

Haycock, N.E. & Pinay, G. (1993) Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. *Journal of Environmental Quality,* **22,** 273-278.

Hefting, M.M., Bobbink, R. & De Caluwe, H. (2003) Nitrous oxide emission and denitrification in chronically nitrate-loaded riparian buffer zones. *Journal of Environmental Quality,* **32,** 1194-1203.

Hefting, M.M. & De Klein, J.M.M. (1998) Nitrogen removal in buffer strips along a lowland stream in the Netherlands: a pilot study. *Journal of Environmental Quality,* **102,** 521-526.

Hennings, L.A. & Edge, W.D. (2003) Riparian bird community structure in Portland, Oregon: Habitat, urbanization, and spatial scale patterns. *Condor,* **105,** 288-302.

Herron, N.F. & Hairsine, P.B. (1998) A scheme for evaluating the effectiveness of riparian zones in reducing overland flow to streams. *Australian Journal of Soil Research,* **36,** 683-698.

Hewlett, J.D. & Fortson, J.C. (1982) Stream temperature under an inadequate buffer strip in the southeast Piedmont. *Water Resources Bulletin,* **18,** 983-988.

Hickman, T. & Raleigh, R.F. (1982) *Habitat suitability index models: cutthroat trout*, U.S. Fish and Wildlife Service,

Hill, A.R., Devito, K.G., Campagnolo, S. & Sanmugadas, K. (2000) Subsurface Denitrification in a Forest Riparian Zone: Interactions between Hydrology and Supplies of Nitrate and Organic Carbon. *Biogeochemistry,* **51,** 193-223.

Hodges Jr, M.F. & Krementz, D.G. (1996) Neotropical migratory breeding bird communities in riparian forests of different widths along the Altamaha River, Georgia. *Wilson Bulletin,* **108,** 496-506.

Holland, K.L., Tyerman, S.D., Mensforth, L.J. & Walker, G.R. (2006) Tree water sources over shallow, saline groundwater in the lower River Murray, south-eastern Australia: implications for groundwater recharge mechanisms. *Australian Journal of Botany,* **54,** 193-205.

Holland-Clift, S. & Davies, J. (2007) Willows national management guide: current management and control options for willows (*Salix* spp.) in Australia. Victorian Department of Primary Industries. Geelong.

Hopmans, P. & Bren, L.J. (2007) Long-term changes in water quality and solute exports in headwater streams of intensively managed radiata pine and natural eucalypt forest catchments in south-eastern Australia. *Forest Ecology and Management,* **253,** 244-261.

Horn, R. & Richards, K. (2007) Flow-Vegetation Interactions in Restored Floodplain Environments. In: *Hydroecology and Ecohydrology: Past, Present and Future.* (P.J. Wood & D.M. Hannah & J.P. Sadler), pp. 269-294. John Wiley and Sons Ltd.

Horner, R.R. & Mar, B.W. (1982) *Guide for Water Quality Impact Assessment of Highway Operations and Maintenance*, Washington Department of Transportation. Olympia,

Houlahan, J.E. & Findlay, C.S. (2004) Estimating the 'critical' distance at which adjacent land-use degrades wetland water and sediment quality. *Landscape Ecology,* **19,** 677-690.

Hubbard, R.K. & Lowrance, R. (1997) Riparian forest buffer system research at the coastal plain experiement station, Tifton, GA. *Water, Air and Soil Pollution,* **77,** 409-432.

Hubbard, R.K. & Sheridan, J.M. (1989) Nitrate movement to groundwater in the southeastern coastal plain. *Journal of Soil and Water Conservation,* **44,** 20-27.

Hughes, V., Thoms, M.C., Nicol, S.J. & Koehn, J. (2007) Physical-Ecological Interactions in a Lowland River System: Large Wood, Hydraulic Complexity and Native FIsh Association in the River Murray, Australia. In: *Hydroecology and Ecohydrology: Past, Present and Future.* (P.J. Wood & D.M. Hannah & J.P. Sadler), pp. 387-403. John Wiley and Sons Ltd.

Jacobs, T.C. & Gilliam, J.N. (1985) Riparian losses of nitrate from agricultural drainage waters. *Journal of Environmental Quality,* **14,** 472-478.

Jansen, A. (2005) Avian Use of Restoration Plantings along a Creek Linking Rainforest Patches on the Atherton Tablelands, North Queensland. *Restoration Ecology,* **13,** 275-283.

Jansen, A. & Robertson, A.I. (2001a) Relationships between livestock management and the ecological condition of riparian habitats along an Australian floodplain river. *Journal of Applied Ecology,* **38,** 63-75.

Jansen, A. & Robertson, A.I. (2001b) Riparian bird communities in relation to land management practices in floodplain woodlands of south-eastern Australia. *Biological Conservation,* **100** .

Johansson, M.E., Nilsson, C. & Nilsson, E. (1996) Do Rivers Function as Corridors for Plant Dispersal? *Journal of Vegetation Science,* **7,** 593-598.

Johnson, A.W. & Ryba, D.M. (1992) A Literature Review of Recommended Buffer Widths to Maintain Various Functions of Stream Ripatian Areas. King County Surface Water Management Division (SWM) Special Report.

Johnson, M., Reich, P. & Mac Nally, R. (2007) Bird assemblages of a fragmented agricultural landscape and the relative importance of vegetation structure and landscape pattern. *Wildlife Research,* **34,** 185-193.

Johnston, W.H., Garden, D.L., Rancic, A., Koen, T.B., Dassanayake, K.B., Langford, C.M., Ellis, N.J.S., Rab, M.A., Tuteja, N.K., Mitchell, M., Wadsworth, J., Dight, D., Holbrook, K., Lelievre, K. & Mcgeoch, S.M. (1993) The impact of pasture development and grazing on water-yielding catchments in the Murray-Darling Basin in south-eastern Australia. *Australian Journal of Experimental Agriculture,* **43,** 817-841.

Jones, J.J., Lottie, J.P. & Pierce Jr, U.D. (1988) The identification and management of significant fish and wildlife resources in southern coastal Maine. Maine Dept. Inland Fish and Wildlife, Augusta.

Jordan, T.E., Correll, D.L. & Weller, D.E. (1993) Nutrient Interception by a Riparian Forest Receiving Inputs from Adjacent Cropland. *Journal of Environmental Quality,* **22,** 467-473.

Junk, W.J., Bayley, P.B. & Sparks, R.E. (1989) The Flood Pulse Concept in River-Floodplain Systems. *Canadian Special Publication of Fisheries and Aquatic Sciences,* **106,** 110-127.

Karr, J.R. & Schlosser, I.J. (1977) *Impact of near stream vegetation and stream morphology on water quality and instream biota*, U.S. Enviromental Protection Agency,

Karssies, L. & Prosser, I.P. (2001) Designing grass filter strips to trap sediment and attached nutrient. In: *Third Australian Stream Management Conference.* (I.D. Rutherfurd & F. Sheldon & G. Brierley & C. Kenyon). CRC for Catchment Hydrology.

Keller, C.M.E., Robbins, C.S. & Hatfield, J.S. (1993) Avian communities in riparian forests of different widths in Maryland and Delaware. *Wetlands,* **13,** 137-144.

Kingsford, R.T. (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology,* **25,** 109-127.

Knopf, F.L. & Samson, F.B. (1994) Scale Perspectives on Avian Diversity in Western Riparian Ecosystems. *Conservation Biology,* **8,** 668-676.

Knutson, K.L. & Naef, V.L. (1997) Management recommendations for Washington's priority habitats: riparian. Washington Department of Fisheries and Wildlife. Olympia.

Labonne, J., Ravigné, V., Parisi, B. & Gaucherel, C. (2008) Linking dendritic network structures to population demogenetics: The downside of connectivity. *Oikos,* **117,** 1479-1490.

Lada, H. & Mac Nally, R. (2008) Decline and potential recovery of Yellow-footed Antechinus in parts of south-eastern Australia: A perspective with implications for management. *Ecological Management and Restoration,* **9,** 120-125.

Lake, P.S. (2005) Perturbation, restoration and seeking ecological sustainability in Australian flowing waters. *Hydrobiologia,* **552,** 109-120.

Lake, P.S., Barmuta, L.A., Boulton, A.J., Campbell, I.C. & St Clair, R.M. (1985) Australian streams and Northern Hemisphere stream ecology: Comparisons and problems. *Proceedings of the Ecological Society of Australia,* **14,** 61-82.

Lake, P.S., Bond, N. & Reich, P. (2007) Linking ecological theory with stream restoration. *Freshwater Biology,* **52,** 597-615.

Lamontagne, S., Leaney, F.W. & Herczeg, A.L. (2005) Groundwater–surface water interactions in a large semi-arid floodplain: implications for salinity management. *Hydrological Processes,* **19,** 3063-3080.

Latterell, J.J., Bechtold, J.S., O'keefe, T.C., Van Pelt, R. & Naiman, R.J. (2006) Dynamic patch mosaics and channel movement in an unconfined river valley of the Olympic Mountains. *Freshwater Biology,* **51,** 523-544.

Lee, A.K. & Mercer, E.H. (1967) Cocoon Surrounding Desert-Dwelling Frogs. *Science,* **157,** 87-88.

Lee, P., Smyth, C. & Boutin, S. (2004) Quantitative review of riparian buffer width guidelines from Canada and the United States. *Journal of Environmental Management,* **70,** 165-180.

Lester, R.E. & Boulton, A.J. (2008) Rehabilitating Agricultural Streams in Australia with Wood: A Review. *Environmental Management,* **42,** 310-326.

Likens, G.E., Bormann, F.H., Pierce, R.S. & Reiners, W.A. (1978) Recovery of a Deforested Ecosystem. *Science,* **199,** 492-496.

Likens, G.E., Walker, K.F., Davies, P.E., Brookes, J., Olley, J., Young, W.J., Thoms, M.C., Lake, P.S., Gawne, B., Davis, J.A., Arthington, A.H., Thompson, R. & Oliver, R.L. (2009) Ecosystem science: toward a new paradigm for managing Australia’s inland aquatic ecosystems. *Marine and Freshwater Research,* **60,** 271-279.

Lindenmayer, D.B., Cunningham, R.B., Tanton, M.B. & Smith, A.P. (1990) The Conservation of Arboreal Marsupials in the Montane Ash Forests of the Central Highlands of Victoria, South-East Australia: II. The Loss of Trees with Hollows and its Implications for the Conservation of Leadbeater's Possum *Gymnobelideus leadbeateri* McCoy (Marsupialia: Petauridae). *Biological Conservation,* **54,** 133-145.

Lloyd, A., Law, B. & Goldingay, R. (2006) Bat activity on riparian zones and upper slopes in Australian timber production forests and the effectiveness of riparian buffers. *Biological Conservation,* **129,** 207-220.

Lock, P.A. & Naiman, R.J. (1998) Effects of Stream Size on Bird Community Structure in Coastal Temperate Forests of the Pacific Northwest, U.S.A. *Journal of Biogeography,* **25,** 773-782.

Lockington, D. (1992) Groundwater flow and contaminant transport. In: *The Role of Buffer Strips in the Management of Waterway Pollution from Diffuse and Urban Rural Sources.* (J. Woodfull & B. Finlayson & T. Mcmahon), pp. 67-70. Land and Water Research and Development Corporation.

