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

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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
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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...
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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.

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

* 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
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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.
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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
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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.

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 (Muscott 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.

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.
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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.

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);
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- 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.

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 *vis a 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 deliver 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

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.
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).
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.
Minimum width requirements for riparian zones in Victoria

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 as 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.
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.

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

Abbreviations: Ag Agriculture, biodiv. biodiversity, Conn. connectivity (terrestrial, T, or hydrological, H), GW groundwater
<table>
<thead>
<tr>
<th>Physiographic region</th>
<th>Dominant land uses</th>
<th>Major waterway issues</th>
<th>Major terrestrial issues</th>
<th>Management objective most likely to predominate</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water quality</td>
<td>Shading</td>
</tr>
<tr>
<td>Murray Basin Plains</td>
<td>Ag - grazing (livestock) Ag - cropping Ag - irrigation</td>
<td>Flow regulation Salinity</td>
<td>Erosion Salinity Loss of vegetation (fragmentation)</td>
<td>☑ ☑ ☑ T H ☑</td>
</tr>
<tr>
<td>- Mallee Dunefield</td>
<td></td>
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<tr>
<td>- Wimmera Plain</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>West Victorian Volcanic Plains</td>
<td>Ag - grazing (sheep &amp; cattle)</td>
<td>Catchment hydrology Salinity</td>
<td>Loss of vegetation (fragmentation) Invasive species</td>
<td>☑ ☑ ☑ ☑ T H ☑</td>
</tr>
<tr>
<td>South Victorian Coastal Plains</td>
<td>Ag - grazing (sheep &amp; cattle) Plantations (hard / softwood) Centre-pivot irrigation</td>
<td>Excess nutrient &amp; chemical inputs Erosion Salinity</td>
<td>Invasive species loss of vegetation (fragmentation)</td>
<td>☑ ☑ ☑ T ☑</td>
</tr>
</tbody>
</table>

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

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
Minimum width requirements for riparian zones in Victoria

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 necessarily 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.

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.
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.
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
Minimum width requirements for riparian zones in Victoria

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
Minimum width requirements for riparian zones in Victoria

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 (e.g. 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 ($\text{NH}_4^+$) or nitrate ($\text{NO}_3^-$) (Naiman et al., 2005). Phosphorus is available to plants predominantly in the form of orthophosphate ($\text{PO}_4^{3-}$) (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 $\text{N}_2$, $\text{N}_2\text{O}$ (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)
suggested 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 stream 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 Décamp, 1997, Lowrance, 1998). Thus, plant immobilisation of excess nutrients (especially P) may be counter-balanced by senescence, litter-fall and decomposition (Muscott 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.
Minimum width requirements for riparian zones in Victoria

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).

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
Minimum width requirements for riparian zones in Victoria

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**

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

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°C (Davies et al., 2004) and NZ stoneflies are unable to acclimatise to stream temperatures above 19°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°, and 40m where the slope is 21-30° (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°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° (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-
Minimum width requirements for riparian zones in Victoria

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**

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<td>- Organic matter inputs (from the riparian zone) are important to in-stream productivity</td>
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<td>- Single (mature) tree riparian widths may provide some carbon inputs to small streams but are subject to damage and/or loss due to windthrow</td>
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<tr>
<td>- Standing stocks of POM and DOC in floodplains are mobilised during flood events and may make significant contributions to in-stream productivity</td>
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<tr>
<td>- Long-term retention of carbon by floodplains between flood pulses is not well quantified and may be related to riparian extent</td>
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<tr>
<td>- Widths for provision of food inputs vary between 5 and 30m</td>
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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 (8th 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
Minimum width requirements for riparian zones in Victoria

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 camaldulensis, 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.
2.3.4 **In-stream habitat**

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
Minimun width requirements for riparian zones in Victoria

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, grunter 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.
2.3.5 **Terrestrial habitat**

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

---

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

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...
Minimum width requirements for riparian zones in Victoria

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 passersines). 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
Minimum width requirements for riparian zones in Victoria

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 20th century, which involved removal of snags, removal of native vegetation and channel
Minimum width requirements for riparian zones in Victoria

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.

