Australian Government
Land & Water Australia

Design guideline for the reintroduction of wood into Australian streams

RiverLandscapes

DR ANDREW P. BROOKS

Acknowledgements

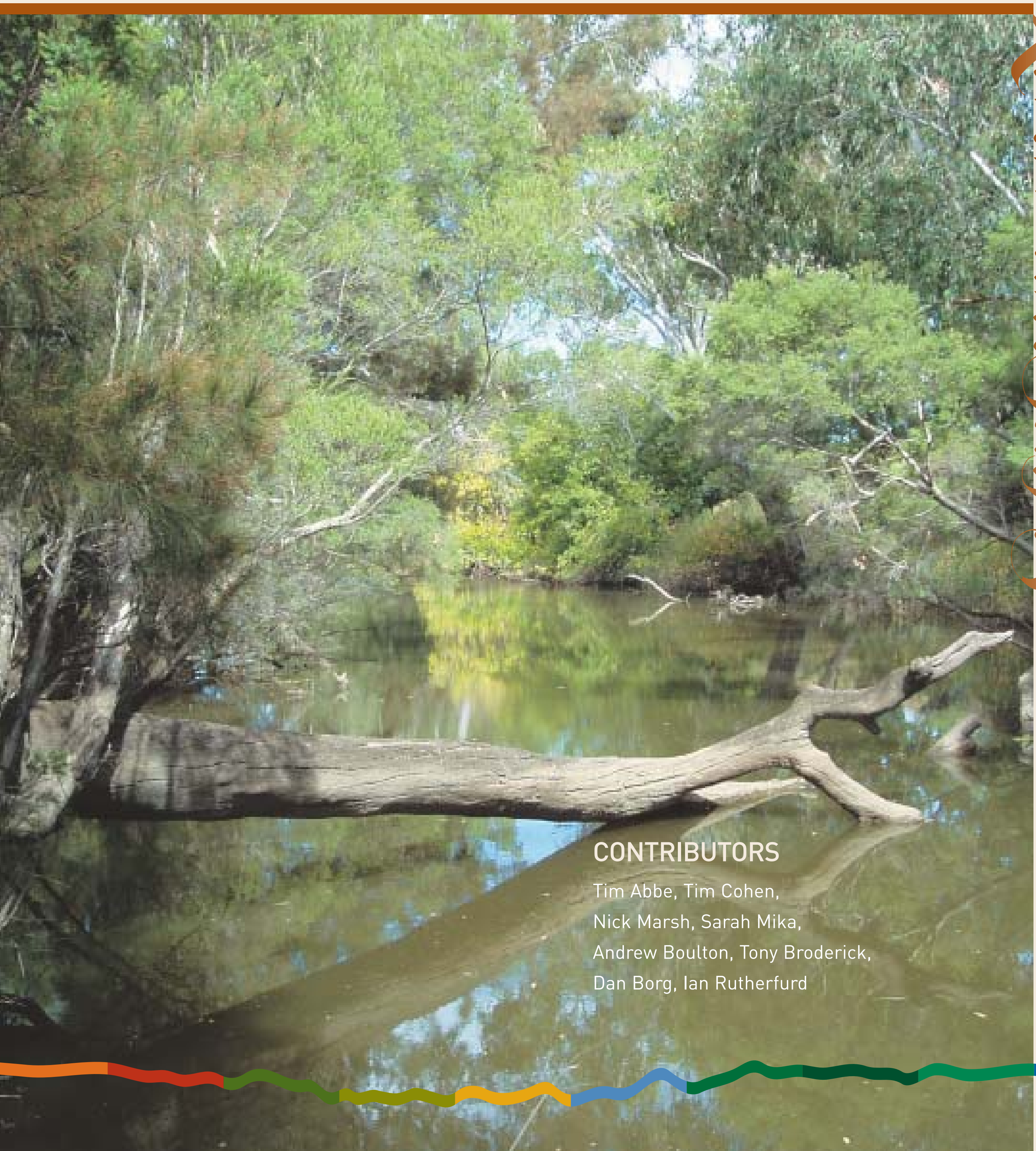
This Guideline is dedicated to the memory of the late Edwin Smith on whose property many of these trial works were undertaken. Special thanks also to Naida Smith and the Woodward family for their ongoing support and access to their land. Much of the research on which these guidelines are based was done under LWA projects MQU9 and GRU27; and ARC Linkage Project LP0346918. This project would never have proceeded without the generous support of Allan Raine from the NSW Department of Natural Resources and Sharon Vernon from the then Hunter Catchment Management Trust who were instrumental in facilitating the adoption of this experimental program within their respective organisations. Special thanks to Rod Gleeson for much of the survey work, the Dungog Work Crew and Rob Argent for their efforts implementing the rehabilitation works. Thanks also to Brian Woodward, Matt Taylor and John Jansen for data collection and analysis; Brian Woodward for the 3D Autocad drawings; Dean Oliver for drafting many of the figures and to John Spencer for GIS analysis. Special thanks to Peter Gehrke for undertaking the initial fish survey work, and to Bob Creese for his support of Tim Howell in undertaking the subsequent monitoring. The project has benefited from the efforts of numerous field assistants over the years, in particular, the NSW Fisheries crew — Simon Hartley, Andrew Bruce, Tony Fowler, Debrah Ballagh, Michael Rodgers, Ian Wooden and Tom Rayner. Thanks also to Scott Babakaiffe and Chris Gippel for their input into the development of the study design. The report has greatly benefited from reviews by Chris Gippel, Phil Price, Siwan Lovett and Tim Cohen.

ANDREW BROOKS

Design guideline for the reintroduction of wood into Australian streams

Dr Andrew P. Brooks

RiverLandscapes



CONTRIBUTORS

Tim Abbe, Tim Cohen,
Nick Marsh, Sarah Mika,
Andrew Boulton, Tony Broderick,
Dan Borg, Ian Rutherfurd

This Guideline was written by Dr Andrew P. Brooks, Australian Rivers Institute, Griffith University, Nathan Qld 4111 with contributions by Tim Abbe (Herrera Environmental Consultants, Seattle); Tim Cohen (University of Wollongong); Nick Marsh (Queensland Environmental Protection Authority); Sarah Mika and Andrew Boulton (University of New England); Tony Broderick (NSW Northern Rivers Catchment Management Authority); and, Dan Borg and Ian Rutherfurd (University of Melbourne).

Design guideline for the reintroduction of wood into Australian streams

Published by: Land & Water Australia
Postal address: GPO Box 2182, Canberra ACT 2601
Office location: L1, The Phoenix
86 Northbourne Avenue, Braddon ACT
Telephone: 02 6263 6000
Facsimile: 02 6263 6099
Email: Land&WaterAustralia@lwa.gov.au
Internet: http://www.lwa.gov.au

ISBN: 1921 253 061 (print), 1921 253 07X (web)
Citation: Brooks, A. et al. 2006, *Design guideline for the reintroduction of wood into Australian streams*, Land & Water Australia, Canberra.
Product code: PX061171

Cover photos: Front cover, Tim Howell; background image, Roger Charlton. Back cover, Dan Keating.
Internal photos: Andrew Brooks, unless otherwise credited. Bark and wood texture photos throughtout, Roger Charlton.
Design: Angel Ink
Print: Paragon Printers
Date: December 2006

Contents

Appendices

List of photos

List of figures

List of tables

chapter 1

Introduction

1.1 Purpose of this Guideline

Community perceptions regarding the benefits of both retaining and reintroducing wood into rivers and streams have fundamentally changed since the early 1990s. In large part this has been brought about by a raft of research into the role that trees and branches falling into our rivers (variously described as snags, large woody debris (LWD), coarse woody debris (CWD), woody debris, wood, log jams or structural woody habitat (SWH)) play in aquatic ecosystem health and channel morphodynamics. We now know that in many respects wood in rivers is akin to the coral reefs in our oceans, as it provides substrate for invertebrates and biofilms, and provides complex habitat that supports a wide range of aquatic species. In addition, it also performs a critical geomorphic role.

Research funded by Land & Water Australia (LWA) has been at the forefront of this rethink, and in particular the communication of the new insights to river managers and the broader community. Over the last seven years LWA has published a number of reports and technical guidelines that have highlighted the role in-stream wood plays as aquatic habitat, as a long-term source of carbon, and as an agent inducing channel complexity and stability. Volume 1 of the *Riparian Land Management Technical Guidelines* (Lovett & Price 1999), and the updated version *Principles for Riparian Lands Management* (Lovett & Price 2007) reviewed the ecological and geomorphological functions and benefits associated with wood in streams, while Volume 2 provided information on how wood can be best managed to protect aquatic ecosystem health. The *River and Riparian Land Management Technical Guideline Update no. 3,* 'Managing wood in streams' (Cottingham et al. 2003) provided an update of the ecological and geomorphological functions of wood on streams contained in the earlier guidelines, with new scientific insights developed since the publication of the original guidelines.

Photo 1. Natural log jam — Allyn River, NSW.

Photo 2. Bank deflector jam under construction — Williams River, NSW.

This Guideline builds on the earlier publications, focusing more on the technical and practical aspects of reintroducing wood into streams, and incorporating insights from recent field trials. Over the last five years there has been considerable research and development into methods for reintroducing wood into streams, focused primarily around a number of field experiments in which wood reintroduction strategies have been designed and tested from an engineering, a geomorphic and an ecological perspective. The outcomes of some of these field trials are presented here, along with the methods employed for their design, construction and monitoring. New insights from additional experimental work under the Upper Hunter River Rehabilitation Initiative will come on line over the next few years. It should be noted that most of the structure designs outlined in this Guideline tend to have a geomorphic or engineering role as their primary function, with the ecological/habitat functions secondary. Nevertheless, the basic physics still apply for the stability analysis, although different designs and anchoring techniques may be required if the objective is purely one of direct habitat augmentation. If your intention is to reintroduce wood purely for fish habitat, there is still a need to develop an understanding of the reach geomorphic conditions as part of the project design process. Geomorphic changes to your stream reach may completely override any measures undertaken on the assumption that the wood is purely for habitat.

The main purpose of this Guideline is to help river managers design a wood reintroduction strategy that will survive for a sufficient period of time to enable natural wood recruitment to take over and reduce the need for artificial reintroduction of wood to streams. In-stream structures often fail because our ability to predict the future behaviour of streams is limited and because the structures have been poorly or inappropriately designed. This Guideline does not deal with predicting stream behaviour, but aims to avoid poor and inappropriate structure design. We have incorporated the most up to date knowledge and experience on wood reintroduction, with a view to improve the likelihood of implementing a successful wood-based stream rehabilitation strategy.

Photo 3. Constructed bed control log structure — Stockyard Creek, NSW.

1.2 Who is this Guideline for?

By necessity, this Guideline requires some technical understanding of channel hydraulics and geomorphology and, as such, is aimed more at the specialist river manager, than at community groups. It is intended primarily to assist staff of government agencies, Catchment Management Authorities and Boards, waterway managers or fisheries officers, to plan and construct a wood based river rehabilitation project. It will, however, also be of value to community groups in helping to conceptualise and plan river rehabilitation projects, to develop costings, and to understand the logistical issues that must be considered before implementing a wood reintroduction project.

1.3 Why bother with planning and design — why not just throw them in?

Many artificial instream habitat structures "fail" or are structurally compromised within their first few years of service (Frissell & Nawa 1992, Bisson et al. 2003). While a fish or a biofilm might not care much if a log structure disintegrates somewhat over time — after all they have coped well for millions of years with trees simply falling into the river in a random fashion — council engineers and farmers, for example, tend to get a bit concerned about "failed" structures, and "logs on the loose" in streams. So the first reason for worrying about proper design and planning is that the community expects nothing less. After all, in the mid 1990s, desnagging was still a widespread practice throughout Australia, and it is only in the last few years that research into the benefits of wood in rivers has caused community attitudes to shift towards thinking about returning wood to streams. While there are now some very enthusiastic proponents of wood reintroduction, after 150–200 years of pulling logs out of rivers there is still a broad cross section of the community who are yet to be convinced of the wisdom of this approach.

At the other end of the spectrum, there is now an increasing chorus of people asking; "why not just throw the logs into the river as nature has done for millennia — why bother with all this expensive design and anchoring?" While there are very good grounds for undertaking some controlled experiments in the right location of just such an approach, on the whole, society is probably not quite ready for such a radical method. Another key reason for proper design and planning is that at many locations where wood reintroduction is being contemplated, river channel dimensions and, hence, in-stream hydraulics have changed dramatically in historical times. Channel capacity has often increased, and roughness decreased, leading to channels with much higher unit stream power than they would have experienced under pre-disturbance conditions. Under these conditions, logs that might have been stable under pre-European river conditions, are now much more likely to move. As a result there is a need to consider how local stream power conditions might have changed and to design structures with appropriate anchoring that can withstand the forces applied to them.

Another reason to not just throw them in is that large pieces of wood suitable for rehabilitation projects are in short supply and, hence, we cannot afford to waste them. It is an unfortunate fact that the millions of pieces of wood pulled out of rivers over the years were mostly burnt on-site. Furthermore, many riparian areas have been cleared and no longer provide natural inputs of wood to their adjacent streams, let alone act as potential sources of wood for rehabilitation programs. Even where trees have been replanted, it will be decades at least, if not centuries, before these plantings begin acting as natural sources of wood recruitment. This means wood will generally need to be sourced from approved clearing sites, will be in relatively limited supply, and likely to be a considerable distance from where it is needed. Transport costs will be high, so every piece counts, and we cannot afford to just throw them in and hope for the best.