Loo, S.E., Mac Nally, R., O'dowd, D.J. & Lake, P.S. (2009) Secondary Invasions: Implications of Riparian Restoration for In-Stream Invasion by an Aquatic Grass. *Restoration Ecology,* **17,** 378-385.

Lorion, C.M. & Kennedy, B.P. (2008) Relationships between deforestation, riparian forest buffers and benthic macroinvertebrates in neotropical headwater streams. *Freshwater Biology,* **54,** 165-180.

Lowe, W.H. & Likens, G.E. (2005) Moving Headwater Streams to the Head of the Class. *BioScience,* **55,** 196-197.

Lowrance, R. (1992) Groundwater Nitrate and Denitrification in a Coastal Plain Riparian Forest. *Journal of Environmental Quality,* **21,** 401-405.

Lowrance, R. (1998) Riparian Forest Ecosystems as Filters for Nonpoint-Source Pollution. In: *Successes, Limitations, and Frontiers in Ecosystem Science.* (M.L. Pace & P.M. Groffman). Springer-Verlag, New York.

Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W. & Todd, A.H. (1997) Water Quality Functions of Riparian Forest Buffers in Chesapeake Bay Watersheds. *Environmental Management,* **21,** 687-712.

Lowrance, R., Sheridan, J.M., Williams, R.G., Bosch, D.D., Sullivan, D.G., Blanchett, D.R., Hargett, L.M. & Clegg, C.M. (2007) Water quality and hydrology in farm-scale coastal plain watersheds: Effects of agriculture, impoundments and riparian zones. *Journal of Soil and Water Conservation,* **62,** 65-76.

Lowrance, R.R., Todd, R.L. & Asmussen, L.E. (1984) Nutrient cycling in an agricultural watershed – I: phreatic movement. *Journal of Environmental Quality,* **13,** 22-27.

Lunn, D.E., Thomas, A., Best, N. & Spielgelhalter, D. (2000) WinBUGS -- a Bayesian modelling framework: concepts, structure, and extensibility. *Statistics and Computing,* **10,** 325-337.

Lunt, I.D., Eldridge, D.J., Morgan, J.W. & Witt, G.B. (2007a) A framework to predict the effects of livestock grazing and grazing exclusion on conservation values in natural ecosystems in Australia. *Australian Journal of Botany,* **55,** 401-415.

Lunt, I.D., Jansen, A., Binns, D.L. & Kenny, S.A. (2007b) Long-term effects of exclusion of grazing stock on degraded herbaceous plant communities in a riparian *Eucalyptus camaldulensis* forest in south-eastern Australia. *Austral Ecology,* **32,** 937-949.

Lynch, J.A., Corbett, E.S. & Mussallem, K. (1985) Best management practices for controlling nonpoint source pollution on forested watershed. *Journal of Soil and Water Conservation,* **40,** 164-167.

Lyon, J.P., Nicol, S.J., Lieschke, J.A. & Ramsey, D.S.L. (2009) Does wood type influence the colonisation of this habitat by macroinvertebrates in large lowland rivers? *Marine and Freshwater Research,* **60,** 384-393.

Mac Nally, R., Molyneaux, G., Thomson, J.R., Lake, P.S. & Read, J. (2008) Variation in widths of riparian-zone vegetation of higher-elevation streams and implications for conservation management. *Plant Ecology,* **198,** 89-100.

Mac Nally, R., Parkinson, A., Horrocks, G. & Young, M. (2002) Current Loads of Coarse Woody Debris on Southeastern Australian Floodplains: Evaluation of Change and Implications for Restoration. *Restoration Ecology,* **10,** 627-635.

Madison, C.E., Blevins, R.L., Frye, W.W. & Barfield, B.J. (1992) Tillage and grass filter strip effects upon sediment and chemical losses. In: *Agronomy Abstracts.* (p. 331. ASA, Madison, WI.

Maron, M. & Fitzsimons, J.A. (2007) Agricultural intensification and loss of matrix habitat over 23 years in the West Wimmera, south-eastern Australia. *Biological Conservation,* **135,** 587-593.

Martin, G. (2003) The role of small ground-foraging mammals in topsoil health and biodiversity: Implications to management and restoration. *Ecological Management and Restoration,* **4,** 114-119.

Martin, T.G., Mcintyre, S., Catterall, C.P. & Possingham, H.P. (2006) Is landscape context important for riparian conservation? Birds in grassy woodland. *Biological Conservation,* **127,** 201-214.

Martin, T.L., Kaushik, N.K., Whiteley, H.R., Cook, S. & Nduhiu, J.W. (1999) Groundwater nitrate concentrations in the riparian zones of two southern Ontario streams. *Canadian Water Resources Journal,* **24,** 125-138.

Mayer, P.M., Reynolds Jr, S.K., Mccutchen, M.D. & Canfield, T.J. (2007) Meta-Analysis of Nitrogen Removal in Riparian Buffers. *Journal of Environmental Quality,* **36,** 1172-1180.

Mayer, P.M., Reynolds, S.K., Mccutchen, M.D. & Canfield, T.J. (2005) *Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: A review of current science and regulations*, U.S. Environment Protection Agency, Cincinnati, OH

Mcdade, M.S., Swanson, F.J., Mckee, W.A., Franklin, J.F. & Van Sickle, J. (1990) Source distances for coarse woody debris entering small streams in western Oregon and Washington. *Canadian Journal of Forest Research,* **20,** 326-330.

Mcdowell, R.W., Biggs, B.J.F., Sharpley, A.N. & Nguyen, L. (2004) Connecting phosphorus loss from agricultural landscapes to surface water quality. *Chemistry and Ecology,* **20,** 1-40.

Mckergow, L.A., Prosser, I.P., Weaver, D.M., Grayson, R.B. & Reed, A.E. (2006a) Performance of grass and eucalyptus riparian buffers in a pasture catchment, Western Australia, part 1: riparian hydrology. *Hydrological Processes,* **20,** 2309-2326.

Mckergow, L.A., Prosser, I.P., Weaver, D.M., Grayson, R.B. & Reed, A.E. (2006b) Performance of grass and eucalyptus riparian buffers in a pasture catchment, Western Australia, part 2: water quality. *Hydrological Processes,* **20,** 2327-2346.

Mckergow, L.A., Weaver, D.M., Prosser, I.P., Grayson, R.B. & Reed, A.E. (2003) Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia. *Journal of Hydrology,* **270,** 253-272.

Mckie, B. & Cranston, P.S. (2001) Colonisation of experimentally immersed wood in south eastern Australia: responses of feeding groups to changes in riparian vegetation. *Hydrobiologia,* **452,** 1-14.

Medin, D.E. & Clary, W.P. (1991) *Breeding bird populations in a grazed and ungrazed riparian habitat in Nevada*, U.F. Service,

Melquist, W.E., Whitman, J.S. & Hornocker, M.G. (1981) Resource partitioning and coexistence of sympatric mink and river otter populations. In: *The Worldwide Furbearer Conference.* (J. Chapman & D. Pursley), pp. 187-220.

Menkhorst, P.W. (1995) *Mammals of Victoria,* Oxford University Press, Melbourne.

Mensforth, L.J., Thorburn, P.J., Tyerman, S.D. & Walker, G.R. (1994) Sources of water Used by Riparian *Eucalyptus camaldulensis* Overlying Highly Saline Groundwater. *Oecologia,* **100,** 21-28.

Mockler, S. & Croke, J. (1999) Prescriptive measures for the prevention of road to stream linkage. In: *Second Australian Stream Management Conference.* (I.D. Rutherfurd & R. Bartley), pp. 451-456. CRC for Catchment Hydrology.

Montgomery, D.R. (1994) Road surface drainage, channel initiation, and slope instability. *Water Resources Research,* **30,** 1925-1932.

Moring, J.R. (1975) The Alsea watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon. Oregon Department of Fish and Wildlife, Corvallis.

Moring, J.R. (1982) Decrease in stream gravel permeability after clear-cut logging: an indication of intragravel conditions for developing salmonid eggs and alevins. *Hydrobiologia,* **88,** 295-298.

Mudd, D.R. (1975) Touchet River Study, Part 1. Wildlife. Appl. Res. Bull. 4. Washington State Game Department, Olympia, WA.

Murphy, M.L. & Koski, K.V. (1989) Input and depletion of woody debris in Alaska streams and implications for streamside management. *North American Journal of Fisheries Management,* **9,** 427-436.

Muscutt, A.D., Harris, G.L., Bailey, S.W. & Davies, D.B. (1993) Buffer zones to improve water quality: a review of their potential use in UK agriculture. *Agriculture, Ecosystems and Environment,* **45,** 59-77.

Naiman, R.J. & Décamps, H. (1997) The Ecology of Interfaces: Riparian Zones. *Annual Review of Ecology and Systematics,* **28,** 621-658.

Naiman, R.J., Décamps, H. & Mcclain, M.E. (2005) *Riparia. Ecology, Conservation, and Management of Streamside Communities,* Elsevier Academic Press, Burlington, Ma.

Naiman, R.J. & Rogers, K.H. (1997) Large Animals and System-Level Characteristics in Riverine Corridors. *BioScience,* **47,** 521-529.

Nakano, S. & Murakami, M. (2001) Reciprocal Subsidies: Dynamic Interdependence between Terrestrial and Aquatic Food Webs. *Proceedings of the National Academy of Sciences of the United States of America,* **98,** 166-170.

Newbold, J.D., Erman, D.C. & Roby, K.B. (1980) Effects of Logging on Macroinvertebrates in Streams With and Without Buffer Strips. *Canadian Journal of Fisheries and Aquatic Sciences,* **37,** 1076-1085.

Newbold, J.D., O'neill, R.V., Elwood, J.W. & Van Winkle, W. (1982) Nutrient Spiralling in Streams: Implications for Nutrient Limitation and Invertebrate Activity. *American Naturalist,* **120,** 628-652.

Nguyen, M.L., Sheath, G.W., Smith, C.M. & Cooper, A.B. (1998) Impact of cattle treading on hill land 2. Soil physical properties and contaminant runoff. *New Zealand Journal of Agricultural Research,* **41,** 279-290.

Norris, R.H., Prosser, I.P., Young, B., Liston, P., Bauer, N., Davies, N., Dyer, F., Linke, S. & Thoms, M. (2001) *The Assessment of River Conditions (ARC). An Audit of the Ecological Condition of Australian Rivers*, CSIRO, National Land and Water Resources Audit Office, Canberra

Ocampo, C.J., Sivapalan, M. & Oldham, C.E. (2006) Field exploration of coupled hydrological and biogeochemical catchment responses and a unifying perceptual model. *Advances in Water Resources,* **29,** 161-180.

Opperman, J.J., Meleason, M., Francis, R.A. & Davies-Colley, R.J. (2008) “Livewood”: Geomorphic and Ecological Functions of Living Trees in River Channels. *BioScience,* **58,** 1069-1078.

Osborne, L.L. & Kovacic, D.A. (1993) Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology,* **29,** 243-258.

Packer, P.E. (1967) Criteria for Designing and Locating Logging Roads to Control Sediment *Forest Science,* **13,** 2-18.