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
Minimum width requirements for riparian zones in Victoria

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 20th 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

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<tr>
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<tr>
<td>• Hydrological flow paths are influenced by riparian vegetation, which in turn, influence riparian zone function through efficient delivery of water, energy and propagules</td>
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<td>• Lateral hydrological connectivity is provided by flows but is mediated by vegetation</td>
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<td>• Longitudinal hydrological connectivity is related to discharge, but is regulated by unmodified headwater catchments</td>
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<td>• Structural and functional connectivity between fragmented populations of non-mobile taxa may be strongly influenced by the presence of intact and continuous riparian zones</td>
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<td>• 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</td>
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<td>• Riparian corridors for North American migratory species (usually birds and mammals) are typically between 100 and 200m</td>
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<tr>
<td>• The role of riparian zones in providing movement corridors in unmodified Australian landscapes is poorly quantified</td>
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Connectivity can be defined as pertaining both to hydrology (flow paths of water and waterborne 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
Minimum width requirements for riparian zones in Victoria

- 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
Minimum width requirements for riparian zones in Victoria

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.
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,
Minimum width requirements for riparian zones in Victoria

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.
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.

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.
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
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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.
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, Brosowske et al., 1997, Knutson and Naef, 1997, Lowrance et al., 1997, Naiman and Décamp, 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. 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 Décamp, 1997,
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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
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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.
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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
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- 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).

**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.

Rods

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.
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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.

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
Minimum width requirements for riparian zones in Victoria

streams on slopes exceeding 20\(^\circ\)), 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 allochthonous 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
Minimum width requirements for riparian zones in Victoria

(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 (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

<table>
<thead>
<tr>
<th>Key points</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The greater the land use intensity, the wider the riparian zone needs to be to buffer against catchment modifications and disturbances</td>
</tr>
<tr>
<td>• 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</td>
</tr>
<tr>
<td>• Based on a meta-analysis of &gt;200 studies, riparian buffer widths of between 30 and 200 m are recommended, dependant on land use intensity and management objective</td>
</tr>
<tr>
<td>• Recommended widths apply to both banks</td>
</tr>
<tr>
<td>• 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</td>
</tr>
</tbody>
</table>

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.

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 25th 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.

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

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.
Minimum width requirements for riparian zones in Victoria

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 25th 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.
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.

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

* 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 \(^1\))
- irrigated dairy
- dryland cropping (e.g. canola, wheat)
- high intensity grazing (high stocking rates - beef, horses, deer, etc.)
- swine and poultry (CAFO)
- market gardens (where crops are irrigated)
- high fertilizer application rates (>15kg P/Ha/yr \(^3\))
- sealed roads within 30m

**MODERATE**
- dairy (all other stocking rates ≤ 10 DSE/ha/annum)
- grazing (medium stocking rates 5-15 DSE/ha/annum)
- other forms of dryland cropping (e.g. lucerne) where irrigation is not used
- orchards (including citrus)
- other production crops including vines hops olives
- medium-low fertilizer application rates (<15 kg P/Ha/yr)
- high-medium intensity sheep grazing
- unsealed roads within 30m

**LOW**
- grazing (low stocking rates <5 DSE/ha/annum all stock)
- pasture cropping
- timber plantations
- forestry operations
- 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:

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High = green</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Moderate = yellow</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Low = red</strong></td>
<td>Overseas studies are not applicable to Victorian systems; no data from Australian studies; general principles are unlikely to apply in Victorian systems.</td>
</tr>
</tbody>
</table>
### 3.2 Key Knowledge Gaps and Research Priorities

<table>
<thead>
<tr>
<th>Key points</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Targeted monitoring of ecological responses to riparian restoration is generally very poorly done in Australia.</td>
</tr>
<tr>
<td>• 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</td>
</tr>
<tr>
<td>• Applicability of international research findings to Australian systems is mostly uncertain</td>
</tr>
<tr>
<td>• Effects of fragmentation of riparian zones (both longitudinal and lateral) on the dispersal capability of riparian biota is poorly understood</td>
</tr>
</tbody>
</table>