1.4 Not the last word

It must be stressed that the science and art of wood reintroduction as a river rehabilitation strategy is still very much in its infancy and these guidelines are not intended to be the last word on this topic. Rather, presented here is the experience gained to date, with some principles for safely designing and implementing a wood reintroduction strategy. There is an obvious bias in the strategies outlined here towards the higher energy coastal rivers, given that

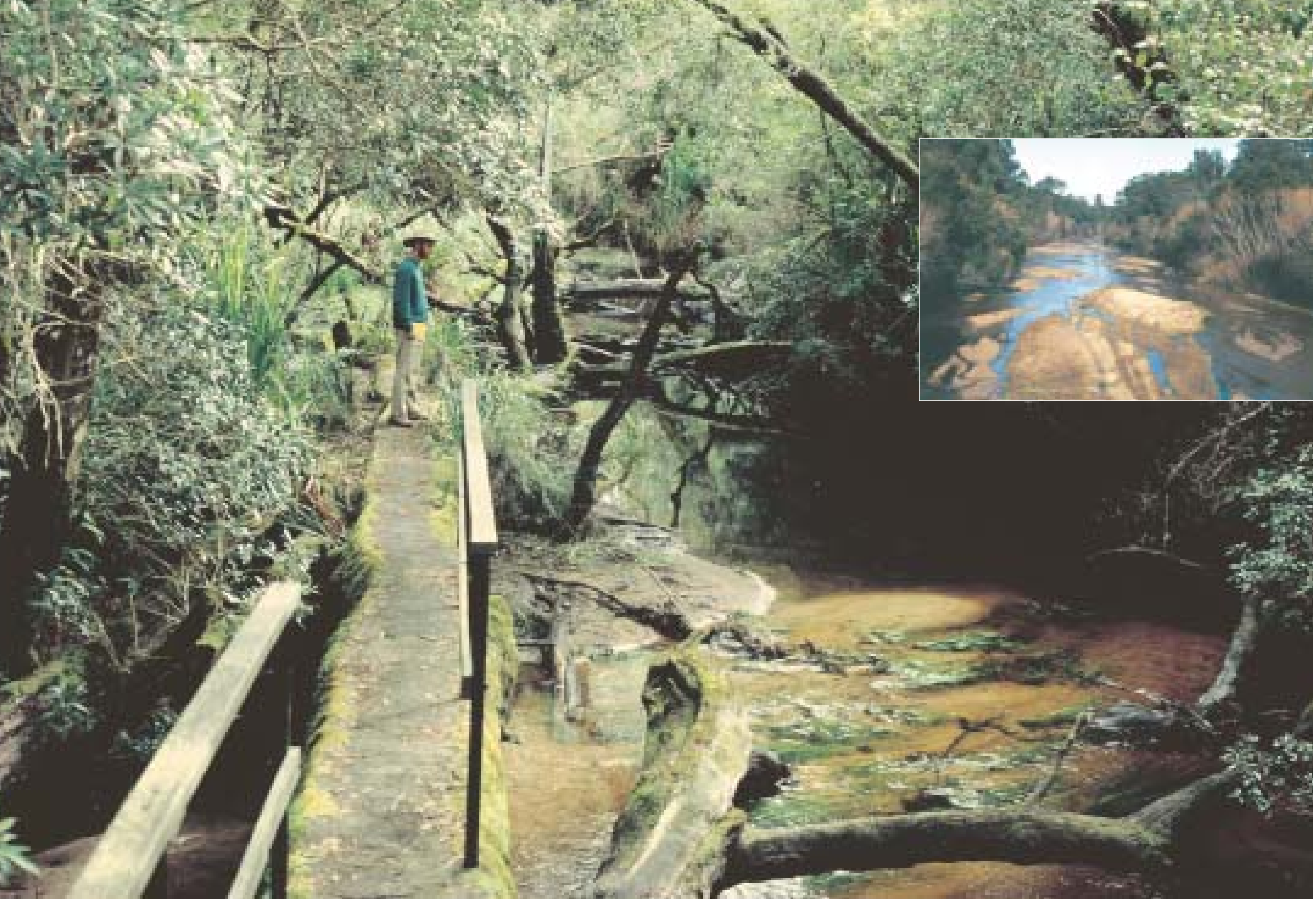
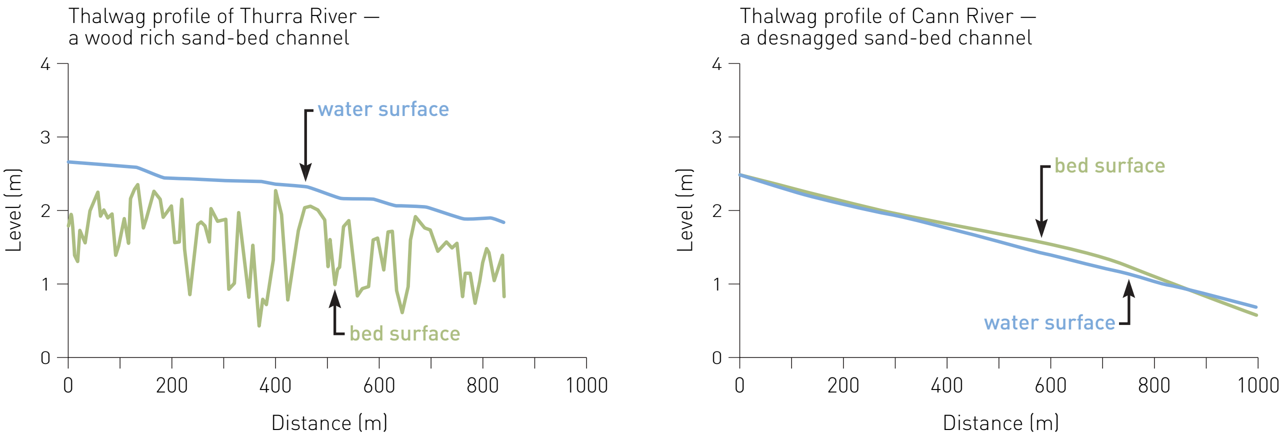
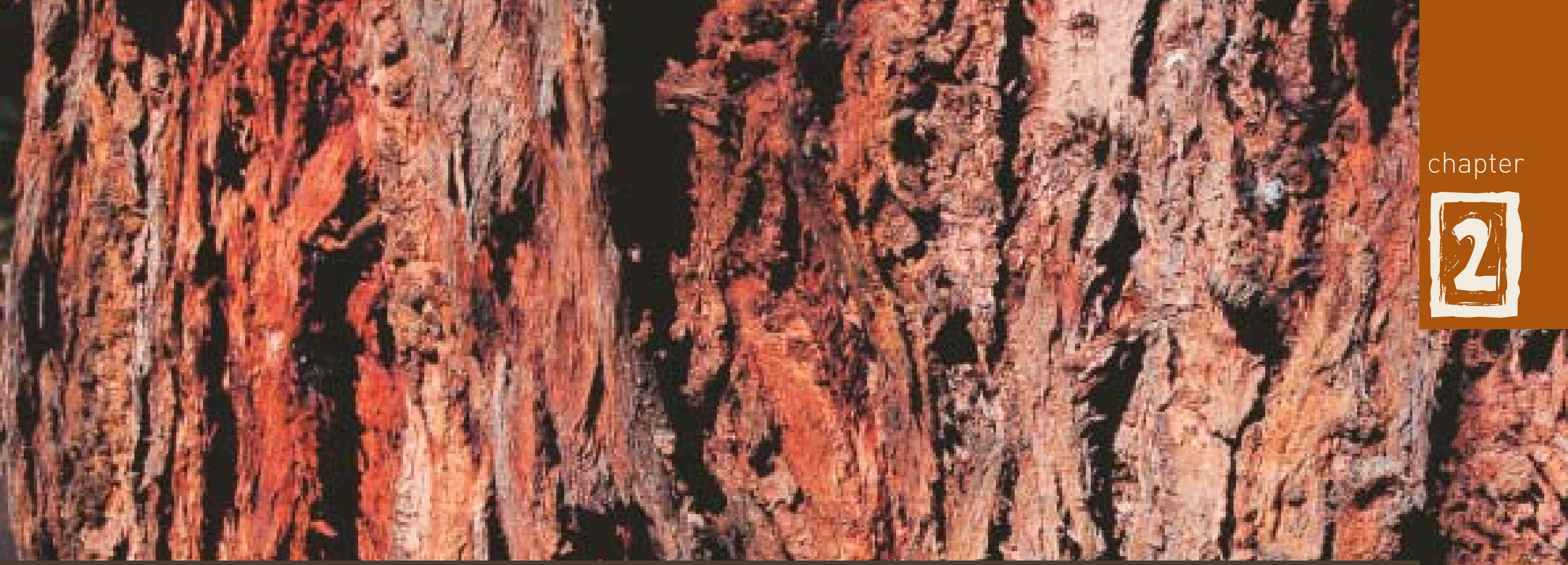


Photo 4. Natural sand-bed river with a high wood loading and high morphologic diversity — Thurra River, Victoria. Inset: A desnagged sand-bed channel — Cann River, Victoria.

experience to date is predominantly derived from these areas, and structural stability tends to be more of an issue in these rivers. It must be stressed that this is not a recipe book, and there is no standard log structure that is suitable for all situations. Indeed, it is hoped that by encouraging practitioners to understand river processes and dynamics, and by learning from natural analogues, that they will be spurred to develop new designs and new strategies. In many respects, the experience gained to date is coloured by the circumstances of the day in which we were attempting to turn around the centuries of bad press that wood in rivers has received. Consequently, the initial structures employed within the experimental reaches (summarised in Section 3.3) were extremely conservative, constructed with considerable factors of safety. We fully expect that as community concerns about wood in rivers are allayed, less conservative designs can be developed with lower factors of safety. Some examples of approaches used by others are included in Appendix A.

Figure 1. Bed morphological variability with and without in-stream wood. The thalwag profile is a survey of the deepest point at each survey cross section down the channel. Note the base flow water level in the Thurra (left) provides extensive, diverse aquatic habitat. In contrast, the Cann River (right) under similar flow conditions provides very little usable aquatic habitat, as most flow is sub-surface and there are no pools to provide refugia.





chapter 2

The functions of wood in rivers

2.1 Summary

A considerable body of research has built up over the last few decades highlighting the important functional role of wood in rivers. A detailed review of much of this literature is contained within Chapter 7 of the *Principles for Riparian Lands Management* (Lovett & Price 2007) and for this reason will not be repeated in detail here. The following is a summary of the primary functional attributes of wood from the above reference. The full version can be found at the following website http://www.rivers.gov.au/publicat/guidelines.htm

- Riparian vegetation increases stream channel complexity and directly contributes to aquatic habitat through inputs of logs and branches. In turn, the provision of complex habitat has a major influence on aquatic biodiversity.
- Logs and branches can enhance stream stability, regulate sediment transport and exert significant control on channel complexity in bedrock rivers, and channel geomorphology in alluvial rivers.
- Logs contribute to the formation of physical features in streams, such as scour pools and channel bars, which serve as habitat for in-stream biota.
- Logs provide physical habitat for biota at all levels of the food chain, ranging from microscopic bacteria, fungi and algae, to macroinvertebrates, fish and turtles.
- Logs also provide sites where bacteria, fungi and algae can process carbon and other nutrients such as nitrogen and phosphorus, thus contributing to ecosystem processes such as productivity and respiration.
- In alluvial rivers, logs can modify surface water/ground water exchange and enhance nutrient processing.
- Logs from Australian riparian zones are relatively immobile. Our streams tend to have a low average stream power, the wood has a high density and many riparian trees have a complex branching structure that ensures they are easily anchored in position after falling into a stream.
- Although vast amounts of wood have been removed from many Australian rivers, what does remain provides important habitat for microbes, invertebrates, fish and other animals.
- Retention and reinstatement of logs should be a priority for river rehabilitation, instead of removal or even realignment.

Photo 5. Natural log jam — Allyn River, NSW.

In NSW the removal of woody debris (wood) from rivers is now listed as a key threatening process under the *Fisheries Management Act 1994*. Under this act, a threatening process is defined as a "process that threatens, or that may threaten, the survival or evolutionary development of a species, population or ecological community of fish".

2.2 New research: Using wood to restore hyporheic processes

Following the initial trials of engineered log jams at the Williams River experimental site (Section 3.3), subsequent collaboration with Professor Andrew Boulton, Sarah Mika and co-workers from the University of New England, highlighted the potential for using log structures to help rehabilitate the hyporheic zone. The following Section provides an overview of this emerging field in river rehabilitation research by those leading the research. As this work is not covered in the updated version of the *Principles for Riparian Lands Management* (Lovett & Price 2007) a brief explanation of the "hyporheic zone" is included here along with some of the ideas on how wood can help to rehabilitate this important, and seldom considered, part of the riverine ecosystem.

Can we use wood introductions to restore hyporheic processes?

Sarah Mika and Andrew Boulton
Ecosystem Management, University of New England,
Armidale, NSW 2351
smika@une.edu.au

Virtually all studies of the ecological benefits of introduced wood focus on processes or biota in the surface stream. However, scientists are beginning to understand more fully the fundamental ecological significance of the hyporheic zone to surface ecosystem processes (reviews in Boulton et al. 1998, Dent et al. 2000). The hyporheic zone is the saturated sediments lying below and alongside river channels, and in many rivers it directly links surface water to permeable alluvial aquifers below the riparian zones and 'true' groundwater further below (Figure 2). Exact boundaries of the hyporheic zone are difficult to identify and these fluctuate in response to variations in the depth and volume of water exchange with the surface stream (White 1993), which are in turn affected by surface river discharge and channel shape (Thibodeaux & Boyle 1987, Boulton 1993).