Palmer, G.C. & Bennett, A.F. (2006) Riparian zones provide for distinct bird assemblages in forest mosaics of south-east Australia. *Biological Conservation,* **130,** 447-457.

Palmer, M.A., Ambrose, R.F. & Poff, N.L. (1997) Ecological Theory and Community Restoration Ecology. *Restoration Ecology,* **5,** 291-300.

Parkyn, S. (2004) Review of Riparian Buffer Zone Effectiveness. Ministry of Agriculture and Forestry, Wellington. MAF Technical Paper No: 2004/05: MAF Technical Paper No: 2004/05.

Parris, K.M. & Mccarthy, M.A. (1999) What influences the structure of frog assemblages at forest streams? *Australian Journal of Ecology,* **24,** 495-502.

Paton, P.W.C. (2004) The Effect of Edge of Avian Nest Success: How Strong is the Evidence? *Conservation Biology,* **8,** 17-26.

Payne, N.J., Helson, B.V., Sundaram, K.M.S. & Fleming, R.A. (1988) Estimating buffer zone widths for pesticide applications. *Pesticide Science,* **24,** 147-161.

Pearson, S.F. & Manuwal, D.A. (2001) Breeding Bird Response to Riparian Buffer Width in Managed Pacific Northwest Douglas-fir Forest. *Ecological Applications,* **11,** 840-853.

Peterjohn, W.T. & Correll, D.L. (1984) Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest. *Ecology,* **65,** 1466-1475.

Petersen, R.C., Petersen, L.B.M. & Lacoursiere, I. (1992) A building-block model for stream restoration. In: *River conservation and management.* (P.J. Boon & P. Calow & G.E. Petts), p. 470. Wiley and Sons, New York.

Peterson, B.J., Wollheim, W.M., Webster, J.R., Meyer, J.L., Tank, J.L., Martí, E., Bowden, W.B., Valett, H.M., Hershey, A.E., Mcdowell, W.H., Dodds, W.K., Hamilton, S.K., Gregory, S. & Morrall, D.D. (2001) Control of Nitrogen Export from Watersheds by Headwater Streams. *Science,* **292,** 86-90.

Pinay, G. & Decamps, H. (1988) The role of riparian woods in regulating nitrogen fluxes between the alluvial aquifer and surface water: A conceptual model. *Regulated Rivers: Research and Management,* **2,** 507-516.

Pinay, G., Roques, L. & Fabre, A. (1993) Spatial and Temporal Patterns of Denitrification in a Riparian Forest. *Journal of Applied Ecology,* **30,** 581-591.

Plamondon, A.P. (1982) Increase in suspended sediments after logging, and duration of the effect. *Canadian Journal of Forest Research,* **12,** 883-892.

Polis, G.A., Anderson, W.B. & Holt, R.D. (1997) Toward an Integration of Landscape and Food Web Ecology: The Dynamics of Spatially Subsidized Food Webs. *Annual Review of Ecology and Systematics,* **28,** 289-316.

Pollock, M.M. & Kennard, P.M. (1998) A low-risk strategy for preserving riparian buffers needed to protect and restore salmonid habitat in forested watersheds of Washington State. 10,000 Years Institute, Bainbridge Island, Washington.

Pope, T.R. (1992) The influence of dispersal patterns and mating system on genetic differentiation within and between populations of the red howler monkey (*Alouatta seniculus*). *Evolution,* **46,** 1112-1128.

Prach, K. & Rauch, O. (1992) On filter effects of ecotones. *Ekologia (CSFR),* **11,** 293-298.

Price, P., Lovett, S. & Lovett, J. (2005) *Managing riparian widths*, Fact Sheet 13, Land and Water Australia, Canberra

Prose, B.L. (1985) *Habitat suitability index models: belted-kingfisher*, U.S. Fish and Wildlife Service,

Prosser, I.P., Rutherfurd, I.D., J.M., O., Young, W.J., Wallbrink, P. & Moran, C.J. (2001) Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research,* **52,** 81-99.

Puckett, L.J., Cowdery, T.K., Mcmahon, P.B., Tornes, L.H. & Stoner, J.D. (2002) Using chemical, hydrologic, and age dating analysis to delineate redox processes and flow paths in the riparian zone of a glacial outwash aquifer-stream system. *Water Resources Research,* **38,** 1134.

Pusey, B.J. & Arthington, A.H. (2003) Importance of the riparian zone to the conservation and management of freshwater fish: a review. *Marine and Freshwater Research,* **54,** 1-16.

Qassim, A., Dunin, F. & Bethune, M. (2008) Water balance of centre pivot irrigated pasture in northern Victoria, Australia. *Agricultural Water Management,* **95,** 566-574.

Quinn, J.M., Cooper, A.B., Davies-Colley, R.J., Rutherford, J.C. & Williamson, R.B. (1997) Land use effects on habitat, water quality, periphyton, and benthic invertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research,* **31,** 579-597.

Quinn, J.M., Cooper, A.B. & Williamson, R.B. (1993) Riparian Zones as Buffer Strips: A New Zealand Perspective. In: *Ecology and Management of Riparian Zones in Australia.* (S.E. Bunn & B.J. Pusey & P. Price). Land and Water Resources Research and Development Corporation.

Quinn, J.M., Steele, G.L., Hickey, C.W. & Vickers, M.L. (1994) Upper thermal tolerances of twelve New Zealand stream invertebrate species. *New Zealand Journal of Marine and Freshwater Research,* **28,** 391-397.

Radcliffe, J.C. (2002) Pesticide Use in Australia. Australian Academy of Technological Sciences and Engineering, Parkville, Victoria.

Raleigh, R.F. (1982) *Habitat suitability index models: brook trout*, U.S. Fish and Wildlife Service,

Raleigh, R.F., Hickman, T., Soloman, R.C. & Nelson, P.C. (1984) *Habitat suitability information: rainbow trout*, U.S. Fish and Wildlife Service,

Raleigh, R.F., Miller, N.J. & Nelson, P.C. (1986) *Habitat Suitability Index Models: Chinook Salmon*, U.S. Fish Wildlife Service,
Rassam, D.W., Fellows, C.S., De Hayr, R., Hunter, H. & Bloesch, P. (2006) The hydrology of riparian buffer zones; two case studies in an ephemeral and a perennial stream. *Journal of Hydrology,* **325,** 308-324.
Reed, J.L., Campbell, I.C. & Bailey, P.C.E. (1994) The relationship between invertebrate assemblages and available food at forest and pasture sites in three south- eastern Australian streams. *Freshwater Biology,* **32,** 641-652.
Reid, D.J., Lake, P.S., Quinn, G.P. & Reich, P. (2008a) Association of reduced riparian vegetation cover in agricultural landscapes with coarse detritus dynamics in lowland streams. *Marine and Freshwater Research,* **59,** 998-1014.
Reid, D.J., Quinn, G.P., Lake, P.S. & Reich, P. (2008b) Terrestrial detritus supports the food webs in lowland intermittent streams of south-eastern Australia: a stable isotope study. *Freshwater Biology,* **53,** 2036-2050.
Renöfält, B.M. & Nilsson, C. (2007) Hydroecological Patterns of Change in Riverine Plant Communities. In: *Hydroecology and Ecohydrology: Past, Present and Future.* (P.J. Wood & D.M. Hannah & J.P. Sadler), pp. 317-337. John Wiley and Sons Ltd.
Ridley, A.M., Christy, B.P., White, R.E., Mclean, T. & Green, R. (2003) North-east Victoria SGS National Experimental Site: water and nutrient losses from grazing systems on contrasting soil types and levels of input. *Australian Journal of Experimental Agriculture,* **43,** 799-815.
Roberts, J. (2004) Floodplain Forests and Woodlands in the southern Murray-Darling Basin. Australian Conservation Foundation, Canberra. JR 03/2004: JR 03/2004.
Robison, E.G. & Beschta, R.L. (1990) Identifying trees in riparian areas that can provide coarse woody debris to streams. *Forest Sciences,* **36,** 790-801.
Rodriguez-Iturbe, I., Muneepeerakul, R., Bertuzzo, E., Levin, S.A. & Rinaldo, A. (2009) River networks as ecological corridors: A complex systems perspective for integrating hydrologic, geomorphologic, and ecologic dynamics. *Water Resources Research,* **45,** W01413.
Rounick, J.S. & Winterbourn, M.J. (1983) The formation, structure and utilization of stone surface organic layers in two New Zealand streams. *Freshwater Biology,* **13,** 57-72.
Rudolph, D.C. & Dickson, J.G. (1990) Streamside zone width and amphibian and reptile abundance. *The Southwestern Naturalist,* **35,** 472-476.
Runge, F.D. (1977) Whole catchment management. *Victoria's Resources,* **19,** 15-17.
Rutherford, J.C., Marsh, N.A., Davies, P.M. & Bunn, S.E. (2004) Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? *Marine and Freshwater Research,* **55,** 737-748.
Sabo, J.L. & Power, M.E. (2002) River-Watershed Exchange: Effects of Riverine Subsidies on Riparian Lizards and Their Terrestrial Prey. *Ecology,* **83,** 1860-1869.
Sabo, J.L., Sponsellar, R., Dixon, M., Gade, K., Harms, T., Heffernan, J., Jani, A., Katz, G., Soykan, C., Watts, J. & Welter, J. (2005) Riparian zones increase regional species richness by harbouring different, not more, species. *Ecology,* **86,** 56-62.
Schellinger, G.R. & Clausen, J.C. (1992) Vegetative Filter Treatment of Dairy Barnyard Runoff in Cold Regions. *Journal of Environmental Quality,* **21,** 40-45.
Schlorff, R.W., Herron, G., Kaiser, G., Kebbe, C., Kramer, G. & Littlefield, C.D. (1983) *Pacific flyway management plan for the Central Valley population of the greater sandhill crane,*, Pacific Flyway Council. Us Fish and Wildlife Service, Portland, Oregon

Schmitt, T.J., Dosskey, M.G. & Hoagland, K.D. (1999) Filter Strip Performance and Processes for Different Vegetation, Widths and Contaminants. *Journal of Environmental Quality,* **28,** 1479-1489.

Schoonover, J.E. & Williard, K.W.J. (2003) Ground water nitrate reduction in giant cane and forest riparian buffer zones. *Journal of the American Water Resources Association,* **39,** 347-354.

Schroeder, R. (1983) *Habitat suitability index models: pileated woodpecker*, U.S. Fish and Wildlife Service,

Schultz, R.C., Colletti, J.P., Isenhart, T.M., Simpkins, W.W., Mize, C.W. & Thompson, M.L. (1995) Design and placement of a multi-species riparian buffer strip system. *Agroforestry Systems,* **29,** 201-226.

Schwartz, S.S. (2006) Riparian Setbacks: Technical Information for Decision Makers. I. Chagrin River Watershed Partners. Cleveland, Ohio.

Schwer, C., B, & Clausen, J.C. (1989) Vegetative Filter Treatment of Dairy Milkhouse Wastewater. *Journal of Environmental Quality,* **18,** 446-451.

Sedgwick, J.A. & Knopf, F.L. (1986) Cavity-nesting birds and the cavity-tree resource in plains cottonwood (*Populus sargentii*) bottomlands. *Journal of Wildlife Management,* **50,** 247-252.