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).
<table>
<thead>
<tr>
<th>Theme</th>
<th>Knowledge gap</th>
<th>Description</th>
<th>Potential research / management approach</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Monitoring</td>
<td>Little information available on the effectiveness of restoration projects</td>
<td>Targeted monitoring, evaluation and reporting</td>
<td>Monitoring, evaluation and reporting with respect to a given set of management goals should be a compulsory part of any restoration activity</td>
<td>Information will be available to inform the guideline process and ensure its accuracy and applicability to Victorian systems</td>
</tr>
<tr>
<td>2. Hydrology</td>
<td>The effects of flow regulation on riparian zone function</td>
<td>The role of hydrology in mediating riparian zone functions (including off-stream water bodies) and its relationship to riparian width is unclear</td>
<td>Compare riparian zone performance in achieving stated objectives (for example, improving terrestrial biodiversity) above and below impoundments in a variety of landscape contexts</td>
<td>The benefits of narrower or wider riparian zones can be assessed where flow regulation occurs</td>
</tr>
<tr>
<td>3. Management objectives</td>
<td>Best approach for managing riparian zones to achieve multiple objectives</td>
<td>Collection of empirical data on augmenting or initiating multiple functions to riparian zones under different restoration strategies</td>
<td>Collect data before, during and after restoration works that relates to different objectives, e.g. N &amp; P interception, riparian vegetation quality and lateral extent, and invertebrate and avian biodiversity</td>
<td>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)</td>
</tr>
<tr>
<td></td>
<td>The effectiveness of riparian management zones</td>
<td>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)</td>
<td>Experimentally evaluate the effectiveness of riparian management zones in restoration where improving water quality is a primary objective</td>
<td>Targeted application of riparian management zones in areas of high N, P and sediment exports</td>
</tr>
<tr>
<td>4. Landscape contexts</td>
<td>The relationship between stream size and riparian function</td>
<td>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</td>
<td>A long-term dedicated project across an entire catchment or sub-catchment which simultaneously assesses aquatic and terrestrial processes</td>
<td>This would provide a powerful knowledge base for making recommendations about restoration design, riparian/waterway management and ultimately, implementing policy for</td>
</tr>
<tr>
<td>Theme</td>
<td>Knowledge gap</td>
<td>Description</td>
<td>Potential research / management approach</td>
<td>Outcomes</td>
</tr>
<tr>
<td>-------</td>
<td>---------------</td>
<td>-------------</td>
<td>------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>NPS pollution control in different physiographic regions</td>
<td>The broad-scale classification of dominant mechanisms for removal of NPS pollutants by different physiographic region.</td>
<td>Characterise dominant flow paths in sub-catchments where excess nutrients and sedimentation are dominant environmental issues (<em>sensu</em> Lowrance et al 1997).</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td>5. Riparian community persistence</td>
<td>An understanding of what constitutes a self-sustaining riparian zone</td>
<td>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</td>
<td>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 &quot;self-sustaining&quot;. This can only be achieved through multidisciplinary research into natural history, ecology, population biology and quantitative genetic traits of key plant and faunal species</td>
<td>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</td>
</tr>
<tr>
<td>6. Data transferability</td>
<td>The applicability of international studies to Victorian systems</td>
<td>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)</td>
<td>Assess the applicability of research data from other systems to Victorian catchments, either via new experimental comparisons or by analysing existing riparian data</td>
<td>Improved scientific certainty in extrapolating width recommendations from studies in non-Victorian systems</td>
</tr>