The main ecological role of the hyporheic zone is the alteration of water chemistry and the generation of nutrients that potentially limit productivity in the surface stream (Coleman & Dahm 1990, Valett et al. 1994). Much of the decomposition and microbial processing of organic matter occurs in the sediments, and the hyporheic zone serves as a storage and processing site for this material (Marmonier et al. 1995). The hyporheic zone is also a potential refuge for surface stream invertebrates from flooding and drying (review in Boulton 2000a) and even surface water pollution (Jeffrey et al. 1986). The significance of the

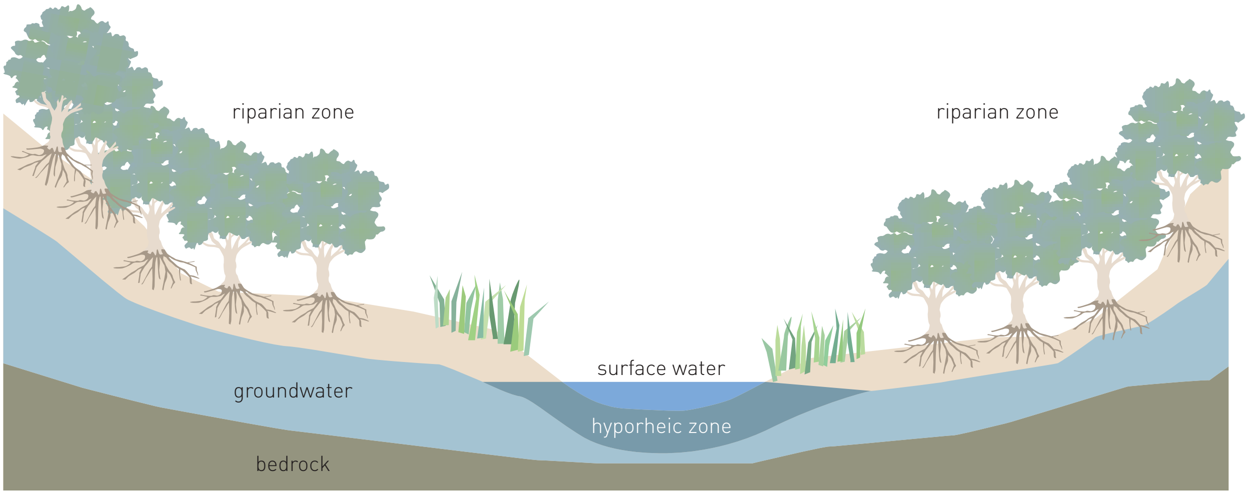


Figure 2. The central location of the hyporheic zone linking surface water, groundwater and the riparian zone.

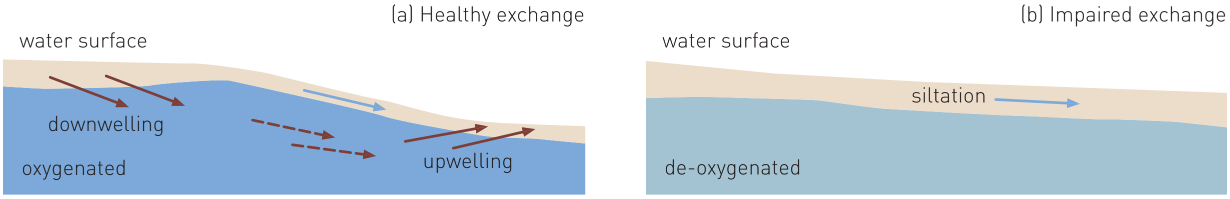
hyporheic zone for successful recruitment of gravel-spawning fish has long been known in the northern hemisphere (Vaux 1962) and probably holds true for Australian native fish such as freshwater catfish.

Hydrological exchange drives interactions between the surface stream and hyporheic zone. However, sedimentation and the loss of geomorphic complexity smooths out the longitudinal profile of the stream bed (Brooks 2004), reducing hydrological exchange between the surface stream and hyporheic zone by several mechanisms. Firstly, there is reduced convectional exchange arising through pressure differences between the topography of the streambed, surface flow, and the groundwater table. A stream flowing over a bedform, such as a crest of sediment, results in a pressure distribution that drives flow into the bed (Thibodeaux & Boyle 1987). Alternating high and low pressure areas along an undulating streambed generates a ‘pumping exchange’, and advective porewater movement that promotes hydrological exchange of stream and subsurface water (Packman & Bencala 2000, Figure 3a). Interaction of the stream and porewater flow produces a slip velocity at the bed surface and a gradient of exponentially decreasing flow velocities within the bed (Packman & Bencala 2000). Streamflow at the bed surface ‘drags’ the porewater upwards, and this process is largely a response to turbulent flow in gravel-bed rivers. In sand-bed rivers, the smaller pore spaces restrict stream-driven turbulence to a thinner layer near the surface of the bed, substantially reducing the amount of hydrological exchange (Packman & Bencala 2000).

A second means of disrupting surface and subsurface water exchanges is through siltation and deposition of inorganic fine sediments along the channel (Schälchli 1992, Figure 3b). Fine sediments percolate deep into the streambed (colmation) and, because hydrological exchange has been weakened by the loss of topographic relief, there is progressively less flushing until the hyporheic zone is clogged with fine, inorganic silt. This surface deposition and resultant colmation, effectively severs the surface stream from the subsurface zone (Figure 3b). Colmation arising from uncontrolled sediment release into streams and rivers causes many of the serious impacts of human activities upon the hyporheic zone (Boulton 2000b, Hancock 2002). Deeply ingrained fine silt appears remarkably resistant to most flushing flows and floods unless bed material is moved substantially. Frequently, the deposition of fine silt on the streambed promotes dense mats of filamentous algal growth. When light levels and nutrient concentrations are high; these mats trap additional silt and further exacerbate the loss of surface/sub-surface flow connection.

Given that the main impact of human activities on the hyporheic zone appears to have been the effects of sedimentation, siltation and colmation in severing the hydrological linkages (Boulton et al. 2000, Hancock 2002), the most common suggestion for restoring these linkages has focused on the use of environmental water allocations to provide flushing flows (Hancock 2003). Early indications seem to be that very large flows may be needed and the bed material may have to be shifted so that flushing can occur properly (Hancock & Boulton 2005). It is also likely that silt will rapidly infiltrate the interstices after the flushing flows and, therefore, may only be a short-term solution that shifts the problem downstream. Obviously, silt inputs must be controlled to resolve the issue properly, but in areas where rehabilitation is planned or underway, the severe impacts of sedimentation (Wood & Armitage 1997) may neutralise the process.

Another alternative to renewing hydrological linkages with the hyporheic zone may be to reintroduce topographic relief into the stream channel by using wood to create a physical bedform, or induce changes in patterns of sediment deposition within the channel or along the lateral bars. When a log lies across the path of flow and is partially embedded in the sediment (‘log sill bed controls’ (LSC) sensu Brooks et al. 2004, Figure 4), water moving over it would be expected to enhance hydrological exchange (Figure 4). At the leading edge of the log, downwelling may occur in response to the stepped relief while at the ‘plunge pool’ downstream, further downwelling may occur in a localised region. The displacement of porewater by these two downwelling zones is hypothesised to generate a more diffuse upwelling


(a) Healthy exchange

(b) Impaired exchange

Figure 3. This longitudinal schematic of an idealised streambed illustrates the direction and strength of hydrological exchange between the hyporheic zone and surface stream in response to natural geomorphic complexity (a), and the loss of this exchange when the bed profile is smoothed and sedimentation occurs (b).

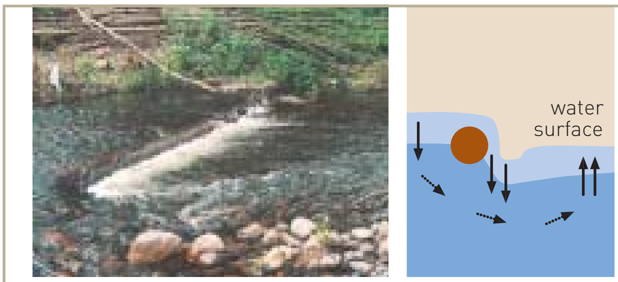


Figure 4. A log (LS) lying half-buried in the streambed across a channel in the Williams River is capable of inducing localised upwelling and downwelling of streamwater, represented by arrows in the schematic diagram.

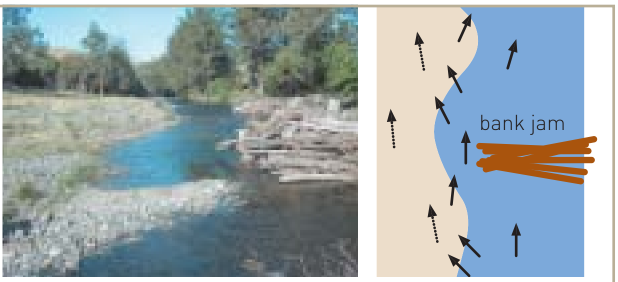


Figure 5. This constructed deflector jam (DFJ) extending into the channel in the Williams River caused scalloping of the edge of the gravel bar across the channel, enhancing the surface area for lateral hydrological exchange, represented by arrows in the schematic diagram.

zone downstream of the LSC (Figure 4). Furthermore, sediments may pile against the leading edge of the LSC and 'dunes' may form downstream of the plunge pool so that there is a cascade effect of the creation of topographic relief (Figure 4).

More complicated is the potential effect of logs anchored to the bank and extending into the channel ('deflector jams' (DFJ) sensu Brooks et al. 2004, Figure 5). Plausibly, water may be forced to downwell upstream of the bank jam, but it is more likely that the majority of flow will be deflected. If there is a gravel bar on the opposite side of the channel, 'scalloping' occurs that increases the complexity of the bar's edge and potentially enhances the exchange of water laterally into the parafluvial zone (Figure 5). This creation of a series of 'mini-bars' could substantially increase the total area for biological and physical filtration (Malard et al. 2002, Boulton et al. 2004).

Photo 6 (right). Constructed hyporheic-jam (log step) — Hunter River, NSW.
Photo 7 (below). Constructed hyporheic jam (i.e. log step with paired abutment jams) — Williams River, NSW.

chapter

3

The engineered log jam concept

3.1 Historical background

Large scale efforts to reintroduce wood to streams began in the Pacific Northwest of North America, particularly in rural forest land, in the early 1980s (e.g. House & Boehne 1985, 1986). In Australia, the awareness of the beneficial role of wood in rivers did not really gain traction until the mid 1990s, with many rivers still actively being "desnagged" up to this time. While most of the early wood reintroduction projects in North America were well intentioned, some projects met with limited success due to insufficient understanding of the fluvial processes structures would be subjected to, how the project would influence these processes, and the consequences to habitat (Frissell & Nawa 1992). Preconceived perceptions of wood being inherently unstable in streams and rivers, along with inadequate physical explanations of why wood was naturally stable, also led to the widespread use of steel cables and artificial anchors or ballast for wood placements in North America (e.g. D'Aoust & Millar 1999, 2000; Fischenich & Morrow 1999, Shields et al. 2000, Nichols & Sprague 2003). Obviously, the stability of natural wood never depended on such methods, however, concerns about the stability of reintroduced logs among the engineering community, who were responsible for many of the early projects, understandably fostered an overly cautious approach to the design and stabilisation of log structures. Consequently, many of the early wood reintroduction projects met with considerable criticism from river users, such as canoeists and trout fishers, due to the unsightly and often dangerous (to canoeists) use of steel cable. It was in this context that the concept of engineered log jams (ELJs) evolved, as a more natural alternative to the highly engineered and typically unnatural looking structures that were the mainstay of river engineering at the time.

Prior to the 1990s in Australia, as in North America, in-stream wood received extremely bad press. Virtually from the earliest days of European colonisation in the

Photo 8. Early model log bank revetment, with cable and rock ballast — Obi Obi Creek, Queensland.

18th century, "desnagging" of rivers was practised widely until the mid 1990s, generally with the aim of flood mitigation and to assist navigation. Given the extensive history of wood removal from rivers, the notion of wood reintroduction was initially often met with derision and scepticism, and in large part this necessitated the adoption of an approach that was least threatening to those responsible for, and affected by, river management at the time. The ELJ concept was proposed to help counter these fears. This approach uses sound engineering principles to perform structure stability analysis, but the structures are modelled on naturally occurring log accumulations and, as a result, look more natural and provide a range of ecosystem functions as well.

3.2 Principles underpinning engineered log jams

The term "engineered log jams" was coined by Dr Tim Abbe (Abbe et al. 1997, Abbe 2000) to describe a log groyne type structure designed primarily as an erosion control measure, using a natural log jam as his model. The assumption was made that some of the most elegant solutions to what we perceive to be problems can be found in nature. Natural log accumulations tend to be the most stable parts of dynamic alluvial landscapes, and have been shown to be stable for up to 700 years in North America (Abbe 2000), and even longer in particular settings in Australia (Nanson & Barbetti 1995). The observation that log jams act as a natural type of bank protection over long periods of time led to the idea that similar structures could be "engineered" to provide bank protection that better reflects the natural character of rivers than traditional engineering measures such as rock revetments, bulkheads, and spur dikes. Thus, ELJs are modelled on naturally occurring log jams, with the Australian version modified somewhat to suit local conditions (Brooks et al. 2001, Brooks et al. 2004).

Under natural conditions, the stability of the log jams is a function of the burial of the key log root wads into the river bed, the interlocking of accreted logs within the structure, ballast associated with subsequent sediment deposition, and vegetation, which tends to colonise the whole structure. The same principles for structural stability were applied in the engineered versions; hence, ideally logs with intact root wads should be used as the primary structural elements of all ELJs. Logs with root wads tend to anchor themselves into the bed of a river in much the same way that boat anchors dig themselves into the seabed with a force applied to the anchor chain; and like anchors, once buried, they are difficult to dislodge.

Photo 9. Constructed log jam — Hunter River, NSW.

Photo 10. Naturally recruited log demonstrating the tendency of logs with root wads to dig themselves into the river bed and become anchored.