Semlitsch, R.D. & Bodie, J.R. (2003) Biological Criteria for Buffer Zones around Wetlands and Riparian Habitats for Amphibians and Reptiles. *Conservation Biology,* **17,** 1219-1228.

Sheldon, F. & Thoms, F.C. (2006) In-channel geomorphic complexity: The key to the dynamics of organic matter in large dryland rivers? *Geomorphology,* **77,** 270-285.

Shirley, S. (2004) The influence of habitat diversity and structure on bird use of riparian buffer strips in coastal forests of British Columbia, Canada. *Canadian Journal of Forest Research,* **34,** 1499-1510.

Shisler, L.K., Jordan, R.A. & Wargo, R.N. (1987) *Coastal wetland buffer delineation*, New Jersey Department of Environmental Protection. Division of Coastal Resources, Trenton, NJ

Short, H.L. (1985) *Habitat suitability index models: red-winged blackbird*, U.S. Fish and Wildlife Service,

Short, H.L. & Cooper, R.J. (1985) *Habitat suitability index models: great blue heron*, U.S. Fish and Wildlife Service,

Siebentritt, M.A., Ganf, G.G. & Walker, K.F. (2004) Effects of an enhanced flood on riparian plants of the River Murray, South Australia. *River Research and Applications,* **20,** 765-774.

Simmons, R.C., Gold, A.J. & Groffman, P.M. (1992) Nitrate Dynamics in Riparian Forests: Groundwater Studies. *Journal of Environmental Quality,* **21,** 659-665.

Small, M. (1982) Wildlife management in riparian habitats. Maine Agricultural Experimental Station, Orono.

Smith, B.J. & Collier, K.J. (2000) Interactions of Adult Stoneflies (Plecoptera) with Riparian Zones II. Diet. *Aquatic Insects,* **22,** 285-296.

Smith, C.M. (1989) Riparian pasture retirement effects on sediment, phosphorus, and nitrogen in channellised surface run-off from pastures. *New Zealand Journal of Marine and Freshwater Research,* **23,** 139-146.

Sousa, P.J. & Farmer, A.H. (1983) *Habitat suitability index models: wood duck*, U.S. Fish and Wildlife Service,

Sovell, L.A., Vondracek, B., Frost, J.A. & Mumford, K.G. (2000) Impacts of Rotational Grazing and Riparian Buffers on Physicochemical and Biological Characteristics of Southeastern Minnesota, USA, Streams. *Environmental Management,* **26,** 629-641.

Spence, B.C., Lomnicky, G.A., Hughes, R.M. & Novitski, R.P. (1996) An Ecosystem Approach to Salmonid Conservation. Mantech Environmental Research Services Corporation, Corvallis, OR.

Spruill, T.B. (2004) Effectiveness of riparian buffers in controlling ground-water discharge of nitrate to streams in selected hydrogeological settings of the North Carolina Coastal Plain. *Water Science and Technology,* **49,** 63-70.

Stalmaster, M.V. (1980) Management strategies for wintering bald eagles in the Pacific Northwest. In: *Proceedings of the bald eagle symposium.* (R.L. Knight & G.T. Allen & M.V. Stalmaster & C.W. Servheen), pp. 43-67.

Stauffer, F. & Best, L.B. (1980) Habitat Selection by Birds of Riparian Communities: Evaluating Effects of Habitat Alterations. *Journal of Wildlife Management,* **44,** 1-15.

Stein, J.L., Stein, J.A. & Nix, H.A. (2002) Spatial analysis of anthropogenic river disturbance at regional and continental scales: identifying the wild rivers of Australia. *Landscape and Urban Planning,* **60,** 1-25.

Steinblums, L.L., Froehlich, H.A. & Lyons, J.K. (1984) Designing stable buffer strips for stream protection. *Journal of Forestry,* **88,** 49-52.

Storey, R.G. & Cowley, D.R. (1997) Recovery of three New Zealand rural streams as they pass through native forest remnants. *Hydrobiologia,* **353,** 63-76.

Strong, T.R. & Bock, C.E. (1990) Bird species distribution patterns in riparian habitats in southeastern Arizona. *Condor,* **92,** 866-885.

Szaro, R.C. & Jakle, M.D. (1985) Avian Use of a Desert Riparian Island and Its Adajcent Scrub Habitat. *Condor,* **87,** 511-519.

Tassone, J.F. (1981) *Utility of hardwood leave strips for breeding birds in Virginia's central piedmont.* MSc, Virginia Polytechnic Institute and State University, Blacksburg.

Taylor, R.S., Oldland, J.M. & Clarke, M. (2008) Edge geometry influences patch-level habitat use by an edge specialist in south-eastern Australia. *Landscape Ecology,* **23,** 377-389.

Terrell, C.R. & Perfetti, P.B. (1989) *Water quality indicators guide: surface waters*, U.S. Soil Conservation Service, Washington, D.C.

Thomas, J.W. (1979) *Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington,* US Forest Service, Portland, Oregon.

Thomas, J.W., Miller, R.J., Black, H., Rodiek, J.E. & Maser, C. (1976) Guidelines for maintaining and enhancing wildlife habitat in forest management in the Blue Mountains of Oregon and Washington. pp. 452-476. Transactions of the North American Wildlife and Natural Resources Conference.

Thomas, J.W., Raphael, M.G., Anthony, R.G., Forsman, E.D., Gunderson, A.G., Holtahausen, R.S., Marcot, B.G., Reeves, G.H., Sedell, J.R. & Solis, D.M. (1993) *Viability assessments and management considerations for species associated with late-successional and old-growth forests of the Pacific Northwest: the report of the scientific analysis team*, U.S. Forestry Service, Washington, D.C.

Till, B., Davies, P.M. & Torre, A. (2001) The importance of Large Woody Debris Replacement in Sandy River Systems. In: *Third Australian Stream Management Conference.* (I.D. Rutherfurd & F. Sheldon & G. Brierley & C. Kenyon). CRC for Catchment Hydrology.

Timm, R.K., Wissmar, R.C., Small, J.W., Leschine, T.M. & Lucchetti, G. (2004) A Screening Procedure for Prioritizing Riparian Management. *Environmental Management,* **33,** 151-161.

Towns, D.R. (1983) Terrestrial oviposition of two species of caddisfly on South Australia (Trichoptera: Leptoceridae). *Journal of the Australian Entomological Society,* **22,** 113-118.

Trimble, G.R. & Sartz, R.S. (1957) How far from a stream should a logging road be located? *Journal of Forestry,* **55,** 339-341.

Triquet, A.M., Mcpeek, G.A. & Mccomb, M.C. (1990) Songbird diversity in clearcuts with and without a riparian buffer strip. *Journal of Soil and Water Conservation,* **45,** 500-503.

Valett, H.M., Thomas, S.A., Mulholland, P.J., Webster, J.R., Dahm, C.M., Fellows, C.S., Crenshaw, C.L. & Peterson, C.G. (2008) Endogenous and exogenous control of ecosystem function: N cyclng in headwater streams. *Ecology,* **89,** 3515-3527.

Van Sickle, J.V. & Gregory, S.N. (1990) Modeling inputs of large woody debris to streams from falling trees. *Canadian Journal of Fisheries and Aquatic Sciences,* **20,** 1593-1601.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C.E. (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences,* **37,** 130-137.

Vellidis, G., Lowrance, R., Gay, P. & Hubbard, R.K. (2003) Nutrient Transport in a Restored Riparian Wetland. *Journal of Environmental Quality,* **32,** 711-726.

Vidon, P.G.F. & Hill, A.R. (2004a) Landscape controls on nitrate removal in stream riparian zones. *Water Resources Research,* **40,** W03201.

Vidon, P.G.F. & Hill, A.R. (2004b) Landscape controls on the hydrology of stream riparian zones. *Journal of Hydrology,* **292,** 210-228.

Vignieri, S. (2005) Streams over mountains: influence of riparian connectivity on gene flow in the Pacific jumping mouse (*Zapus trinotatus*). *Molecular Ecology,* **14,** 1925-1937.

Vink, S., Ford, P.W., Bormans, M., Kelly, C. & Turley, C. (2007) Contrasting nutrient exports from a forested and an agricultural catchment in south-eastern Australia. *Biogeochemistry,* **84,** 247-264.

Vos, D.K., Ryder, R.A. & Graul, W.D. (1985) Response of Breeding Great Blue Herons to Human Disturbance in Northcentral Colorado. *Colonial Waterbirds,* **8,** 13-22.

Walker, K.F. (1993) Issues in the Riparian Ecology of Large Rivers. In: *Ecology and Management of Riparian Zones in Australia.* (S.E. Bunn & B.J. Pusey & P. Price), pp. 31-40. Land and Water Resources Research and Development Corporation.

Wallbrink, P., Martin, C. & Wilson, C. (2001) Contribution of sediment and sediment bound P from different landuses to two contrasting streams in temperate and tropical Australia. In: *Third Australian Stream Management Conference.* (I.D. Rutherfurd & F. Sheldon & G. Brierley & C. Kenyon). CRC for Catchment Hydrology.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M. & Morgan Ii, R.P. (2005) The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society,* **24,** 706-723.

Ward, J.V., Tockner, K., Arscott, D.B. & Claret, C. (2002) Riverine landscape diversity. *Freshwater Biology,* **47,** 517-539.

Webb, A.A. & Erskine, W.D. (2001) Large Woody Debris, Riparian Vegetation and Pool Formation on Sand-bed, Forest Streams in Southeastern Australia. In: *Third Australian Stream Management Conference.* (I.D. Rutherfurd & F. Sheldon & G. Brierley & C. Kenyon). CRC for Catchment Hydrology.

Webb, A.A. & Erskine, W.D. (2003) A practical scientific approach to riparian vegetation rehabilitation in Australia. *Journal of Environmental Management,* **68,** 329-341.

Weller, D.E., Jordan, T.E. & Correll, D.L. (1998) Heuristic Models for Material Discharge from Landscapes with Riparian Buffers. *Ecological Applications,* **8,** 1156-1169.

Welsch, D.J. (1991) *Riparian Forest Buffers: Function and Design for Protection and Enhancement of Water Resources*, United States Department of Agriculture. Forest Service, Radnor, Pennsylvania

Welty, J.F., Beechie, T., Sullivan, K., Hyink, D.M., Bilby, R.E., Andrus, C. & Pess, G. (2002) Riparian aquatic interaction simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. *Forest Ecology and Management,* **162,** 299-318.

Wenger, S. (1999) A Review of the Scientific Literature on Riparian Buffer Width, Extent and Vegetation. I.O.E. Office of Public Service and Outreach. University of Georgia, Athens.

Wentworth Group (2003) A new model for landscape conservation in New South Wales. WWF Australia, Sydney.

Wilcove, D.S., Mclellan, C.H. & Dobson, A.P. (1986) Habitat fragmentation in the temperate zone. In: *Conservation biology: the science of scarcity and diversity.* (M.E. Soulé), pp. 237-256. Sinauer Associates, Sunderland, Massachusets.

Wilkinson, S.N., Olley, J.M., Prosser, I.P. & Read, A.M. (2005) Targeting erosion control in large river systems using spatially distributed sediment budgets. In: *Geomorphological Processes and Human Impacts in River Basins.* (R.J. Batalla & C. Garcia), pp. 56-64. Wallingford, Oxfordshire, U.K.