<tr>
<td>7. Fragmentation and function of riparian habitat</td>
<td>The performance of fragmented riparian zones</td>
<td>The effects of riparian vegetation fragmentation (which is rarely defined clearly) is poorly understood and should be a major area of rigorous research</td>
<td>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</td>
<td>Targeted restoration of stream sections in different parts of the drainage network</td>
</tr>
<tr>
<td>Theme</td>
<td>Knowledge gap</td>
<td>Description</td>
<td>Potential research / management approach</td>
<td>Outcomes</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>The relationship between riparian vegetation width and length</td>
<td>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</td>
<td>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</td>
<td>Experimentally evaluate minimum patch sizes for riparian zones harbouring different vegetation classes and faunal assemblages</td>
<td>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)</td>
</tr>
<tr>
<td>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</td>
<td>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</td>
<td>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</td>
<td>Experimentally assess terrestrial habitat use by aquatic invertebrate communities, especially where there is flow regulation and land use modifications</td>
<td>Improvement of ecological assessments (for example, ISC) and better translation of biotic indices into terrestrial habitat management for in-stream fauna</td>
</tr>
<tr>
<td>The influence of invasive species on riparian functions</td>
<td>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.</td>
<td>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.</td>
<td>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</td>
<td>The ability to make pragmatic trade-offs between the level of riparian function or performance and the level of management effort</td>
</tr>
<tr>
<td>Habitat use by riparian obligate versus generalist species</td>
<td>The relative reliance of riparian-dependent versus generalist species on intact riparian zones in different landscape contexts requires investigation</td>
<td>The relative reliance of riparian-dependent versus generalist species on intact riparian zones in different landscape contexts requires investigation</td>
<td>Experimentally assess habitat use by key terrestrial fauna of riparian zones in modified and unmodified landscapes. This should be conducted in both regulated and unregulated systems</td>
<td>This will provide better information relating terrestrial biodiversity management goals to riparian restoration design in different landscape contexts</td>
</tr>
<tr>
<td>8. Nutrient cycling and subsidies</td>
<td>Riparian carbon contributions and DOC dynamics</td>
<td>The role of riparian vegetation in influencing carbon inputs, and the ecological role of DOC in-stream and soils is still poorly understood</td>
<td>Experimentally investigate floodplain plant-soil carbon dynamics in riparian restoration projects. Differences between regulated and unregulated systems should be explored</td>
<td>Improvement of riparian and in-stream carbon stocks for both biotic processes and climate change mitigation (through sequestration)</td>
</tr>
<tr>
<td>Theme</td>
<td>Knowledge gap</td>
<td>Description</td>
<td>Potential research / management approach</td>
<td>Outcomes</td>
</tr>
<tr>
<td>-------</td>
<td>---------------</td>
<td>-------------</td>
<td>-----------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>The link between terrestrial and aquatic function</td>
<td>There is virtually no research on reciprocal subsidies and their relevance for terrestrial-aquatic linkages in Australian systems</td>
<td>Increase the focus of research on linking processes (e.g. exploration of the relationship between avian communities and aquatic invertebrate diversity)</td>
<td>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)</td>
</tr>
<tr>
<td></td>
<td>Knowledge of N turnover / processing rates</td>
<td>Yet to be quantified for Australian systems</td>
<td>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</td>
<td>Characterisation and spatial delineation of riparian zones that make the most efficient contribution to nutrient retention</td>
</tr>
</tbody>
</table>
REFERENCES