Photo 11. Natural log constriction forced pool — Allyn River, NSW.
Photo T. Abbe.

ELJs have now been constructed on numerous rivers in North America (Shields et al. 1995, 2000; Abbe et al. 1997, Abbe et al. 2003), at two experimental sites in Australia — at Munni on the Williams River (Brooks et al. 2001, Brooks et al. 2006) and Stockyard Creek a tributary of Wollombi Brook, and at an increasing number of sites through the Hunter Valley and within other NSW coastal rivers. In Australia as in North America, early successes from experimental projects have led to the incorporation of this approach into a wide range of river rehabilitation and asset protection projects, and their perceived effectiveness has led to them no longer being regarded as an experimental technology in some areas. Following is a summary of the outcomes of the Williams River experimental project — and many of the lessons learnt and principles outlined in this Guideline stem from this and similar projects that have evolved from the early experiments. Experience from these trials suggests the approach may be superior to rock revetment as a treatment for bank erosion problems for several reasons.

3.2.1 Cost

Providing a source of logs is available, ELJs are at least price-competitive with rock revetment and probably significantly cheaper on the basis of cost per linear metre of bank protected (see Abbe et al. 1997, Brooks et al. 2001).

3.2.2 Function

ELJs are designed with a multi-purpose goal in mind from the outset. While their primary purpose is for bank protection, the way they achieve this is significantly different to rock revetment. An ELJ acts to alter the flow path impinging on the bank, deflecting flow away from eroding banks as well as providing revetment or toe protection. Rock revetment generally acts only to harden the bank while the flow path remains the same. ELJs also have a range of characteristics that are highly beneficial for the aquatic ecosystem. They are designed to create scour pools, hence improving the fish habitat, while the log structure itself provides complex cover and breeding habitat of the type many native freshwater fish evolved with in natural systems. Results from fish monitoring surveys carried out on the Williams River site suggest that the bank attached ELJs are by far the most effective type of structure from a fish habitat perspective (Brooks et al. 2006). Wood also provides substrate upon which biofilms can establish within the wetted channel perimeter. Wood structures like this can potentially enhance hyporheic zone exchange, by creating more diverse riffle-pool and lateral bar morphology (Boulton et al. 2003, Mika et al. 2005, see also Section 2.2). Improved hyporheic zone exchange is beneficial to sub-benthic macroinvertebrates and can aid the sequestration of nutrients within the river system, improving water quality.

Photo 12 (above). Constructed log jams — Stockyard Creek, Hunter Valley, NSW.
Photo 13 (right). Constructed log jams — Hunter River, NSW.
Photo 14 (below). Natural log jam — Tasmania. Photo T. Cohen.
Photo 15 (bottom). Natural log jam — Tasmania. Photo T. Cohen.

3.2.3 Engineering properties

The primary failure mechanism for most engineered bank revetments (such as rock rip rap) is through the action of scour at the bank toe, which undercuts the base of the structure leading to catastrophic structure failure. ELJs are designed in the knowledge that significant scour will occur around the front and streamward edge of the structure, however, the engineering properties of the logs comprising the structure, and the way a log jam is constructed as an interlocking network of logs, are such that they can withstand not only significant scour along the edge of the structure, but complete scour underneath the structure, of up to a third of the structure width. Furthermore, providing good quality hardwood timber species are used, the timber structure should be functional over timeframes of 50 years and greater.

3.2.4 Downside of ELJs

On the downside, the biggest drawback for the use of this technique is finding suitable quantities of appropriate logs with roots near to the site where they are to be used.

3.3 The Williams River experimental wood reintroduction project

At the time this rehabilitation experiment was proposed in 1998, river management in Australia was undergoing a radical transformation from the utilitarian, engineering-based approach that had prevailed since the end of World War II, with its focus on flood mitigation and water resources development, to a more ecologically focused approach (Hillman & Brierley 2005). Under this new paradigm, the inherent ecological functions of rivers were incorporated into the management equation, and new approaches were required that enhanced the natural biophysical processes within rivers, while at the same time meeting some required engineering functions. It is fair to say that at this time not all were convinced of the wisdom of this new approach, particularly when it involved returning large numbers of logs to a section of river from which management authorities had spent the last 30 years removing them. In this context, the experiment was as much about allaying people's fears of having logs in rivers at all — let alone using them to meet particular engineering, geomorphic and ecological objectives. The conventional wisdom at the time was that logs caused floods, and that any attempt to reintroduce logs to a river would end in catastrophe, with logs being washed away in the first flood, causing log jams on downstream bridges, massive flooding and bridge failures.

With this background, the broad study objectives were:

1. to demonstrate an approach for safely reintroducing logs to medium/high energy rivers, ensuring the structural stability of the reintroduced timber,
2. to test whether a reach based rehabilitation strategy focused on the reintroduction of wood could help to stabilise the reach by reducing bank erosion, and increasing reach sediment storage,
3. to test whether a reach based wood reintroduction strategy could increase morphological diversity (as a proxy for micro-habitat diversity) within the reach and thereby have a measurable affect on improving fish habitat and fish population dynamics.

Results from this experiment have been published at two separate time intervals since the project inception: after the first 12 months (Brooks et al. 2004), and after five years (Brooks et al. 2006). The detail of these results will only be summarised here, however, together they provide an interesting insight into the changing nature of both the geomorphic and ecological response to treatment through time. In the first year following treatment, it was apparent that there had been a major geomorphic response at the reach scale and a significant response in the fish population, compared with the upstream control. After five years, the trend in geomorphic response has persisted, albeit showing signs that the maximum extent of change has been reached, but the ecological response as measured by the fish response seems to have diminished. The outcomes of this research have serious implications for the extent of intervention that is required to induce long term measurable change.

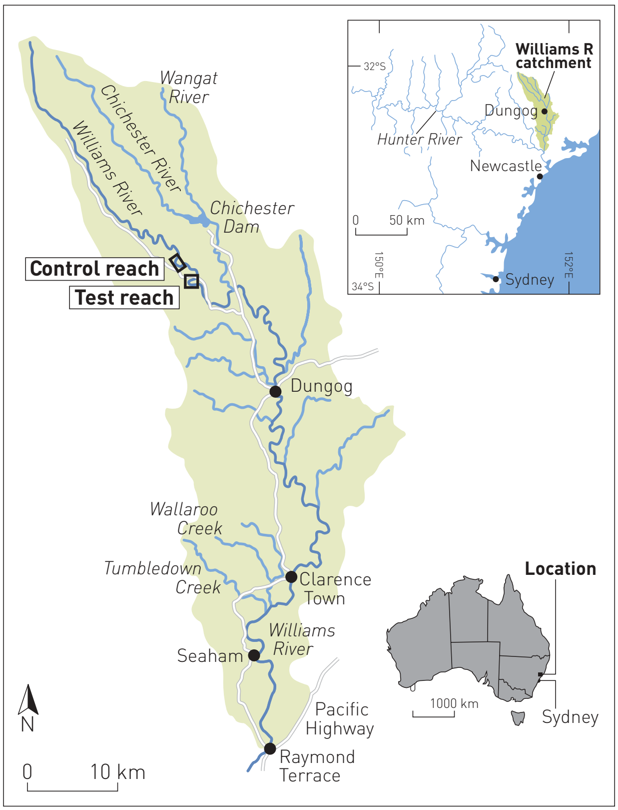


Figure 6. Williams River study site.

3.3.1 Wood reintroduction strategy and rationale in the Williams River study

In September 2000, 20 ELJs incorporating 436 logs were constructed in the test reach at Munni on the Williams River, NSW (Figure 6). The ELJ structures included both flow deflection structures along the river's banks, and channel spanning grade control structures intended to prevent channel incision and to trap additional sediment within the test reach (Figure 7). All of the structures were built without artificial anchoring such as cabling or imported ballast. The treated reach was compared with a control (untreated) reach 3.5 km upstream, through initial baseline and repeat surveys following ELJ construction.

The logs used were primarily eucalypt species with root wads (totalling 350 tonnes of wood), and were placed in 20 ELJs within the 1100 m test reach (Figure 7). Four types of ELJ were designed for the test reach: deflector jams, bar apex jams, bank revetment structures and log-sill bed control structures. The volume of wood introduced to the test reach equates with an average reach loading of 0.014 m^3/m^2, which falls within the guidelines outlined in Marsh et al. (1999) for temperate rivers in southeast Australia.

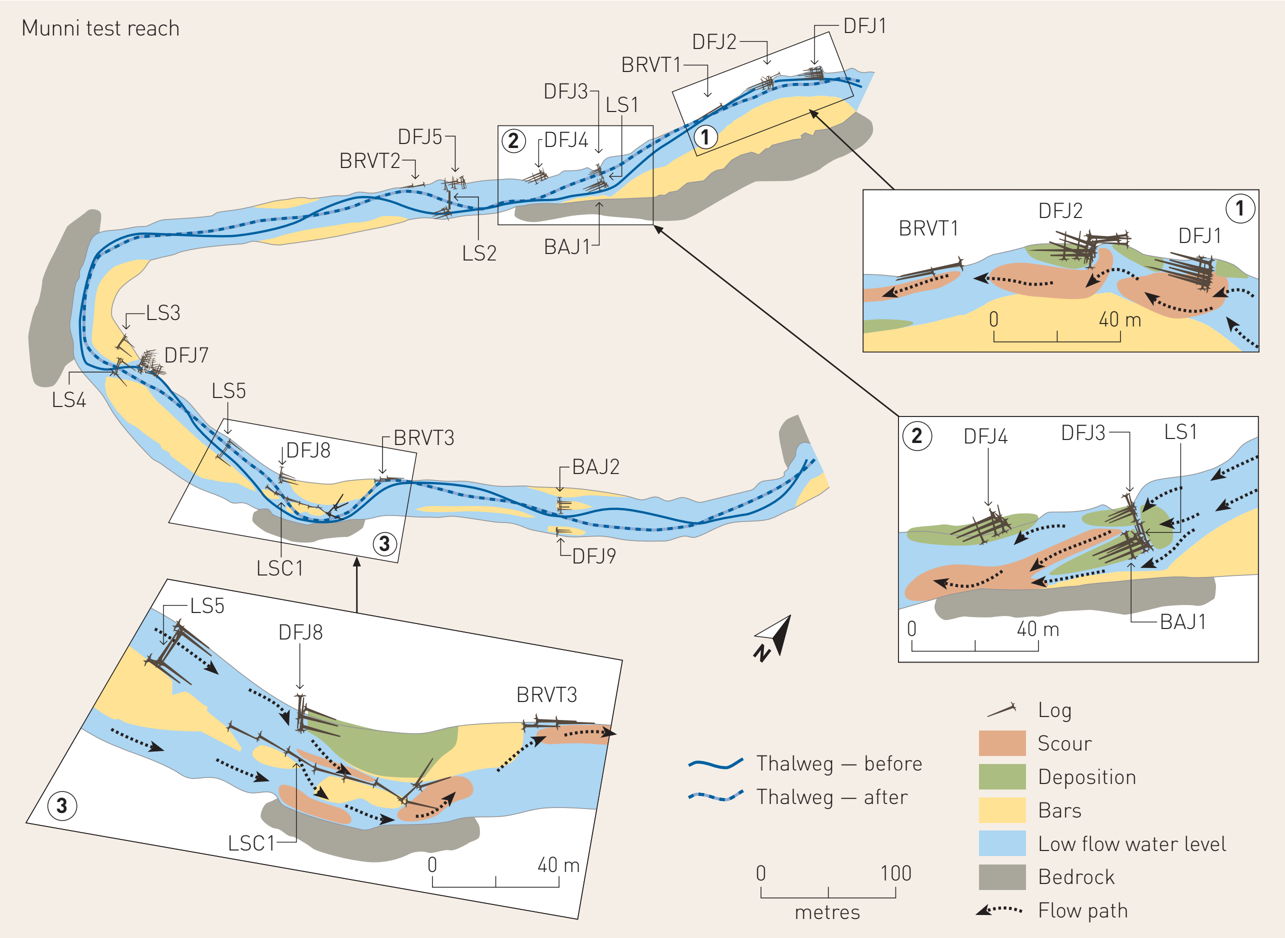
The rehabilitation strategy was designed to address specific reach and sub-reach scale geomorphic "problems" arising from larger-scale land use and management impacts. Three key management problems were identified in the study reaches:

1. bed homogenisation (i.e. the loss or degradation of meso-habitat units such as riffle-pool sequences through flattening of riffles and infilling of pools),
2. excessive bed mobility and high sediment flux,
3. local bank erosion, particularly in the areas downstream of bedrock-forced pools where gravel-bars accrete and deflect the channel thalweg laterally (Brooks et al. 2001).

A range of ecological implications was hypothesised to stem from each of these geomorphic problems:

1. the loss of physical habitat and habitat diversity both at the meso- and micro-habitat unit scale,
2. a loss of ecosystem processes as a result of point 1 — e.g. hyporheic zone function,
3. a deficit of viable habitat for some benthic species (e.g. mussels) given the high bed shear stresses and bed material mobility,
4. increased bank erosion raises sediment supply to the river (both fine and coarse fractions) increasing turbidity during flood flows, with the attendant impacts that reduced water quality has on fish and other aquatic species, and further exacerbating points 1–3.

Figure 7. Reach scale log structure layout.



Reach-scale principles of rehabilitation

The broad aim of the rehabilitation strategy was to improve channel stability and maximise geomorphic complexity and habitat diversity. More specifically, the reach strategy was devised in accordance with the following guiding principles.