Williams, L., Cavagnaro, T.R., Reich, P. & Lake, P.S. (2008a) *Phalaris* in Australian Ecosystems: Understanding its biology, ecology and threats as the first step towards effective management. School of Biological Sciences, Monash University, Clayton.

Williams, L., Reich, P., Capon, S.J. & Raulings, E. (2008b) Soil seed banks of degraded riparian zones in southeastern Australia and their potential contribution to the restoration of understorey vegetation. *River Research and Applications,* **24,** 1002-1017.

Wissmar, R.C., Beer, W.N. & Timm, R.K. (2004) Spatially explicit estimates of erosion-risk indices and variable riparian buffer widths in watersheds. *Aquatic Sciences,* **66,** 446-455.

Wong, S.L. & Mccuen, R.H. (1982) The Design of Vegetative Buffer Strips For Runoff and Sediment Control. Technical Paper. Maryland Coastal Zone Management Program.

Woodard, S.E. & Rock, C.A. (1995) Control of residential stormwater by natural buffer strips. *Lake and Reservoir Management,* **11,** 37-45.

Wylie, R.E. (1975) Forest operations to safeguard water and soil resources. In: *Proceedings of Water and Soils Division, Course No. 2.* (National Water and Soil Conservation Organization, Rotorua.

Xu, L., Gilliam, I.N. & Daniels, R.B. (1992) Nitrate movement and loss in riparian buffer areas. In: *Agronomy Abstracts.* (ASA, Madison, WI.

Young, R.S., Huntrods, T. & Anderson, N. (1980) Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. *Journal of Environmental Quality,* **9,** 483-497.

Zelman, M. (1977) Some aspects of management of stream frontages. *Victoria's Resources,* **19,** 4-10.

**APPENDIX 1.**

Information relating to riparian zone widths and their function or management application summarised from Australian literature, both peer-reviewed and grey (generally government reports). Minimum widths refer to the minimum riparian buffer width required to perform the stated function or relevant in the stated context.

| State / region | Minimum width | Stream size | Function / context | Study |
|---|---|---|---|---|
| *Peer-reviewed* | | | | |
| nationwide | >40m | small <15m | ISC criteria - highest score riparian condition | Ladson *et al.*, 1999 |
| nationwide | 3 channel widths | large >15m | ISC criteria - highest score riparian condition | Ladson *et al.*, 1999 |
| nationwide | $W$=8+0.6$S$ † | various | Water quality (pollutant removal) | Barling and Moore, 1994 |
| nationwide | 30m | not specified | Summary from forestry operations | Barling and Moore, 1994 |
| SWWA | 100m | headwater | Maintaining macroinvertebrate communities | Growns and Davis, 1991 |
| QLD | 10m | $1^{st}$ / $2^{nd}$ order | Extent of riparian vegetation | Catterall *et al.*, 2001 |
| QLD | >106m | variable | Habitat for avifauna | Bentley and Catterall, 1997 |
| VIC | 20m | headwater | Runoff attenuation | Bren and Turner, 1980 |
| NSW | <40m | headwater | Slope (<33%) erosion control | Chalmers, 1979 |
| VIC | 5-55m | $1^{st}$ order | Extent of riparian vegetation | Mac Nally *et al.*, 2008 |
| VIC | 5-35m | $2^{nd}$ order | Extent of riparian vegetation | Mac Nally *et al.*, 2008 |
| VIC | 15-85m | $3^{rd}$ order | Extent of riparian vegetation | Mac Nally *et al.*, 2008 |
| VIC | 15-55m | $4^{th}$ order | Extent of riparian vegetation | Mac Nally *et al.*, 2008 |
| WA | >10m | headwater | Grass buffer - subsurface contaminant removal >50% | McKergow *et al.*, 2006b |
| NSW | >>30m | mid-high order | Greater to prevent edge effects from invasive species | Webb and Erskine, 2003 |
| SA | >50m | Murray floodplain | Bank recharge for riparian vegetation | Holland *et al.*, 2006 |
| NSW | 3 channel widths | Murrumbidgee River | Highest score riparian condition | Jansen and Robertson, 2001a |
| QLD | 80-120m | not specified | Corridor for mainly-rainforest bird species | Jansen, 2005 |
| QLD | 51-200m | not specified | Maintain high avian biodiversity | Bengsen and Pearson, 2006 |
| TAS | >30m | Class 2 | In-stream habitat / biodiversity (forestry) | Davies and Nelson, 1994 |
| experimental | 1m | not specified | Filtering sediment - Kikuyu grass buffer | Karssies and Prosser, 2001 |
| NSW | >30m | Nepean River | Low disturbance criteria for grazing modification | Brainwood *et al.*, 2006 |

| State / region | Minimum width | Stream size | Function / context | Study |
|---|---|---|---|---|
| QLD | 20m | small (6m) | Highest condition score perennial stream | Rassam *et al*., 2006 |
| VIC | <1000m | Murray floodplain | Groundwater discharge zone | Lamontagne *et al*., 2005 |
| *Grey* | | | | |
| nationwide | 5m †† | all | Bank stability | Abernethy and Rutherfurd, 1999 |
| nationwide | 5-10m | not specified | Water quality | Price *et al*., 2005 |
| nationwide | 5-10m | not specified | Erosion control | Price *et al*., 2005 |
| nationwide | 5-10m | not specified | Shading and stream temperature control | Price *et al*., 2005 |
| nationwide | 5-10m | not specified | Food inputs / in-stream habitat | Price *et al*., 2005 |
| nationwide | 5-30m | not specified | In-stream habitat (fish) | Price *et al*., 2005 |
| nationwide | 10-30m | not specified | Terrestrial habitat | Price *et al*., 2005 |
| nationwide | 5-10m | not specified | Contaminant removal (agricultural source) | Price *et al*., 2005 |
| nationwide | 100-2000m | wetland | Water quality | Price *et al*., 2005 |
| nationwide | 20-50m | wetland | Food inputs / in-stream habitat | Price *et al*., 2005 |
| nationwide | 250m | wetland | Salinity mitigation | Price *et al*., 2005 |
| NSW | 40+10m | not specified | Terrestrial connectivity | DIPNR, 2004 |
| NSW | 20+10m | not specified | Terrestrial and aquatic habitat | DIPNR, 2004 |
| NSW | 10m | not specified | Bank stability and water quality | DIPNR, 2004 |
| nationwide | 20m | all | Works prohibited within this distance | *Water Act 1989* |
| VIC | 30m | all | Permit required to undertake works within this distance | *Planning and Environment Act 1987* |
| VIC | 20m | permanent streams | Water quality low risk (forestry) | *Code of Practice for Timber Production 2007* |
| VIC | 10m | temporary streams | Water quality low risk (forestry) | *Code of Practice for Timber Production 2007* |
| VIC | 10m | drainage lines | Water quality low risk (forestry) | *Code of Practice for Timber Production 2007* |
| NSW | 50-100m | rivers / wetlands | Water quality | Wentworth Group, 2003 |
| NSW | 20-50m | creeks | Water quality | Wentworth Group, 2003 |
| NSW | 10-20m | streams | Water quality | Wentworth Group, 2003 |

| State / region | Minimum width | Stream size | Function / context | Study |
|---|---|---|---|---|
| NSW | 40m | river | Permit required to undertake works within this distance | *Rivers and Foreshore Improvement Act 1948* |
| SEQLD | 5-10m | not specified | Improve denitrification potential of riparian zone | Fellows *et al.*, 2007 |
| SEQLD | 100m | variable | Wildlife conservation | Catterall, 1993 |

† where *W* is the buffer strip width in metres and *S* is the slope (%). This formula is from the guidelines of Trimble and Sartz (1957) and was used by soil conservation officers in the State of Victoria (Barling and Moore, 1994).

†† base width 5m plus a height allowance (equal to bank height) and an establishment allowance (equal to erosion rate × time to maturity of vegetation)

## APPENDIX 2.

Riparian zone widths summarised from the literature (both international and Australian). Minimum buffer widths given are those reported to perform/provide the stated function. * country codes given at bottom of table

| Country* | Minimum buffer width (m) | Function<br>(for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | Study |
|---|---|---|---|
| US | 55 | edge effects: bird communities | Tassone, (1981) |
| US | 52-137 | edge effects: forest structure & function | Chen *et al*., (1992) |
| US | 160 | edge effects: forest structure & function | Franklin and Forman, (1987) |
| US | 160 | edge effects: forest structure & function | Harris, (1984) |
| AUS | 150-300 | edge effects: noisy miner invasion (not riparian-specific, any woodland) | Clarke and Oldland, (2007) |
| AUS | 100 | edge effects: noisy miner invasion (not riparian-specific, any woodland) | Taylor *et al*., (2008) |
| US | 670 | edge effects: predation risk | Wilcove *et al*., (1986) |
| US | 450 | edge effects: reducing avian invasion | Hennings and Edge, (2003) |
| US | 30 | food inputs & resources to stream | Erman *et al*., (1977) |
| US | 57 | food inputs & resources to stream | Spence *et al*., (1996) |
| AUS | 30 | in-stream habitat for aquatic biota | Davies and Nelson, (1994) |
| CR | 15 | in-stream habitat: aquatic invertebrates | Lorian and Kennedy, (2008) |
| AUS | 100 | in-stream habitat: aquatic invertebrates | Growns and Davis, (1991) |
| US | 33 | in-stream habitat: coarse wood inputs | Pollock and Kennard, (1998) |
| US | 46 | in-stream habitat: coarse wood inputs | Robison and Beschta, (1990) |
| CAN | 30 | in-stream habitat: coarse wood inputs | Van Sickle and Gregory, (1990) |
| CAN | 50 | in-stream habitat: coarse wood inputs | Van Sickle and Gregory, (1990) |
| US | 31 | in-stream habitat: coarse wood inputs | Bottom *et al*., (1983) |
| US | 20 | in-stream habitat: coarse wood inputs | McDade *et al*., (1990) |
| US | 30 | in-stream habitat: coarse wood inputs | Murphy and Koski, (1989) |
| US | 55 | in-stream habitat: coarse wood inputs | Thomas *et al*., (1993) |
| CAN | 20 | in-stream habitat: cover for trout | Cormack, (1949) |
| US | 67 | in-stream habitat: fish | Castelle *et al*., (1992) |
| US | 100 | in-stream habitat: fish | FEMAT, (1993) |