Minimum width requirements for riparian zones in Victoria


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


Minimum width requirements for riparian zones in Victoria


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


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


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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.


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


Minimum width requirements for riparian zones in Victoria


Minimum width requirements for riparian zones in Victoria


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.

<table>
<thead>
<tr>
<th>State / region</th>
<th>Minimum width</th>
<th>Stream size</th>
<th>Function / context</th>
<th>Study</th>
</tr>
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<tr>
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<td>ISC criteria - highest score riparian condition</td>
<td>Ladson et al., 1999</td>
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<td>nationwide</td>
<td>3 channel widths</td>
<td>large &gt;15m</td>
<td>ISC criteria - highest score riparian condition</td>
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<td>nationwide</td>
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<td>SWWA</td>
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<td>Maintaining macroinvertebrate communities</td>
<td>Growsns and Davis, 1991</td>
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<tr>
<td>QLD</td>
<td>10m</td>
<td>1st / 2nd order</td>
<td>Extent of riparian vegetation</td>
<td>Catterall et al., 2001</td>
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<tr>
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<td>Runoff attenuation</td>
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<td>NSW</td>
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<td>Slope (&lt;33%) erosion control</td>
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<tr>
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<td>15-55m</td>
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<td>WA</td>
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<td>Grass buffer - subsurface contaminant removal &gt;50%</td>
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<td>Greater to prevent edge effects from invasive species</td>
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<td>Bank recharge for riparian vegetation</td>
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<td>Class 2</td>
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<td>Filtering sediment - Kikuyu grass buffer</td>
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<td>Nepean River</td>
<td>Low disturbance criteria for grazing modification</td>
<td>Brainwood et al., 2006</td>
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<td>Stream size</td>
<td>Function / context</td>
<td>Study</td>
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<td>--------------------------------------------------------</td>
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<td>Bank stability</td>
<td>Abernethy and Rutherfurd, 1999</td>
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<td>Water quality</td>
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<td>Shading and stream temperature control</td>
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<tr>
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<td>5-30m</td>
<td>Food inputs / in-stream habitat</td>
<td>Price et al., 2005</td>
</tr>
<tr>
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<td>10-30m</td>
<td>In-stream habitat (fish)</td>
<td>Price et al., 2005</td>
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<tr>
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<td>Terrestrial habitat</td>
<td>Price et al., 2005</td>
</tr>
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<td>Contaminant removal (agricultural source)</td>
<td>Price et al., 2005</td>
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<td>Water quality</td>
<td>Price et al., 2005</td>
</tr>
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<td>Terrestrial connectivity</td>
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<td>DIPNR, 2004</td>
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<td>creeks</td>
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<tr>
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<td>Stream size</td>
<td>Function / context</td>
<td>Study</td>
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<td>SEQLD</td>
<td>100m</td>
<td>variable</td>
<td>Wildlife conservation</td>
<td>Catterall, 1993</td>
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</tbody>
</table>

† 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 $\times$ 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

<table>
<thead>
<tr>
<th>Country*</th>
<th>Minimum buffer width (m)</th>
<th>Function (for N, P &amp; sediment removal, only widths achieving 50% or greater removal efficiency are reported)</th>
<th>Study</th>
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<tbody>
<tr>
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<td>52-137</td>
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<td>Chen et al., (1992)</td>
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<td>edge effects: forest structure &amp; function</td>
<td>Franklin and Forman, (1987)</td>
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<td>US</td>
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<td>edge effects: forest structure &amp; function</td>
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<td>Taylor et al., (2008)</td>
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<td>food inputs &amp; resources to stream</td>
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<td>57</td>
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<td>Cormack, (1949)</td>
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<td>in-stream habitat: fish</td>
<td>FEMAT, (1993)</td>
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### Minimum width requirements for riparian zones in Victoria

<table>
<thead>
<tr>
<th>Country*</th>
<th>Minimum buffer width (m)</th>
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<td>riparian litter inputs</td>
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## Minimum width requirements for riparian zones in Victoria

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### Minimum width requirements for riparian zones in Victoria

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<tr>
<th>Country*</th>
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### Minimum width requirements for riparian zones in Victoria

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<tr>
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<td>20</td>
<td>hazard specific</td>
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Minimum width requirements for riparian zones in Victoria

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
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 \( W=8+0.6S \), 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°) 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

**Source**
- Land use intensity
- Climate
- Source N & P

**Baseline**
- River Disturbance Index
- Slope

**Delivery**
- Dominant flow path
- Groundcover
- Soil permeability

**Retention**
- Interception by riparian zone
- Soil carbon
- Riparian vegetation cover
- Stream size

**Fragmentation**
- Continuity of riparian zone
- Catchment land use

**Notes**
- Potentially feed in erosion control
- Potentially feed in reducing stream temps
- Feed in other management objective e.g. connectivity
- Potentially feed in biodiversity & subsidies