1. The strategy should enhance and stabilise incipient or transient geomorphic units within a framework that accounts for reach and catchment setting, and reach and catchment scale disturbance processes.
2. In-stream rehabilitation using wood should operate in conjunction with efforts to optimise the ecological and structural integrity of the riparian vegetation corridor.
3. At sites where it can be reasonably assumed that sediment flux is elevated as a result of past land-use and management practices, the strategy should aim to minimise sediment flux and maximise the potential for increasing habitat complexity.
4. Within the constrictions placed by flood hazards associated with local infrastructure, hydraulic roughness (and thus energy dissipation) should be maximised within the channel through increased wood roughness, form roughness, and in-channel vegetation.
5. When combating bank erosion, causal mechanisms should be treated as well as the traditional treatment of symptoms of erosion via revetment or bank hardening (in large part this will involve addressing bed instability and redirecting flow away from eroding banks).
6. In situations where the channel is incised or enlarged as a result of disturbance processes, and hence local flooding is not a key concern, channel contraction should be induced as a mechanism to facilitate pool scour.
7. Where possible, pool scour should be maximised by deflecting flow towards resistant banks, particularly bedrock or well-vegetated areas (however, where flow is deflected into hard banks, to prevent initiation of new bank erosion further downstream, bank reinforcement measures must also be taken in the zones receiving the deflected flow).

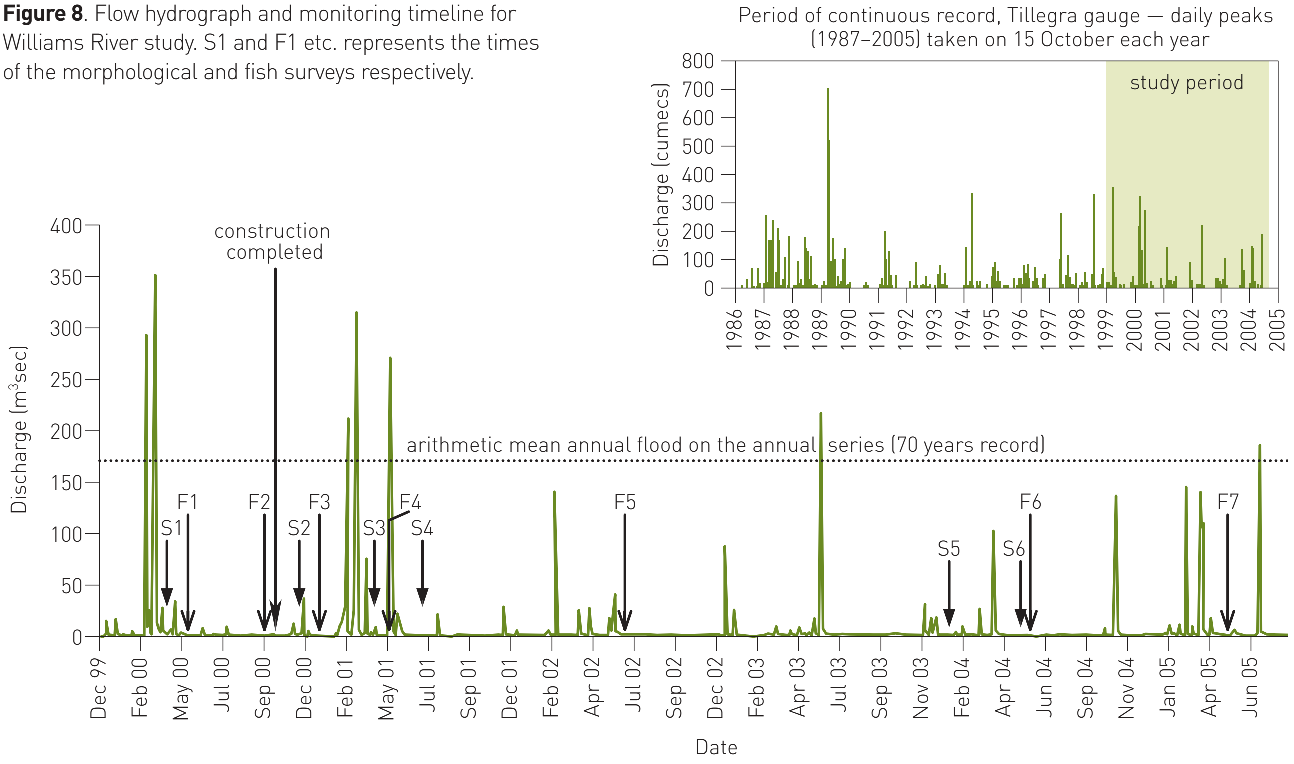
3.3.2 Key findings

The following summarises the findings from the Williams River experimental site as published in Brooks et al. (2004) and Brooks et al. (2006). For full details refer to these publications.

Flood events since construction

Within the life of the study the structures have been subjected to 21 days of overtopping flow in 10 separate events. However, the largest floods were all experienced within the first year after construction. In the first nine months after construction (to June 2001), the test reach was subjected to five overtopping flows, three of which were larger than the mean annual flood. Flows from 2002 to survey 6 (May 2004) were of unusually low discharge, as was the case across much of south-eastern Australia, with only four flow days greater than 100 cumecs in three events (Figure 8).

Figure 8. Flow hydrograph and monitoring timeline for Williams River study. S1 and F1 etc. represents the times of the morphological and fish surveys respectively.



Period of continuous record, Tillegra gauge — daily peaks (1987–2005) taken on 15 October each year

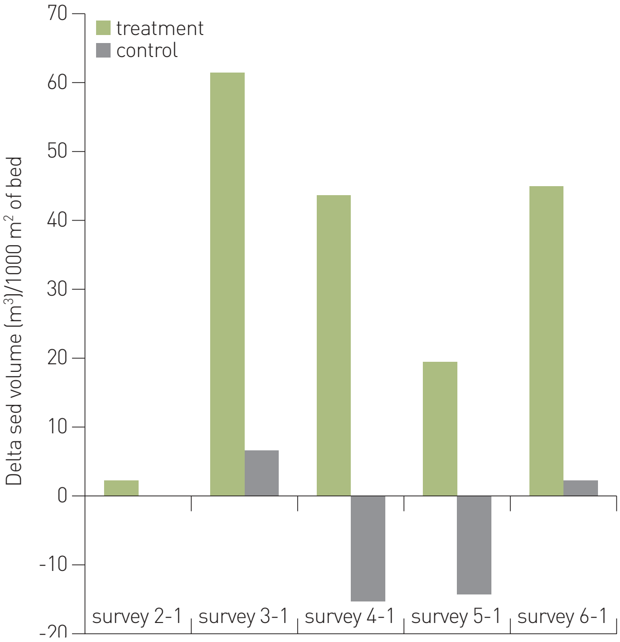


Figure 9. Sediment retention/loss at each morphological survey period (see Figure 8) compared to the baseline (survey 1).

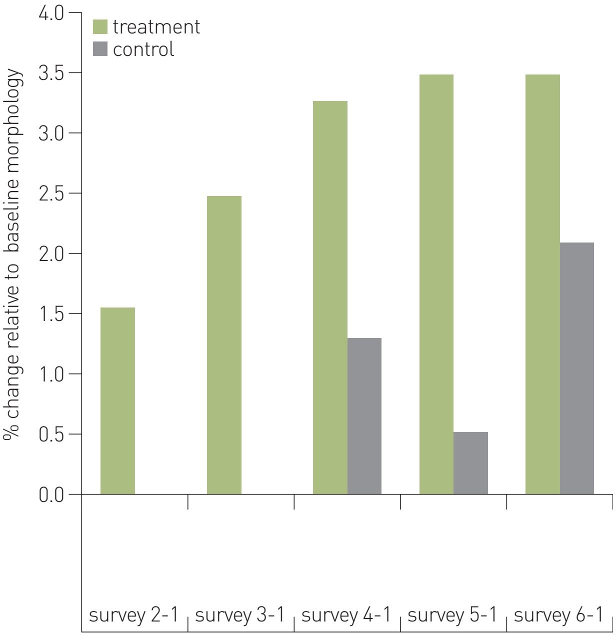


Figure 10. Change in bar area at each survey period post wood reintroduction compared to the baseline (survey 1).

Nevertheless, given that it is the floods that drive geomorphic change and test the engineering aspects of the log structures, and to some extent drive the fish response, the study has provided ample opportunity to test the effectiveness of the employed strategy from each of these perspectives.

Key results

First 12 months

- **Reach geomorphology**
  - Substantial readjustment of reach geomorphology (Figure 14, page 19).
  - Net increase in test reach sediment storage of 40 m^3/1000 m^2 with net loss over the same period in the control reach (-15 m^3/1000 m^2) (Figure 9).
  - Greater increase in bar and pool area in test reach compared with control.
  - Pool/riffle amplitude increases in treatment reach.
  - Riffle area increased in test reach.
  - Bed material finer in test reach after treatment than before (see Brooks et al. 2004).
  - Greater spatial variability in particle size distribution (see Brooks et al. 2004).
  - Greater increase in 3D reach complexity in test reach compared with control.
- **Ecological impacts**
  - Mean abundance of fish species per electrofishing shot increased by 53.4% in the treatment reach following wood reintroduction ($P<0.001$) while there was a corresponding 13.2% decrease in the control over the same period ($P>0.05$).
- **Engineering characteristics of ELJs**
  - Structures survived a series of major floods with little damage (12 non-structural rack logs moved, 1 structural log moved). No logs moved out of the study reach.
  - Measured stage increase at 3/4 bankfull flow <10% (within gauge measurement error). Most stage increase due to secondary geomorphic change induced by the structures rather than wood roughness per se.
  - All bank erosion control structures proved to be extremely effective at halting erosion.

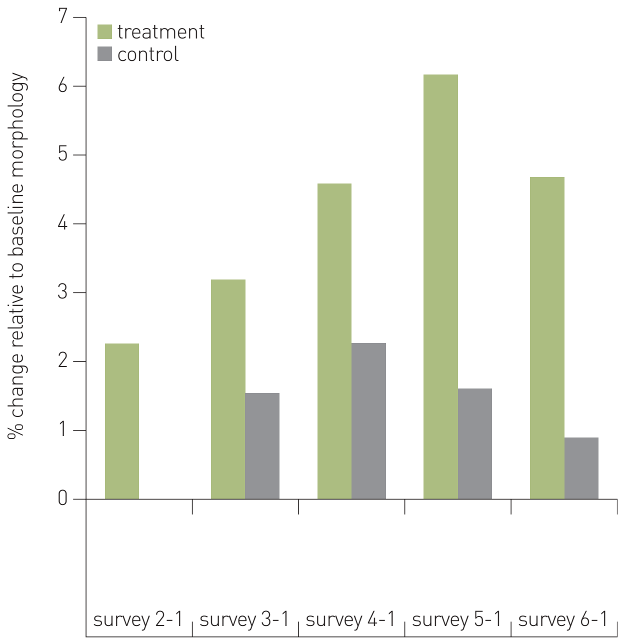


Figure 11. Change in pool area through time post wood reintroduction.

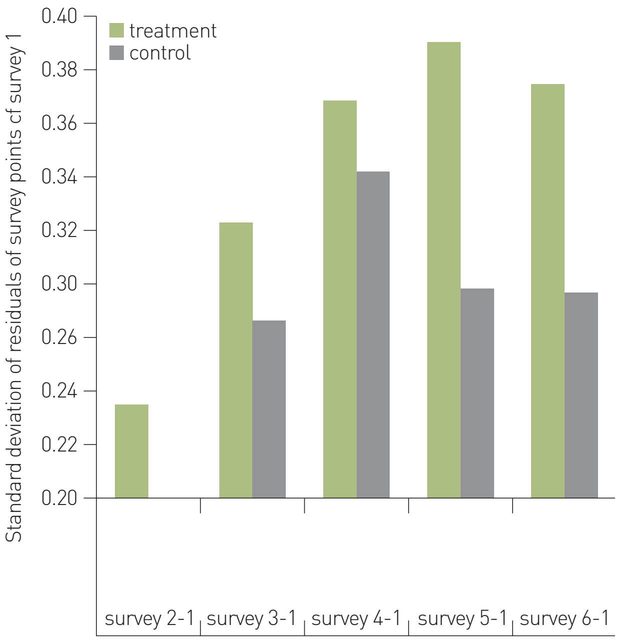


Figure 12. Change in channel complexity through time after wood reintroduction.

Results five years on

- **Reach geomorphology**
  - Readjustment of reach geomorphology continues, largely maintaining and amplifying the initial changes (Figure 14).
  - Test reach sediment storage fluctuates considerably with each flood but appears to have attained a new dynamic equilibrium of around 40 m^3/1000 m^2. Over the same period the control fluctuates around the baseline condition (i.e. no new sediment storage) (Figure 9).
  - Additional sediment storage amounts to 3.5 m^3 per m^3 of wood added.
  - Trend toward greater increase in bar and pool area in test reach compared with Control maintained (Figures 10, 11).
  - Pool/riffle amplitude increases less after 4.5 years than after first 12 months, due to partial reworking of sediment deposited on riffles in floods immediately post-construction.
  - Riffle area increased in test reach.
  - Greater increase in 3D reach complexity in test reach compared with control (Figure 12).
  - Net increase in sediment storage represents around 2% of the sediment lost in the disturbance phase following European settlement.
  - In a sediment supply limited system such as this, the level of intervention undertaken here would have to be repeated every five years for 200 years to return the channel capacity back to its pre-disturbance state (all other things being equal, and assuming this was a desirable management goal. In reality, this would not necessarily be the case, because with best management practice, a significant amount of vegetation could be encouraged to establish within the channel, which would further stabilise the channel and trap more sediment).
- **Ecological impacts**
  - Reach average data suggests that five years on there is now no significant difference in fish species richness or total abundance detectable in the test reach compared with the control.