| **Country*** | **Minimum buffer width (m)** | **Function** (for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | **Study** |
|---|---|---|---|
| US | 30 | in-stream habitat: fish | Hickman and Raleigh, (1982) |
| US | 33 | in-stream habitat: fish | Raleigh, (1982) |
| US | 33 | in-stream habitat: fish | Raleigh *et al.*, (1984) |
| US | 30 | in-stream habitat: fish | Raleigh *et al*., (1986) |
| AUS | 50 | riparian litter inputs | Campbell *et al*., (1992) |
| AUS | 50 | riparian litter inputs | Reid *et al*., (2008a) |
| CAN | 20 | contaminant removal | Payne *et al*., (1988) |
| US | 183 | filtering animal waste | Terrell and Perfetti, (1989) |
| US | 4.6 | nitrogen & phosphorus removal | Madison *et al*., (1992) |
| US | 9.1 | nitrogen & phosphorus removal | Madison *et al*., (1992) |
| US | 19 | nitrogen & phosphorus removal | Shisler *et al*., (1987) |
| CAN | 2250 | nitrogen phosphorus & sediment removal | Houlahan and Findley, (2004) |
| US | 4.6 | nitrogen phosphorus & sediment removal | Dillaha *et al*., (1989) |
| US | 9.1 | nitrogen phosphorus & sediment removal | Dillaha *et al*., (1989) |
| NZ | 10-13 | nitrogen phosphorus & suspended solid removal | Smith, (1989) |
| US | 30 | nitrogen removal | Grismer, (1981) |
| US | 30 | nitrogen removal | Johnson and Ryba, (1992) |
| US | 10 | nitrogen removal | Xu *et al*., (1992) |
| US | 50 | nitrogen removal | Peterjohn and Correll, (1984) |
| EU | 100 | nitrogen removal: subsurface flows | Prach and Rauch, (1992) |
| CAN | 50 | nitrogen removal: subsurface flows | Martin *et al*., (1999) |
| CAN | 11-65 | nitrogen removal: subsurface flows | Vidon and Hill, (2004b) |
| CAN | 5-30 | nitrogen removal: subsurface flows | Vidon and Hill, (2004b) |
| FR | 200 | nitrogen removal: subsurface flows | Fustec *et al*., (1991) |
| FR | 30 | nitrogen removal: subsurface flows | Pinay and Decamps, (1988) |
| FR | 30 | nitrogen removal: subsurface flows | Pinay *et al*., (1993) |
| IT | 6 | nitrogen removal: subsurface flows | Borin and Bigon, (2002) |
| NE | 25-50 | nitrogen removal: subsurface flows | Hefting and de Klein, (1998) |
| NE | 10-50 | nitrogen removal: subsurface flows | Hefting *et al*., (2003) |
| NZ | 1 | nitrogen removal: subsurface flows | Burns and Nguyen, (2002) |

| Country* | Minimum buffer width (m) | **Function** (for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | Study |
|---|---|---|---|
| NZ | 3-4 | nitrogen removal: subsurface flows | Cooper, (1990) |
| UK | 16 | nitrogen removal: subsurface flows | Haycock and Burt, (1993) |
| UK | 16 | nitrogen removal: subsurface flows | Haycock and Pinay, (1993) |
| UK | 50 | nitrogen removal: subsurface flows | Jacobs and Gilliam, (1985) |
| US | 15 | nitrogen removal: subsurface flows | Cey *et al*., (1999) |
| US | 5 | nitrogen removal: subsurface flows | Clausen *et al*., (2000) |
| US | 31 | nitrogen removal: subsurface flows | Hanson *et al*., (1994) |
| US | 165 | nitrogen removal: subsurface flows | Hill *et al*., (2000) |
| US | 70 | nitrogen removal: subsurface flows | Hubbard and Lowrance. (1997) |
| US | 15 | nitrogen removal: subsurface flows | Hubbard and Sheridan, (1989) |
| US | 60 | nitrogen removal: subsurface flows | Jordan *et al*., (1993) |
| US | 50 | nitrogen removal: subsurface flows | Lowrance, (1992) |
| US | 55 | nitrogen removal: subsurface flows | Lowrance *et al*., (1984) |
| US | 40 | nitrogen removal: subsurface flows | Puckett *et al*., (2002) |
| US | 10 | nitrogen removal: subsurface flows | Schoonover and Willard, (2003) |
| US | 20 | nitrogen removal: subsurface flows | Schultz *et al*., (1995) |
| US | 14.6 | nitrogen removal: subsurface flows, sandy soils | Simmons *et al*., (1992) |
| US | 6.6 | nitrogen removal: subsurface flows, loamy soils | Simmons *et al*., (1992) |
| US | 100 | nitrogen removal: subsurface flows | Spruill, (2004) |
| US | 38 | nitrogen removal: subsurface flows | Vellidis *et al*., (2003) |
| US | 30 | nitrogen removal: surface flows | Lynch *et al*., (1985) |
| AUS | 10 | nitrogen removal: surface flows | McKergow *et al*., (2006b) |
| DAN | 15-25 | nitrogen removal: surface flows | Brüsch and Nilsson, (1993) |
| US | 15 | nitrogen removal: surface flows | Schmitt *et al*., (1999) |
| US | 26 | nitrogen removal: surface flows | Schwer and Clausen, (1989) |
| US | 33 | nutrient removal | Peterson *et al*., (1992) |
| US | 50 | nutrient removal | Castelle *et al*., (1992) |
| US | 4 | nutrient removal | Doyle *et al*., (1977) |
| US | 190 | nutrient removal | Terrell and Perfetti, (1989) |
| US | 30 | nutrient removal | Terrell and Perfetti, (1989) |
| US | 36 | nutrient removal | Young *et al*., (1980) |

| Country* | Minimum buffer width (m) | Function (for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | Study |
|---|---|---|---|
| US | 15 | phosphorus removal | Woodard and Rock, (1995) |
| US | 42 | reduce streambank erosion | Cederholm, (1994) |
| US | 57 | reduce streambank erosion | Spence *et al*., (1996) |
| US | 30 | erosion control for maintaining fish habitat | Raleigh *et al*., (1986) |
| US | 32 | erosion risk low (slope $0^o$) | Balmer *et al*., (1982) |
| US | 55 | erosion risk low (slope $30^o$) | Balmer *et al*., (1982) |
| US | 9 | erosion risk low (slope $60^o$) | Balmer *et al*., (1982) |
| AUS | 20 | erosion risk low | Bren and Turner, (1980) |
| NZ | 30 | erosion risk moderate | Graynoth, (1979) |
| US | 12 | erosion risk moderate (slope $0^o$) | Balmer *et al*., (1982) |
| US | 43 | erosion risk moderate (slope $30^o$) | Balmer *et al*., (1982) |
| US | 71 | erosion risk moderate (slope $60^o$) | Balmer *et al*., (1982) |
| AUS | 40 (max) | erosion risk severe | Chalmers, (1979) |
| NZ | 30 | erosion risk severe | Wylie, (1975) |
| US | 14 | erosion risk severe (slope $0^o$) | Balmer *et al*., (1982) |
| US | 52 | erosion risk severe (slope $30^o$) | Balmer *et al*., (1982) |
| US | 88 | erosion risk severe (slope $60^o$) | Balmer *et al*., (1982) |
| US | 30 | erosion risk severe | Erman *et al*., (1977) |
| US | 43 | erosion risk severe | Haupt and Kidd, (1965) |
| US | 6 | erosion risk severe | Haupt, (1959) |
| US | 46 | erosion risk severe | Packer, (1967) |
| US | 30 | filtering sediment | Lynch *et al*., (1985) |
| US | 22.9 | filtering sediment | Schellinger and Clausen, (1992) |
| AUS | 1 | filtering sediment | Karssies and Prosser, (2001) |
| CAN | 10-15 | filtering sediment | Plamondon, (1982) |
| US | 9.1 | filtering sediment | Ghaffarzadeh *et al*., (1992) |
| US | 61 | filtering sediment | Horner and Mar, (1982) |
| US | 30 | filtering sediment | Johnson and Ryba, (1992) |
| US | 30-38 | filtering sediment | Karr and Schlosser, (1977) |
| US | 30 | filtering sediment | Moring, (1982) |
| US | 30.5-61 | filtering sediment | Wong and McCuen, (1982) |

| **Country*** | **Minimum buffer width (m)** | **Function**<br>(for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | **Study** |
|---|---|---|---|
| US | 24.4 | filtering sediment | Young *et al*., (1980) |
| CAN | 100 | riparian vegetation delineation | Shirley, (2004) |
| US | 25-50 | riparian vegetation delineation | Medin and Clary, (1991) |
| US | 20-50 | riparian vegetation delineation | Strong and Bock, (1990) |
| AUS | 5-55 | riparian vegetation delineation 1st order stream (slope 4-5$^o$) | Mac Nally *et al*., (2008) |
| AUS | 5-35 | riparian vegetation delineation 2nd order stream (slope 27-38$^o$) | Mac Nally *et al*., (2008) |
| AUS | 15-85 | riparian vegetation delineation 3rd order stream (slope 20-37$^o$) | Mac Nally *et al*., (2008) |
| AUS | 15-55 | riparian vegetation delineation 4th order stream (slope 3-6$^o$) | Mac Nally *et al*., (2008) |
| US | 30 | shading & water temperature control | Lynch *et al*., (1985) |
| US | 35-125 | shading & water temperature control | Steinblums *et al*., (1984) |
| US | 30 | shading & water temperature control | Beschta *et al*., (1987) |
| US | 35-125 | shading & water temperature control | Brazier and Brown, (1973) |
| US | 83 | shading & water temperature control | Brosofske *et al*., (1997) |
| US | 39 | shading & water temperature control | Corbett and Lynch, (1985) |
| US | 20-30 | shading & water temperature control | Corbett *et al*., (1978) |
| US | 33 | shading & water temperature control | FEMAT, (1993) |
| US | 50-98 | shading & water temperature control | Hewlett and Fortson, (1982) |
| US | 30-125 | shading & water temperature control | Johnson and Ryba, (1992) |
| US | 30-43 | shading & water temperature control | Jones *et al*., (1988) |
| US | 18 | shading & water temperature control | Moring, (1975) |
| US | 33 | shading & water temperature control | Spence *et al*., (1996) |
| US | 35 | stream shading | Brown and Krygier, (1970) |
| US | 46 | stream shading | Steinblums *et al*., (1984) |
| IT | 300-1500 | terrestrial habitat: amphibian metapopulation persistence | Ficetola *et al*., (2008) |
| IT | 100-400 | terrestrial habitat: amphibians | Ficetola *et al*., (2008) |
| CAN | 30 | terrestrial habitat: aquatic invertebrates | Newbold *et al*., (1980) |
| NZ | 30-200 | terrestrial habitat: aquatic invertebrates | Collier and Smith, (1998) |
| US | 30 | terrestrial habitat: aquatic invertebrates | Gregory *et al*., (1987) |
| US | 119 | terrestrial habitat: bald eagle breeding | Grubb, (1980) |
| US | 100 | terrestrial habitat: bald eagle breeding | Small, (1982) |

| **Country*** | **Minimum buffer width (m)** | **Function** (for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | **Study** |
|---|---|---|---|
| US | 50 | terrestrial habitat: bald eagle roosts | Stalmaster, (1980) |
| US | 30-100 | terrestrial habitat: beavers | Allen, (1983) |
| US | 30 | terrestrial habitat: beavers | Hall, (1960) |
| US | 30-60 | terrestrial habitat: belted kingfisher breeding | Prose, (1985) |
| US | 200 | terrestrial habitat: birds | Castelle *et al*., (1992) |
| US | 125 | terrestrial habitat: birds | Croonquist and Brooks, (1993) |
| US | 30 | terrestrial habitat: birds | Dickson *et al*., (1995) |
| US | 100 | terrestrial habitat: birds | Hodges and Krementz, (1996) |
| US | 75-200 | terrestrial habitat: birds | Jones *et al*., (1988) |
| US | 45 | terrestrial habitat: birds | Pearson and Manuwal, (2001) |
| US | 127 | terrestrial habitat: birds | Sedgewick and Knopf, (1986) |
| US | 50 | terrestrial habitat: birds | Tassone, (1981) |
| US | 50-75 | terrestrial habitat: birds | Triquet *et al*., (1990) |
| US | 200 | terrestrial habitat: blackbird | Short, (1985) |
| US | 100 | terrestrial habitat: blue heron | Short and Cooper, (1985) |
| US | 250-300 | terrestrial habitat: blue heron breeding | Bowman and Siderius, (1984) |
| US | 250 | terrestrial habitat: blue heron breeding | Short and Cooper, (1985) |
| US | 250-300 | terrestrial habitat: blue heron disturbance | Vos *et al*., (1985) |
| US | 50 | terrestrial habitat: chickadee breeding | Cross, (1985) |
| US | 240 | terrestrial habitat: cowbirds | Gates and Griffin, (1991) |
| US | 800 | terrestrial habitat: crane breeding | Schlorff *et al*., (1983) |
| US | 91 | terrestrial habitat: cuckoos | Gaines and Laymon, (1984) |
| US | 25 | terrestrial habitat: disturbance sensitive species | Croonquist and Brooks, (1993) |
| US | 305 | terrestrial habitat: elk breeding | Thomas, (1979) |
| US | 100 | terrestrial habitat: fox & fisher | Small, (1982) |
| US | 50 | terrestrial habitat: harlequin breeding | Cassirer and Groves, (1990) |
| US | 30-95 | terrestrial habitat: herpetofauna | Rudolph and Dickson, (1990) |
| US | 192-339 | terrestrial habitat: herpetofauna | Semlitsch and Bodie, (2003) |
| US | 23-50 | terrestrial habitat: wildlife | Mudd, (1975) |

| **Country*** | **Minimum buffer width (m)** | **Function** (for N, P & sediment removal, only widths achieving 50% or greater removal efficiency are reported) | **Study** |
|---|---|---|---|
| US | 100 | terrestrial habitat: large mammals | Jones *et al*., (1988) |
| US | 100 | terrestrial habitat: mink | Melquist *et al*., (1981) |
| US | 180 | terrestrial habitat: mule deer breeding | Thomas *et al*., (1976) |
| US | 57 | terrestrial habitat: nuthatch breeding | Stauffer and Best, (1980) |
| CAN | 200 | terrestrial habitat: passerines | Hannon *et al*., (2002) |
| US | 200 | terrestrial habitat: redstart & towhee breeding | Stauffer and Best, (1980) |
| AUS | 50 | terrestrial habitat: river red gum water sources | Holland *et al*., (2006) |
| US | 50 | terrestrial habitat: scaup breeding | Allen, (1986) |
| US | 183 | terrestrial habitat: shrews | Clothier, (1955) |
| US | 71-99 | terrestrial habitat: small mammals | Allen, (1983) |
| US | 39-230 | terrestrial habitat: small mammals | Cross, (1985) |
| US | 50 | terrestrial habitat: squirrels | Dickson, (1989) |
| US | 40 | terrestrial habitat: vireo & woodpecker breeding | Stauffer and Best, (1980) |
| US | 90 | terrestrial habitat: vireo breeding | Gilmer *et al*., (1978) |
| US | 80 | terrestrial habitat: wood duck breeding | Gilmer *et al*., (1978) |
| US | 183 | terrestrial habitat: wood duck breeding | Grice and Rogers, (1965) |
| US | 183 | terrestrial habitat: wood duck breeding | Sousa and Farmer, (1983) |
| US | 150 | terrestrial habitat: woodpecker | Castelle *et al*., (1992) |
| US | 150 | terrestrial habitat: woodpecker breeding | Conner *et al*., (1975) |
| US | 50 | terrestrial habitat: woodpecker breeding | Cross, (1985) |
| US | 150 | terrestrial habitat: woodpecker breeding | Schroeder, (1983) |
| US | 100 | terrestrial habitat: woodpecker breeding | Small, (1982) |
| AUS | 10-30 | light attenuation by riparian zone | Dignan and Bren, (2003) |
| US | 25 | microclimate maintenance | Pollock and Kennard, (1998) |
| US | 83 | microclimate maintenance | Brosofske *et al*., (1997) |
| US | 100 | riparian terrestrial connectivity for bird migration | Keller *et al*., (1993) |
| US | 183 | riparian terrestrial connectivity for fisher migration | Freel, (1991) |
| US | 100 | riparian terrestrial connectivity for fox & marten migration | Small, (1982) |
| US | 46 | riparian terrestrial connectivity for marten migration | Freel, (1991) |
| AUS | 20 | hazard specific | Cornish, (1975) |

US = United Stated of America
CAN = Canada
AUS = Australia
NZ = New Zealand
EU = Europe
IT = Italy
FR = France
NE = Netherlands
UK = United Kingdom
DAN = Denmark
CR = Costa Rica

# APPENDIX 3

## Designing riparian width guidelines - a proposed framework for land managers and field assessors

Guidelines for designating riparian widths may vary tremendously depending upon the resources available, the skill of the personnel, the practicality of the guidelines and the applicability of those guidelines to catchment locations that have not been mapped or for which there are few data. The standard approach by many organizations (especially government, both in Australia and overseas) is to provide a fixed width that is subject to simple variations, e.g. wider riparian zones for larger waterways. Some research studies have used a modeling approach to relate relevant factors to particular widths (height and overhang of vegetation along streams of different widths for the purpose of shading the stream). The important point that arises from modeling and GIS-based approaches is the sensitivity of the analysis to landscape context and management objective. Many North American studies use the presence of salmonid populations as the basis for improving stream quality, either through direct additions of habitat components or by improvement of riparian quality (see for example DeWalle, 2008). Land use and desired restoration endpoint is therefore the most critical factor in designing riparian width guidelines. Clearly single metric-based approaches are totally inadequate to meet different management objectives in different landscape contexts and should be avoided.

Lowrance (1998) comments that policy success in the United States of America for riparian ecosystem science is derived from flexibility being built into scientifically-based management recommendations. With this in mind, we recommend developing guidelines that not only allow for on-the-ground assessment of riparian zones and subsequent assignment of widths appropriate to meet the dominant management objectives at a location, but also have the ability to incorporate new information as it becomes available through research.

## Published approaches for designing riparian width guidelines

### *1. A fixed width with simple scaling*

The simplest approach to delineating riparian zones is the use of fixed widths, which may be scaled by (usually) a single modifier, for example, stream width (sometimes based on Strahler Stream order: Naiman *et al.*, 2005).

Forestry operations in Australia and overseas, usually take a standard approach to riparian buffer width specifications. In Victoria, the *Code of Practice for Timber Production* (Department of Sustainability and Environment, 2007) designates a riparian zone width of either 10m (drainage lines and temporary streams) or 20m (permanent streams). The Department of Planning and Community Development specifies a waterway setback width of 30m for the issuing of a works permit, under the *Planning and Environment Act 1987*. The Wentworth Group (2003) recommends widths of 10-20m for streams and 50-100m for rivers and wetlands.

Fixed width approaches have the advantage of being simple to implement and incorporate into policy and planning provisions. The disadvantages are numerous, and include the lack of scientific defensibility, the high probability of failing to meet dominant management objectives at any given location and the failure to account for variable land use impacts and landscape influences. Furthermore, by adopting this approach there is no scope for future updating or improvement of the guidelines, which instead require an entirely new revision.

### *2. A fixed width for each management objective*

A slightly more sophisticated approach for determining setback widths is to define a width that meets a certain management objective. The most commonly defined management objectives in Australia (but often also overseas) are the control of streambank erosion and the reduction of nutrient inputs to streams.

Land and Water Australia (Price *et al.*, 2005) produced guidelines that designate a single metric (usually 5-10m) to meet a set of specific management objectives (see Appendix 1), plus an additional set of metrics for wetlands. The same approach is adopted by the NSW Department of Infrastructure, Planning and Natural Resources (DIPNR, 2004) where widths are designated to meet three different management objectives, two of which have a single width modifier to account for edge effects.

This approach uses information on dominant environmental issues that potentially occur in different river networks, but does not consider different landscape contexts in applying these recommendations. Therefore, while 5-10m may improve water quality in largely intact headwaters with low intensity agriculture (e.g. sheep grazing), it is unlikely to provide any protection where the upper catchment is cleared and there is intensive fertilizer application adjacent to waterways. Given the problems with excess nitrate and phosphorus inputs to many Victorian streams, it will be important to incorporate land use variations into any guidelines. As with other fixed width approaches, this approach takes a generic form that does not account for natural variability in riparian systems and may be based upon limited or inappropriately extrapolated data.

### *3. Simple mathematical models for a given management objective*

Simple mathematical models enable the incorporation of dominant modifying factors (for example, slope) that usually vary between locations both within and between catchments. These equations are always developed to meet a single, specific management objective.

Barling and Moore (1994) report the use of a simple linear model $W$=8+0.6$S$, where $W$ is the buffer strip width in metres and $S$ is the % slope (modified from Trimble and Sartz, 1957), for determining riparian zone widths to reduce nutrient (non-point source pollutant) inputs to streams in intact catchments subject to forestry activities.

DeWalle (2008) developed a multivariate model of stream shading which incorporates shortwave and longwave radiation sources, latitude, sunrise and sunset times, the view factor (defined by a function using simple geometric riparian vegetation heights and widths for a theoretical stream section), and temperature. The guidelines arising from this model predicted ratios of vegetation height to stream width that ranged from 1.4 to 2.3 for 75% shade restoration at a mid-latitude (40$^{o}$) northern hemisphere site.

Bailey *et al.*, (2005) developed a multiplicative index of riparian disturbance sensitivity incorporating the effects the presence of riparian vegetation, discharge, sediment size and dimensional critical sheer stresses of bed and bank substrate. The index is expressed in terms of unstable (braided) and stable (meandering) channel forms. The correlation between the index and percent change in channel width over approximately 50 years (along 12 disturbed test reaches in British Columbia, Canada) was strong (84%) excluding a single disturbed reach outlier.

The advantage of using simple mathematical models is that they take into account more variability than fixed width guidelines and allow the incorporation of one or more factors that influence riparian zone function, thus making them more likely to meet the dominant management objective. They are disadvantaged by being limited in their accuracy to the system in which they were developed and therefore they are potentially inapplicable to other locations. They are also disadvantaged by their tendency to over-simply important factors and their inability to simultaneously assess multiple factors that may co-vary. In some cases they also fail to account for land use impacts within the catchment. By virtue of their development to address a single management objective, they cannot be adapted to other management objectives.

### *4. GIS-based and complex modelling approaches*

GIS-based approaches make use of available landscape information to assess the combined influence of multiple factors on riparian function. These are often used to prioritise sites for restoration to meet a give management objective, for example, erosion control. They may also use landscape information to develop an index of performance or quality, which is subsequently translated into a setback width related to the magnitude of the index.

Wissmar *et al*., (2004) developed indices of erosion risk for a spatial array of grid cells which reflect a combination of increasing modification to the catchment (in terms of timber production and the presence of roads) plus natural variance in climate, topography and soil stability. Their approach uses land cover information in multiple GIS layers to compute a composite (additive) index, which is subsequently translated into a width. Indices of increasing magnitude result in larger buffer widths. Low indices corresponded to widths 15-30m and high indices corresponded to widths of 90 and 135m.