  - In large part the inability of the study to detect significant change may be a function of measurement and observer error — as the sampling strategy was focused on open water, which is not where the fish were.
  - Complete extraction surveys at individual structures show them to be high quality native fish habitat compared to the rest of the reach and the upstream control. A total of 27 Australian bass, three eel-tailed catfish, four long-finned eels and two Cox's gudgeon were extracted from one structure (structure 2 — the second structure in Figure 13 B & D). Indeed, more Australian bass were caught from this one structure than were caught on average (i.e. 24 ± 14) from the whole test reach during a single survey period.
- **Engineering aspects**
  - Most structures were still performing as designed with the exception of two log sill structures that failed due to outflanking. Some non-structural logs were moved from some structures during the initial flood sequence, however, these had no real bearing on overall structure performance or reach strategy.
  - Log sill bed control structures must be accompanied with abutting bank attached jams on both sides if they are to survive long term.
  - Evidence for high stage flow afflux shown to be in the order of 5–10%. This is most likely to be primarily due to the geomorphic change induced by the structures rather than the hydraulic roughness per se.
- **Management lessons**
  - In sediment supply limited rivers — as most south-eastern Australian rivers are — sediment retention is a significant issue. This study has shown that the amount of additional sediment retained in the study reach over five years is, conservatively, only around 2% of the sediment storage lost in the post-European period. This has significant implications for the medium to long term management of sediment supply and, hence, channel morphology, in many Australian rivers. Continued transport of sediment above the supply rate will cause perpetual bed and bank stability problems.
  - Fish monitoring strategies that aim to measure the effect of constructed log jams on fish assemblages must develop sampling strategies that focus on the log structures themselves, as well as the adjacent open water. Sampling adjacent to the structures alone, will significantly underestimate the effect of the structures on fish numbers.
  - Demonstration sites, such as the Williams River site, are a highly effective community learning tool.

Figure 13. (A) Upper section of Munni test reach at the commencement of construction of DFJ1. Note a 4 m high actively eroding bank was located to the right of the tractor; (B) DFJ 1 and 2 at the completion of construction; (C) Same view in flood (270 m^3 sec^{-1}, 7/05/01) at about 1 m below peak stage; (D) DFJ 1 and 2 after the second major flood since construction — note the aggraded bar upstream of first structure and the increased scour around the two structures. The riffle crest in the foreground was raised, we presume due to backwater effects associated with the structures.

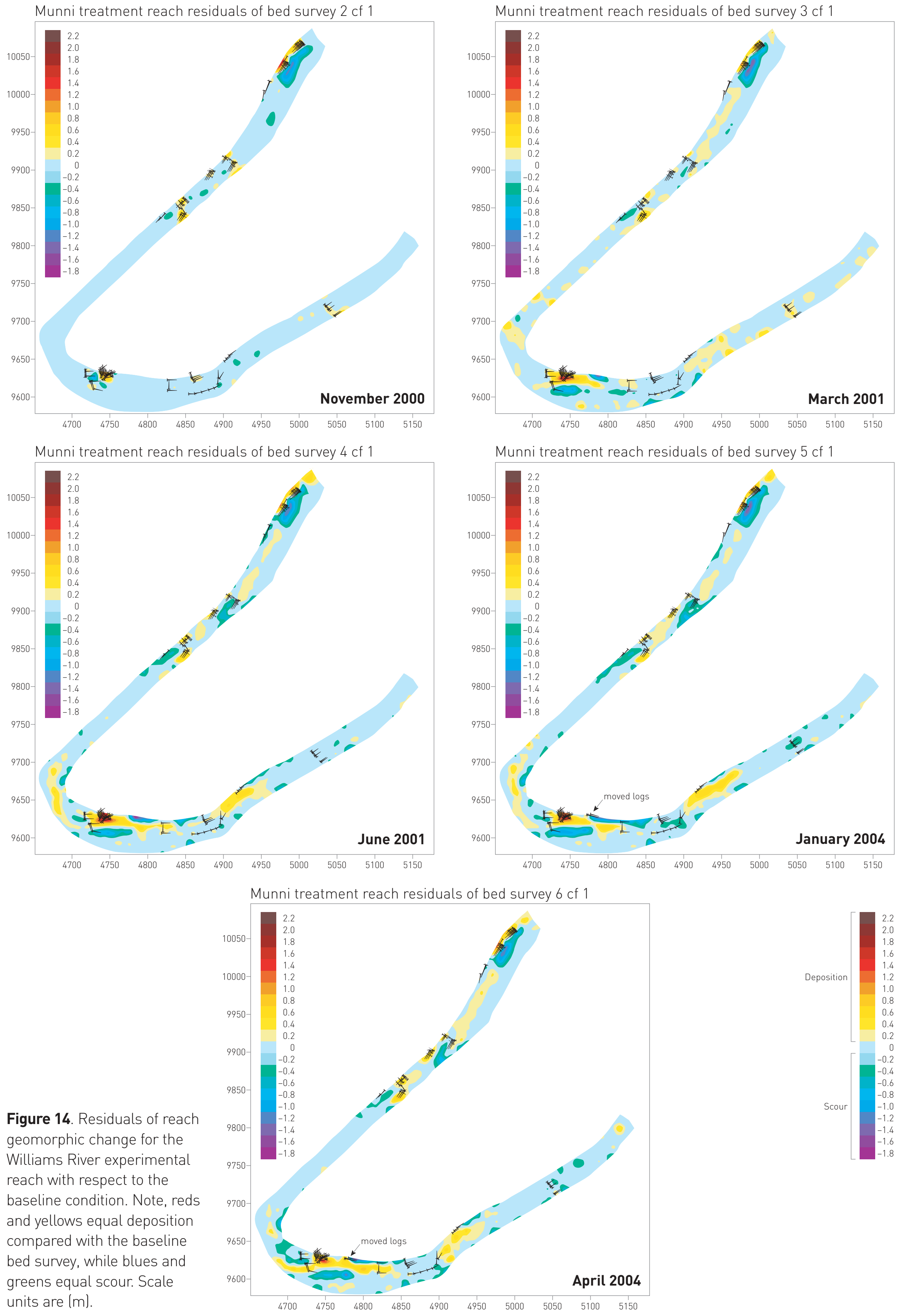


Figure 14. Residuals of reach geomorphic change for the Williams River experimental reach with respect to the baseline condition. Note, reds and yellows equal deposition compared with the baseline bed survey, while blues and greens equal scour. Scale units are (m).

chapter 4

A wood reintroduction planning procedure

It is assumed that anyone who has decided on proceeding with a wood reintroduction program has already been through the 12 step stream rehabilitation framework as set out in Volume 1 of the *Rehabilitation Manual for Australian Streams* (Rutherfurd et al. 2000). Once you have decided to reintroduce wood it is useful to refine your project goals and be realistic about exactly what the reintroduction of wood will do for your stream. In particular, don't assume that it will solve all the problems in your river. Following is an outline of the steps considered to be helpful in planning a wood based rehabilitation strategy.

Step 1: Define your goals

As a general principle your goals should be specific, quantifiable outcomes such as a stated percentage reduction in local bank or bed erosion in a specified reach, or increasing the available deepwater habitat by a specified amount for individual fish species or fish assemblages. General "motherhood statement" type goals such as "improving stream health" are inappropriate unless you quantify exactly how you are going to achieve such a goal, and above all, how you are going to measure its achievement. Goals such as "improving fish habitat" are also inadequate, unless you can identify the specific habitat requirements of the species assemblage in your stream and whether the habitats you are attempting to recreate are indeed the limiting habitats. While it is recognised that there is still much to be learnt about how fish use wood in streams, there is an increasing body of knowledge regarding fish habitat requirements and it should be possible to specify the habitat requirements of key species (see for example Koehn & O'Connor 1990, Pusey et al. 2004).

The benefits of wood in streams are reviewed in the updated *Principles for Riparian Lands Management* (Lovett & Price 2007). In Chapter 2 of this Guideline, some of the benefits of wood in streams are summarised, and some new insights are presented. We suggest you familiarise yourself with these reviews to help in defining some clear descriptions of the achievable outcomes of your wood reintroduction program. The important point is that wood can provide a large range of functions, however no single log structure performs all functions, so it is important to determine what you want from your wood. Bear in mind that you may need to design a range of single and multiple log structures to perform different functions within a given reach. Also, be aware that when working at the reach scale in attempting to redress problems that may be a function of catchment scale processes, some objectives may counteract each other (see Brooks et al. 2006). Furthermore, ensure that there is not some higher order limiting control (such as water quality) that will override any meso- or micro-habitat improvements you can make with wood. ***Above all, try to avoid the scenario where you are forced to make snap decisions about what to do and where to do it because your funding has to be spent by June 30!***

Information to help in identifying your rehabilitation goals

- See recent review of the role of wood in streams in *Principles for Riparian Lands Management* (Lovett & Price 2007).
- See LWA Riparian Program *Technical Update no. 3*, 'Managing wood in streams'.
- Chapter 2 of this Guideline provides a brief summary of the attributes of wood in streams. New insights are also presented into the potential for using wood to rehabilitate surface/sub-surface flow connectivity. Section 3.3 summarises the outcomes of a recent case study that has tested the use of engineered log jam technology as a basis for reintroducing wood into streams, and as the primary component of stream rehabilitation projects.

Step 2: Determine the underlying problems within your river

By concluding that wood reintroduction is required you have already determined that the critical issues in your stream are likely to be solved with wood (almost certainly in concert with other strategies), however, check Chapter 5 of this Guideline to see if your stream is likely to respond to wood reintroduction in the way that you want. Channel stability problems or habitat simplification are rarely the result of a simple, single factor, cause and effect. Furthermore, there is often large hysteresis, or asymmetry, in the time taken to reverse the effects of channel disturbances that might have happened fairly rapidly (see Brooks & Brierley 2005, Brooks et al. 2006). Before embarking on a rehabilitation strategy ensure that you have a sound understanding of the underlying causal mechanisms of the problem. If you are unable to do this yourself, it is far better to seek outside advice first, rather than proceeding and potentially jeopardising the outcomes you are trying to achieve. Avoid importing solutions from elsewhere, unless you are certain that they are appropriate for the local conditions. We are often aware of our own region but fail to consider the differences between stream systems from other regions where rehabilitation techniques may have been developed. What works in coastal NSW may not work in western Victoria. For example, attempting to use wood structures to create permanent scour holes for low flow habitat in a lowland stream is often difficult due to the low flow velocities and the cohesive substrate, as is using wood as a bed control structure in a rapidly eroding gully system.

Information to help in the diagnosis of underlying causes of stream problems

- *A Rehabilitation Manual for Australian Streams* (Rutherfurd et al. 2000).
- Seek advice from an appropriately qualified fluvial geomorphologist, an experienced river engineer, a stream ecologist, or better still a combination of all three.
- Section 6.2 outlines the minimum procedures required to be undertaken to assess contemporary reach-scale conditions and historical constraints. The reach scale data collected here also forms the basis for the structure stability analysis and can form the baseline data for a monitoring strategy.
- A good starting point for diagnosing catchment scale geomorphic constraints on your rehabilitation reach is to undertake an assessment of the catchment wide river styles (Brierley & Fryirs 2005).

Step 3: Develop your reach-scale rehabilitation prescription

You have identified the problem or threat to your reach, and satisfied yourself that wood is likely to be successful in your stream. Depending on the availability of materials and the nature of the underlying geomorphic process in your stream, bear in mind that it may be preferable to combine some "traditional" river engineering approaches with wood to achieve multiple objectives. Refer to Rutherfurd et al. (2000) for an overview of some of the other strategies. The next step is to review the range of common wood structures to find one that is suitable, or more likely which suite of structures are likely to help you achieve your goals. Most wood structures achieve multiple purposes of erosion control and habitat provision. In this Guideline we focus primarily on the design and construction of a standard bank attached deflector jam. Basic outlines of alternative structures that have been built in various locations are also provided. The alternative structures provide a basis from which you might draw in designing a wood reintroduction strategy to suit your specific needs. It should be remembered that the examples shown here are typical designs only, and it is usually necessary to adjust structure configurations, sizes and anchoring strategies depending on local controls and the site.

Information sources to assist in identifying the reach scale prescription

- Review *A Rehabilitation Manual for Australian Streams* (Rutherfurd et al. 2000) for an outline of other possible strategies.
- There are a range of web-based resources for an international perspective — see for example the United States Department of Agriculture stream restoration guidelines — bearing in mind the differences between overseas examples and your site. (http://www.nrcs.usda.gov/technical/stream_ restoration/)
- See Chapter 6.

Step 4: Develop structure designs

Now that you have a wood structure in mind you have to design it to withstand flood, drought and critics. The design component (Chapter 7) provides guidance on anchoring strategies, selecting a design flood, constructing a hydraulic model to predict force loadings on the structure, conducting a stability analysis, determining whether there will be scour holes for habitat near the structure, and what the maximum likely scour hole depth is to help in designing the anchoring strategy.

Information sources to assist in structure design

- Review *A Rehabilitation Manual for Australian Streams* (Rutherfurd et al. 2000) for an outline of complementary strategies.
- See Chapter 7.

Step 5: Identify limitations, problems and logistical constraints

Wood reintroduction is not a panacea for all river health problems, there are many potential solutions to stream management problems, and they all have downsides. You should assess the downsides of wood reintroduction to ensure that it is the best option and be prepared to answer any critics. One of the biggest issues is the availability of wood, and the volume of wood required to achieve your goals. This is ultimately a question of scale and budget, but there are also other considerations. One thing you don't want to be seen to be doing is creating a problem somewhere else to solve your stream management problem. So bulldozing a nice bit of remnant riparian forest for your log supply is probably not going to win you many friends! You will need to consider the probability of structure failure and what the consequences of structural failure are. As well as the survival of the structures, you must consider any unintentional impacts, such as an increased channel roughness that will alter flood levels, or a low log weir that might become a low flow barrier to fish passage. Above all, being able to demonstrate that you have been through a rigorous evaluation, planning and design process is the best way to ensure confidence in the project and to respond to critics. This Guideline is primarily aimed at providing the procedures for doing just this.

Information sources to assist in identifying project limitations and logistical constraints

- Review *A Rehabilitation Manual for Australian Streams* (Rutherfurd et al. 2000), and LWA River Landscapes *Fact Sheet 9* 'Planning for river restoration, http://www.rivers.gov.au/publicat/rehabmanual.htm
- See Chapters 7, 9.

Step 6: Undertake project construction

Having worked your way through the planning and design issues — the construction phase is relatively straight forward once you get the hang of what you are doing. The key to a smooth construction phase is ensuring you do all the necessary preliminary planning, and as much as possible, ensuring you have anticipated the problems likely to arise. Having said this, there will always be issues that arise that you won't have anticipated. This is part of the fun and the challenge of this type of work.

- See Chapter 9.

Step 7: Develop a monitoring and evaluation strategy

Most funding agencies these days require some form of monitoring or project assessment to enable you to determine whether your rehabilitation objectives have been successfully achieved. The lack of river rehabilitation/restoration project monitoring in the USA was highlighted in a recent *Science* article by Bernhardt et al. (2005) and should be compulsory reading for all administrators. Brooks and Lake (2005) (not this Brooks!) suggest the situation is little better in Australia! It is important to define during the project planning stage how you are going to measure success as this will help you to define realistic goals or objectives and to build the monitoring and evaluation into the project design and its budget. Depending on the scale of the problem you are addressing, and the timescales that may be involved to see the full effect of your rehabilitation efforts, it may be a good idea to set a series of interim milestones. In most cases rehabilitation is going to be an ongoing process requiring decades or even generations to fulfil your grand vision. However, significant improvements or milestones can be achieved over much shorter timeframes. So it is important to have regular celebrations of achievements along the way, and remember that these milestones do not all have to be measurable biophysical outcomes: social and procedural milestones are just as important. Clearly, it is not necessary for every community-based rehabilitation project to be monitored using a complete Before After Control Impact design long term monitoring strategy. Simple qualitative, or semi-quantitative, monitoring measures (such as photos) can be undertaken at a level commensurate with the scale of the project and the available resources. The key, however, is to establish some objective basis to determine whether you are meeting your project objectives.

Information sources to assist in developing a monitoring strategy

- See book by Downes et al. (2002).
- See Chapter 9.

Photo 16. Boat electro-fishing — Williams River test reach.

Photo 17. Backpack electro-fishing — Williams River test reach.

chapter 5

Determining the underlying cause of your stream's problem

5.1 What is going on in your stream — historical review of channel change

An essential part of the planning process in any stream rehabilitation project is understanding the geomorphic dynamics of the section of river you are concerned with, the historical legacy associated with past reach and catchment scale processes, and particularly how upstream or downstream disturbances might impact on your river reach. There is a range of techniques for determining historical channel changes and the likely recovery or degradation trajectory of your stream channel, some of which are discussed in step 3 of the 12 step rehabilitation procedure in Volume 1 of the *Rehabilitation Manual for Australian Streams* (Rutherfurd et al. 2000). It should always be remembered, that many changes imposed on river channels in historical times are effectively irreversible over management timeframes (see Brooks 1999a, Brooks & Brierley 2004), and if this is the case, a rehabilitation strategy based on returning the channel to its original condition may prove very difficult, if not impossible, to achieve.

5.2 Common causes of channel change

In addition to identifying how your particular river reach has changed and what some of the underlying geomorphic processes are, it is important to identify what sort of disturbances have been imposed on your river in the past. It should be remembered that this might also include past attempts at river rehabilitation or river engineering. The underlying causes of river channel change in the temperate regions of Australia are now reasonably well established within the scientific literature. The typical processes underlying most river channel change are reviewed in recent publications by Prosser et al. (2001), Brooks et al. (2003), Olley et al. (2003), Brierley and Fryirs (2005). The following is a summary of the key processes, and this can form a check list to guide your historical and geomorphic assessment of the changes imposed on your river. Disturbance processes can be loosely divided into *direct* and *indirect* disturbances.

Photo 18. Desnagging and riparian vegetation clearance were still the primary management responses after extreme floods on the Tambo River, Victoria in 1998. Photo J. Jansen.

Plate 19. Channel incision and widening associated with gravel extraction — Nambucca River, NSW.

5.2.1 Direct disturbances

- Riparian vegetation clearance — and particularly the vegetation on the immediate river banks. This is a ubiquitous disturbance (through clearing and grazing) and the extent to which bank erosion increases as a function of vegetation removal is a function of the bank substrate, the size of the river (both in terms of catchment area and channel capacity), the slope of the river and the flood regime (i.e. highly variable or relatively consistent). Riparian vegetation clearance can also include the disturbance to vegetation on upland swamps.
- Desnagging (i.e. in-stream wood removal).
- Channel straightening or realignment. This typically involves the construction of artificial bend cut-offs that result in the steepening of the channel which then causes the river to readjust by locally eroding the bed and banks.
- Sand or gravel extraction (this is one of the most common causes of bed incision and subsequent channel widening).
- Alluvial mining for minerals such as gold or tin. In some situations this can manifest itself in much the same way as gravel extraction, or in other cases by the injection of large volumes of sediment, see for example the cases of the Ringarooma and King Rivers in Tasmania (Knighton 1989, 1991, Bird 2000).
- Upland swamp drainage. Depending on whether you are referring to the actual swamp or the streams downstream of the swamp, this can be either a direct or an indirect disturbance. Swamp drainage typically leads to massive erosion of these areas, releasing huge volumes of sediment into the downstream network. For those streams downstream this might be considered an indirect disturbance associated with increased sediment load — often referred to as sediment slugs (Bartley & Rutherfurd 2001, 2005).
- In stream stock grazing/trampling. Stock (particularly cattle) in rivers have a number of geomorphic and ecological impacts on streams (see LWA River Landscapes *Fact Sheets 2*, *3*, *6* and *11*). From a geomorphic perspective they tend to eat the vegetation that is holding the bed and banks together, and their trampling causes the bed and banks to erode more readily. Cattle tracks can also form initiation points for riparian gully erosion.
- Dams and weirs. This is another case where the disturbance can be either direct or indirect depending on the proximity of the site to the dam or impoundment. In addition to the effects of the flow regulation, which may increase or decrease flow — and hence induce a range of complex channel responses depending on the individual circumstances, dams trap sediment which can lead to sediment starvation downstream of the dam, leading to channel incision as the stream attempts to supply the missing sediment.

Photo 20. Cattle with access to streams affects both the in-stream and riparian ecosystems. Photo Jenny O'Sullivan.

5.2.2 Indirect disturbances

- Catchment clearance. Again, this is a ubiquitous disturbance which tends to affect river processes through its impact on catchment hydrology, salinisation, and depending on the type of land-use on the cleared land, the increase in surface erosion and delivery of sediment and nutrients to the stream network.

5.3 Sources of evidence to ascertain river channel change

5.3.1 Historical evidence

- *Comparison of current condition with historical airphotos*. When viewed sequentially, a time series of aerial photographs can provide some idea of rates of change (Figure 15). The National Library of Australia in Canberra has an extensive archive of the aerial photographs that were flown around Australia during World War II, and with a few exceptions these generally represent the earliest photography available. State and federal mapping agencies have generally flown regular sets or aerial photographs since World War II. Many of these can now be ordered through the Geosciences Australia website http:// www.ga.gov.au/nmd/products/photos/photo.jsp
- *Comparison of current channel cross section and long profile surveys with historical surveys*. In many regions various government agencies have undertaken river surveys at different times in the past, for a range of reasons. These can be an invaluable reference with which to compare current channel condition, when you can get hold of them. However, there is often no consistent procedure for storing and recording these data so they can be difficult to find. Cross sections are generally available for river gauging sites and bridge crossings, but bear in mind that in both cases these tend to be located at the most stable sections of channel and, as a result, any changes noted are best regarded as minimum changes. It should also be remembered that depending on where you are, many channel changes occurred very soon after the earliest European settlement, and unless there are original surveyors reports, such as exists for many rivers in Victoria, you may not capture the initial phase of channel change. Many of these types of surveys can be found in the State Archives. The various state main roads departments are also a good source of information for old bridge surveys in particular.
- *Explorers diaries and surveyors notebooks*. These can be found in the state Archives.
- *Old photographs or paintings*. State libraries are a good source of early historic photographs. Local historical societies and museums are also good sources of this sort of information.

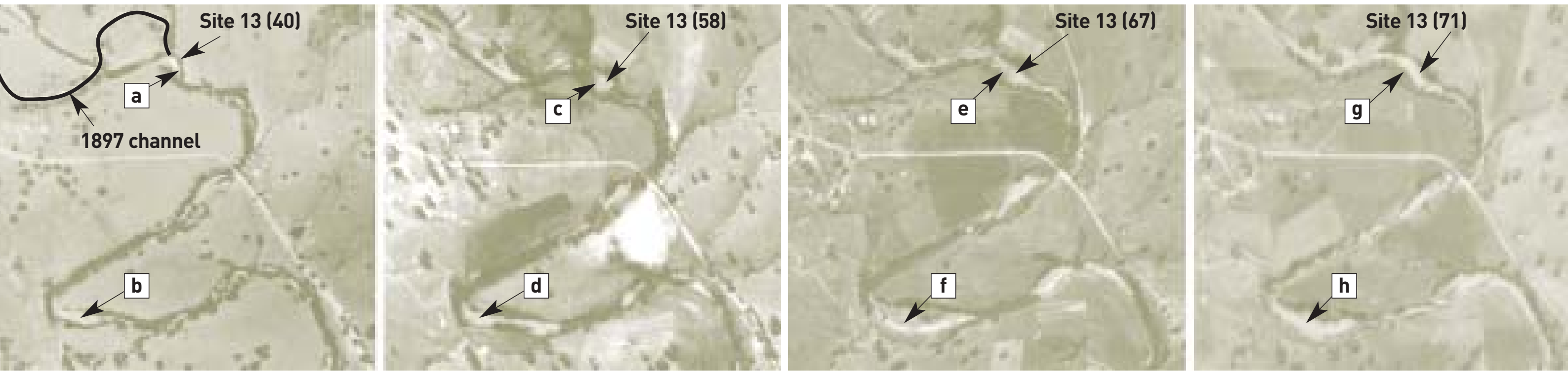


Figure 15. Example of airphoto time series 1940, 1958, 1967, 1971 — showing major channel changes since 1940 on the Williams River (NSW). Note changes at a, c, e and g; b, d, f and h.

- *Portion plans and parish maps*. These can generally be found in state Land Titles Offices. When using resources such as these remember that considerable cartographic licence has often been taken, and that this may vary considerably between individual cartographers. A number of the states now have these resources available on line (e.g. http://www.records.nsw.gov.au/ or http://www.lands.nsw.gov.au/online services/parishmaps/default.htm).
- *Oral histories*. Long-term local residents can be a wonderfully rich source of information regarding the prior condition of a river. In general, however, experience tells that it is generally a good idea to have some additional corroborative evidence from one or more of the other sources mentioned to help place detailed site specific information into a broader context.
- *Landsat imagery*. The earliest Landsat imagery dates back to 1972 and for larger rivers where you are looking at extensive change, this can be a useful source of information on changes over recent decades. The earlier imagery is at 50 m pixel resolution, so it will not be of much use for rivers less than about 300–400 m wide. However, in some parts of northern Australia this is a useful data source. Visible-band multi temporal Landsat mosaics are available from the Australian Greenhouse Office at www.greenhouse.gov.au/ncas/dataviewer/data.html.

5.3.2 Field evidence

- *Palaeo-channels and meander cut-offs (billabongs)*. These can be an extremely useful window into the past for determining pre-European channel dimensions and bedload characteristics, particularly if the age of cut-off can be determined to have occurred prior to European settlement via other historical sources. When interpreting palaeo-channel evidence there are a number of traps for the unwary.
  - Some palaeo-channels that were abandoned thousands of years ago can look like they were abandoned very recently. In some parts of the country there is evidence that it was significantly wetter in the early to mid Holocene (about 3500–8000 years ago) so care should be taken interpreting hydraulic geometry relationships from older abandoned channels.

Photo 21. Palaeo-channel on a floodplain — Cann River, Victoria. This channel was cut-off from the main channel around 2000 years ago.

Photo 22. Channelised swamp on the upper Jingallala River, Victoria showing rock works emplaced to prevent further channel incision.
Photo 23 (below). Floodplain sediments on the lower Bega River showing post-settlement alluvium (lighter coloured sands) in the upper 1.5 m of the sediment stack.

  - If palaeo-channels have been used as irrigation channels they may have eroded and may be larger now than when they were cut off from the main channel.
  - Some palaeo-channels have been significantly in-filled since they were cut off from the main channel, and consequently may appear significantly smaller than they were at the time they were cut off. The excavation of a transverse trench or an auger transect is usually required to determine the palaeo-channel dimensions.
  - Beware of interpreting tributary channels entering a floodplain as prior channels of the main stem channel. Some tributary channels may flow parallel with the main channel for a considerable distance, and for all intents and purposes look like a smaller "pre-disturbance" version of the main channel.
  - Channels that convey flood flows (sometimes called flood runners) may be erosional features that do not really represent some former channel dimension.
  - Palaeo-channels are often used as sand or gravel extraction sites!
- *Delta progradation rates*. Evidence for an increase in the rate of delta formation can provide evidence for increased sediment supply associated with catchment disturbance and/or channel erosion. This can be determined using both field and historical methods as described above.
- *Floodplain sedimentology*. Cores through floodplains or floodplain back swamp environments can provide evidence for increased sedimentation rates and changes in the calibre of deposited sediments. Again there are traps for the unwary regarding the interpretation of these sorts of data, particularly with respect to natural system variability associated with different magnitude floods, or natural changes in the site-specific depositional environment associated with channel migration, cut-offs or channel avulsions.