In a similar fashion, Timm *et al*., (2004) have developed a spatially-explicit additive, linear model for prioritising riparian management that differentiates between a set of anthropogenic and habitat factors, weighted by a distance (decay) function and filtered to identify areas with minimal human influences.

The problem with using additive index-based approaches like those outlined above is that the width may be set by the variable most at risk and may overlook the actual variable that is limiting function. In the above cases, the index does not deal with interactions between factors. Interactions are likely to important for width considerations because many riparian functions (or variables) will operate differently in the presence of multiple impacts, e.g. gaps in riparian vegetation may have a greater impact on riparian vertebrate diversity where there is little or no vegetation in the surrounding catchment compared to a partially modified catchment. Furthermore, to determine an appropriate weighting (e.g. equate a decay function) requires a good understanding of the behaviour of riparian functions and effects of different impacts along a lateral gradient away from the stream.

Some modeling approaches are better equipped to address the issue of interactions between variables (to a certain degree). For example, SedNet (Prosser *et al.*, 2001) is a sediment transport modeling method that was developed to identify catchment source areas of significant suspended sediment supply (Wilkinson *et al.*, 2005). The model uses potential sources of sediment (hillslope, gully, riverbank) offset by potential depositional locations (floodplain and reservoir) to produce an export budget for a given catchment or sub-catchment. It is a good tool for identifying priority restoration areas at a catchment scale, but does not necessarily address site-specific issues of eroding streambanks and excessively meandering channels. These would require a separate assessment.

The approaches outlined above are useful in not being limited to the location in which they were developed, of better incorporating natural variability into the assessment process and of factoring in land uses within the catchment. The output of these approaches will be variable buffer widths, which are recommended as they consider site-specific factors that are important to riparian function (Castelle et al 1994). However, their primary disadvantage is their computationally complex nature, requiring skilled personnel to develop and operate, the investment of substantial amounts of time and resources and the need for substantial amounts of data to parameterise or validate the models.

### *5. Decision making flow diagram or network*

Decision or choice trees are scientifically-defensible whilst still maintaining simplicity in terms of end-user operation. They are designed on the basis of a conceptual framework or model for a system (formulated from current knowledge), which is then adapted according to the data that is available or relevant. They can be structured differently to reflect the level of complexity or the desired generality in their final application. Most importantly, they readily identify knowledge gaps and research priorities.

Linear flow diagrams and dichotomous keys are straightforward to use and can incorporate many levels relating to a specific objective. Due to their linear nature however, they run the risk of restricting the actual number of choices that are available at each point along the decision-making pathway for the sake of simplicity. This erroneously implies to the end-user that the choices presented are the only ones that are important in all potential scenarios (see Craig *et al.*, 2008). Furthermore, they do not necessarily accommodate interactions or other linkages between factors. If the data used to inform the decision-making process is poor or inappropriately extrapolated, then critical factors may be overlooked or underestimated.

A good example of this approach is in Craig *et al.*, (2008), who developed a flow diagram to prioritise restoration strategies for reducing nitrogen loads in aquatic ecosystems. It is simple to use and clearly identifies the factors that are critical for controlling nitrogen inputs and increasing in-stream retention and nutrient cycling.

Non-linear flow diagrams or networks are suitable for incorporating multiple factors and multiple choice pathways. If a particular factor is not important for a given assessment it is skipped in the decision-making process, without affecting progression through the choice pathway, and another factor(s) becomes critical in informing the final decision. Key knowledge gaps are rapidly identified when attempting to quantify levels at each decision step or node. Bayesian Networks are particularly useful for complex approaches as they accommodate uncertainty in their design, which can be updated as new information becomes available. They use the probability of a previous event (or decision) occurring to assign a conditional probability at a subsequent decision / node. They are particularly useful where information relating to an event or factor is poor, and instead relies on expert opinion. For multiple catchment problems like riparian zone widths, this approach will be the most powerful in allowing a scientifically-defensible decision to be made in the absence of empirical data, but also providing the flexibility to incorporate new data when it becomes available.

**Proposed best approach for designing a riparian width management tool**

The development of non-linear networks, based upon a Bayesian framework is likely to be the soundest and most scientifically-defensible approach for determining minimum riparian zone widths in Victoria, where much of the information required to make these decisions is not available. By taking this approach, the best use of available information may be made to quantify levels of each factor or node. This approach allows the use expert opinion where that information is not available or is from systems that differ greatly from Victorian catchments (e.g. tropical). Ultimately, these networks can be parameterised with conditional probabilities in software like Netica (www.norsys.com) or WinBugs (Lunn *et al.*, 2000).

Below we have outlined an example of how a Bayesian Network may be designed and used to assign riparian zone widths.

Initially, it is not necessary to incorporate conditional probabilities, although there is scope to alter the guidelines to achieve this function. For each management objective, a conceptual model is developed and adapted to the Bayesian Network framework. Important factors that influence riparian function are characterised as input nodes in the network and require quantitative data to inform the next step in the network. A baseline riparian zone width is designated at the start of each network and adjustments made to that width in an additive or multiplicative manner for each input node. Where information is lacking to quantify each level of an input node, best professional judgment guided by the most relevant research findings, is used to designate width additions. This tends to result in larger widths than for inputs that are well quantified. When input nodes are difficult to parameterise due to a lack of current information, knowledge gaps and research priorities are clearly identified.

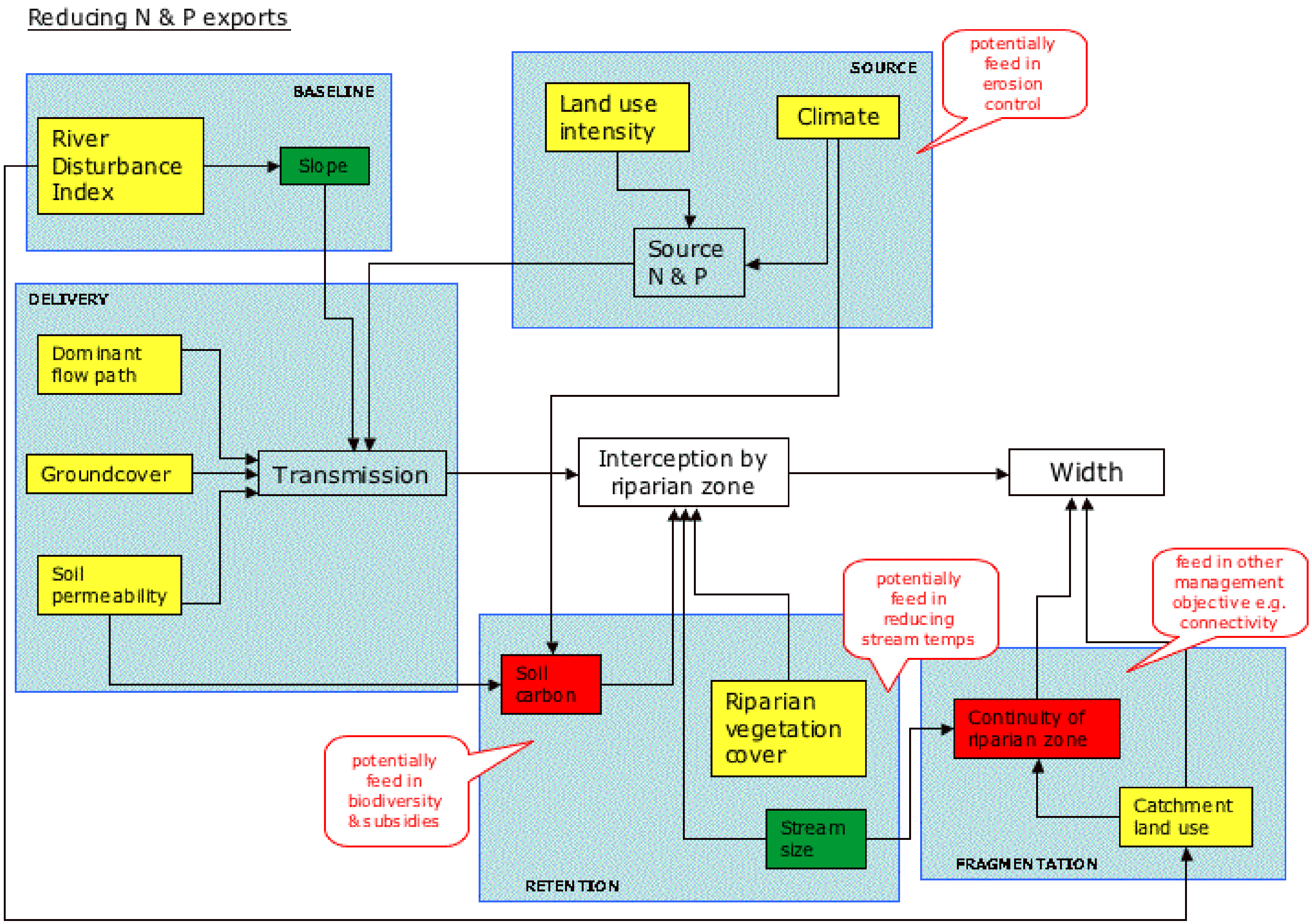
Guideline development steps:

1. develop conceptual models for each management objective - some may need to be combined (e.g. improving aquatic biodiversity and providing food/carbon inputs)
2. adapt conceptual models to a Bayesian Network framework (no probabilities at this stage)
3. for each input node / factor identify the data to be used for the decision-making process, and what level of quantification will be required
4. search for best sources of information and identify the way they will be used

5. summarise a set of widths appropriate for each input node, child node and decision end-point
6. run through the network with a case study to assess its performance or plausibility
7. determine potential locations (input points) for incorporating factors or whole networks relating to other management objectives
8. construct conditional probabilities for each child node

**A potential starting point for every network:** It is a good idea to have a baseline width as a starting point in every network. The River Disturbance Index (RDI) condition scores for Victorian catchments reported in Stein *et al*. (2002) are a potential option for such a starting point (although scores would need to be translated into widths first). This index differs from the ISC in considering alterations to hydrology by classifying rivers on a continuum from undisturbed ("wild") to highly disturbed. Given the difficulties in factoring altered flow regimes into riparian width guidelines, the use of an index like the RDI would allow an *a priori* adjustment for flow regulation that is otherwise difficult to assess in terms of riparian width.

An example network for reducing nitrogen and phosphorus inputs to streams is illustrated on the following page. Important links between factors (nodes) are indicated by arrows. Colours correspond to the level of certainty (where green=high, yellow=moderate and red=low) of scientific data that is available to parameterise the network. Points where other management objectives might be incorporated into the network are shown.



Reducing N & P exports
BASELINE
River Disturbance Index
Slope
SOURCE
Land use intensity
Climate
Source N & P
potentially feed in erosion control
DELIVERY
Dominant flow path
Groundcover
Transmission
Soil permeability
Interception by riparian zone
Width
potentially feed in reducing stream temps
feed in other management objective e.g. connectivity
Soil carbon
Riparian vegetation cover
Continuity of riparian zone
Stream size
Catchment land use
potentially feed in biodiversity & subsidies
RETENTION
FRAGMENTATION