5.4 Common signs for common problems and implications for rehabilitation

It is important to determine whether your channel is experiencing one of the following problems, as they will dictate the types of treatments that you will use. Here are some common signs for some important channel instability problems.

5.4.1 Channel incision

Channel incision is quite common throughout the developed regions of southern Australia, but it is important to define whether the incision is systemic (i.e. throughout the whole channel network) or just a local reach scale effect.

Systemic channel incision tends to occur in fully alluvial rivers without major bedrock controls in the river bed. It also tends to be more difficult to treat given that it is often associated with upstream migrating knickpoints, major bank erosion and downstream migrating sand or gravel slugs resulting from the deposition of the liberated stored alluvium. You should be aware that a knickpoint may have passed through at some stage in the past and there may no longer be much evidence for contemporary knickpoint activity. A good example of systemic channel incision can be seen in the Nambucca River in NSW (see Nanson & Doyle 1999).

Local incision is more likely to be related to a local scale disturbance, such as desnagging or local channel shortening associated with an artificial cut-off. While these sorts of disturbances can sometimes be the triggers for more systemic channel incision in fully alluvial rivers, local incision tends to be more prevalent in rivers that have considerable bedrock controls which prevents the longitudinal propagation of the incision.

Photo 24. Cann River, Victoria — showing exposed bridge pier caps on the West Cann Bridge indicating several metres of channel incision since the bridge was constructed.

Implications

Bed instability is often an underlying cause of bank erosion, so if you are undertaking a wood reintroduction program where one of your objectives is to arrest bank erosion it is important to understand whether your channel is experiencing bed incision. In this case your primary objective will need to be to arrest the bed instability problem. Furthermore, if you are aiming to reintroduce channel complexity (i.e. induce scour pools and reinstate pool/riffle sequences) this will be extremely difficult in a river undergoing active bed incision. Channel incision tends to increase sediment supply and homogenise the channel long profile. Above all, however, it is more difficult to construct stable structures in a river with an unstable bed. To date, there have been very few successful attempts to stabilise incising channels using wood-based strategies alone. This is not to say that it can't be done, however, new structure designs will be required. Some examples of log structures currently being trialled are presented in Appendix A, however, to date some of these have not been fully tested in high flow events.

Signs of systemic channel incision

- Knickpoints (i.e. steps in the longitudinal channel profile).
- Relatively homogeneous bed longitudinal profiles (other than the nickpoints) associated with erosion of riffles and in-filling of pools (this can be difficult to discern in rivers with other lateral or bed controls such as vegetation, bedrock, weirs, road crossings etc).
- Major erosion on both banks (i.e. slumps, cantilever failures etc) over considerable lengths of channel with trees undercut and falling into the stream.
- Secondary incision of tributaries entering the main stem channel (nickpoint migration up tributaries, post dating the incision of the trunk stream).

Photo 25. Knickpoint on the upper Nambucca River resulting from systemic channel incision.

Photo 26. Channel widening on the Tambo River, Victoria resulting from an extreme flood impinging on a deforested floodplain. Photo J. Jansen.

- Gully type erosion into floodplain deposits from the main channel.
- Exposed foundation caps on bridge pylons.
- Exposure of old river works, such as mesh works in which the mesh is left elevated above the bed.

Signs of local incision

- Local incision can exhibit some of the symptoms outlined above, such as bank erosion on both banks, and minor knickpoints, but it will be confined to a discrete river reach.
- Creation of erosional benches on both banks, often associated with tree fall — where trees are present. In semi-alluvial rivers, stable bedrock reaches tend to limit the propagation of incision up or downstream.

5.4.2 Channel widening

Channel widening will, by definition, also be a function of those channels experiencing incision, as outlined above. However, there are other causes of channel widening not always accompanied by channel incision.

- A reduction in bank strength and/or roughness, often caused by excessive stock grazing or vegetation clearing can lead to channel widening. It goes without saying that in situations like this, those causal mechanisms should be addressed before one considers in-stream engineering approaches.
- Extreme floods can cause channel widening irrespective of any other disturbances.
- Other events that affect riparian vegetation, such as fire or an extreme frost, can also trigger channel widening.
- Combination of extreme flood coupled with reduced bank strength and bank roughness can often lead to extreme widening. In the cases where widening is driven by rare high magnitude events, serious consideration should be given as to whether an interventionist engineering “solution” is really required. In general, assisted natural regeneration (Thexton 2001) is probably all that is required in these situations.

Photo 27. Accelerated bank erosion associated with stock trampling. Photo Michael Askey-Doran.

Implications

It is important to understand the primary mechanism underpinning the widening and address this first (if possible) before embarking on the rehabilitation solution (or addressing this as part of the rehabilitation strategy).

5.4.3 Accelerated bank erosion

Bank erosion is a natural process in alluvial or semi-alluvial rivers, so the fact that a channel exhibits “bank erosion” is not necessarily sufficient cause for pursuing an engineering “solution” to stop the erosion, unless important assets are under threat. By definition, determining whether a channel is undergoing “accelerated erosion” requires some understanding of the longer-term average rate of bank erosion, and this can be notoriously hard to determine, particularly when it is not accompanied by channel incision. There is no easy way to determine whether the erosion at a particular site is “normal” or “accelerated”. The only conclusive way to determine this is to undertake a detailed investigation incorporating an historical analysis, using some or all of the techniques described in Section 5.3, coupled with detailed measurements of contemporary erosion rates (using either detailed survey or erosion pins). *Rapid assessment type approaches will inevitably be wrong*, particularly when they are applying a state-wide index, unless an experienced person with extensive local knowledge that has been calibrated to the background rate performs them. It should also be noted that in freely meandering alluvial rivers individual bends on the same river will have different erosion rates due to the difference in bend radius of curvature. Hicken and Nanson (1975) found that the maximum bend migration rates occur when the ratio of the radius of bend curvature to mean channel width (r_m/w_m) approximates to 3.

Implications

As per channel widening.

Photo 28 (above). Classic sand slugged river — Bega River, NSW.
Photo 29 (below). Recovering sand-slugged stream — Wollombi Brook, NSW. Photo A. Raine.

5.4.4 Sedimentation (e.g. sand slug influx)

Excessive in-channel sedimentation, often described as sediment slugs, is commonly associated with some of the more extreme cases of channel and/or gully erosion or with major mining impacts. Sediment slugs, like channel incision, tend to cause the homogenisation of the channel long profile as the pools become infilled, and riffles (where they existed) become completely swamped. As recent rehabilitation experiments in the Granite Creeks (Borg et al. 2004) have found, it is extremely difficult to re-establish channel complexity in a sand slugged stream.

Signs of sediment slugs

If your stream is impacted by a sediment slug it may exhibit one or more of the following symptoms:

- bed form homogenisation,
- reduced channel capacity,
- overbank sedimentation in the form of sand sheets or crevasse splays deposited on fine grained floodplain material,
- channel avulsion and/or excessive lateral channel migration,
- braiding (i.e. multiple low flow pathways with in-channel bars dividing flow threads).

Implications

In-stream structures may become swamped — and completely ineffectual. Sediment slugs, by definition provide greater sediment input to a reach than output, or in other words, sediment supply exceeds sediment transport capacity. If the objective is to create scour pools within a river reach affected by a sediment slug, this will always be a challenge in a transport limited system. Another problem in sediment slugged river reaches is that the bed can degrade (incise) substantially as the sediment slug (which is sometimes referred to as a wave) moves on down the river. Hence, a rehabilitation strategy built within such a reach that is based on the bed level at the time the sediment slug is at its maximum, may find that in a few years time the channel looks completely different as the sediment slug moves on, with structures possibly undermined or no longer functioning in the way they were originally intended. Consequently, it is probably best to avoid any strategy based on bed level control in these types of stream, until the sediment slug has moved through. At the slug maxima, the strategy is probably best framed around channel constriction — if the intention is to attempt to improve in-stream habitat (pools).

chapter 6

Developing your reach rehabilitation prescription

6.1 Wood rehabilitation project design: Key questions

Assuming the catchment context has been established, the underlying reach-scale disturbance and adjustment processes identified and objectives clearly articulated, this Chapter outlines the typical process you will need to undertake to develop and design your reach-scale rehabilitation strategy.

6.1.1 Questions likely to arise when developing reach prescription

Now that you have decided that you want to pursue a wood reintroduction rehabilitation project, a series of questions will need to be confronted.

Q. How much wood will we need?

A. As with any site specific design, the amount of wood required depends on what it is you are trying to accomplish; the size of the channel; the wood loading you are trying to achieve; the extent to which the channel has enlarged in historical times; the stream power; your budget; and probably the overriding factor, the availability of logs. “Restoring” the natural quantities of wood loading in rivers associated with natural log jams may be unrealistic, because the geomorphic consequences might be incompatible with social needs and require time scales beyond the realm of planning. It may also be logistically impossible, due to the lack of timber and the typically larger channel volumes today compared with the past. For example, in the Cann River in East Gippsland, Brooks (1999b) estimated that to re-establish the same hydraulic effect associated with woody debris in the contemporary Cann River channel would require around five times the original wood loading — which by contemporary standards was very high.

Recent research in Australia has highlighted the relationship between the density of vegetation in the riparian zone and wood loading in streams. Although the volume of wood varied widely both within and between rivers, Marsh et al. (2001) found a linear relationship between riparian tree volume and

Photo 30. Natural log jam — White Rock River, NSW

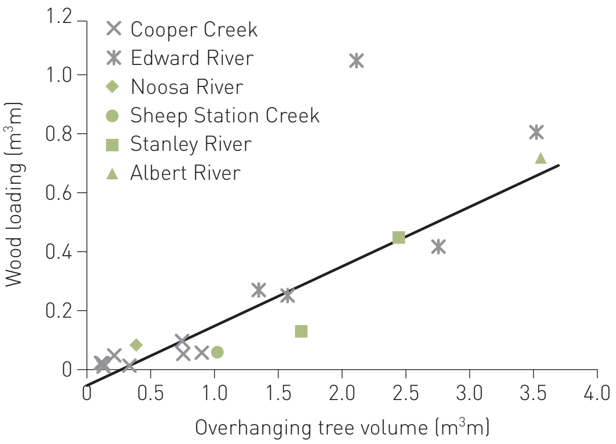


Figure 16. Wood loading and fringing riparian vegetation density along six south-eastern Australian streams (from Marsh et al. 2001).

wood loading in streams across eastern Australia (Figure 16). This model assumes that immediate riparian input is the dominant recruitment process, and that the extant riparian vegetation structure and cover is indicative of the long term state. This relationship is described by the following equation:

Wood volume (m^3/m) = 0.2*overhanging tree volume (m^3/m) – 0.05 ($R^2 = 0.91$)

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

Photo 31. Natural wood loading in a forested stream — D'Entrecasteux region, Tasmania. Photo T. Cohen.

Q. How should the logs be arranged within the channel?

A. There is an infinite number of possible ways in which to arrange logs in a channel, so we can only give guidance. In general, however, a rehabilitation strategy needs to be tailored to each site. There is no single design that can be applied in all circumstances, so the best approach is to use nature as your guide and where they are available try to use natural analogues as a basis for the structures that are being designed. The nature of the structures designed, and the means used to stabilise them, will vary considerably depending on stream type (e.g. gravel-bed, sand-bed or cohesive bed), and on stream energy conditions. The number of structures required will be a function of the channel scale and the nature of the problem being addressed (along with your budget and the availability of wood). If the primary objective is to treat bank erosion, the number of structures is obviously a function of the extent of eroding bank. A general rule of thumb is that the length of bank protected, and hence the spacing between structures, is a function of the extent of structure protrusion into the flow and the bend radius of curvature. On a tight bend bank protection is afforded to a length of bank three times the structure protrusion width; while on a straight section of channel it will be up to five times the structure width (Klingeman et al. 1984, Miller et al. 1984, Drury 1999).

If bed control is the primary concern, the spacing of structures will be a function of stream slope, such that for ***maximum*** bed control, the next structure upstream sits at, or within the maximum upstream extent of the backwater from the downstream structure.

If deflection structures are being constructed, careful consideration needs to be given to the likely consequences of the altered flow paths, and whether this is likely to shift the focus of bank erosion to somewhere else. Bear in mind that the flow paths during the high stage flows, which facilitate most erosion, might be significantly different to the flow paths at low flow (when the field inspection is usually undertaken).

The extent of jam obstruction must also be weighed against the overall effect on the channel cross section, and it is not recommended that in-stream structures obstruct more than a third of the channel width (Johnson et al. 2001).

Q. How high should a structure be to achieve effective bank erosion control?

A. Considerable attention is directed towards the issue of bank erosion control in Rutherfurd et al. (2000), and you should familiarise yourself with this information. To achieve effective erosion control the structure should firstly be of sufficient height to adequately protect the eroding toe zone of the bank. Over and above this, to achieve effective flow deflection the general rule of thumb is that the structure should extend to 0.5 times the "most effective flow" stage height (Klingeman et al. 1984, Miller et al. 1984, Drury 1999). In practice it is often difficult to determine the "most effective flow", and people generally assume it is the morphological bankfull height. However, in many incised channel systems morphological bankfull may be an extremely rare event, making it impractical to build a stable structure of this height.

Q. Will single logs suffice or do we need to construct multiple log structures?

A. This will be a function of what it is you are trying to achieve and the site conditions. Single logs placed in a stream channel will rarely be an appropriate rehabilitation strategy, except in low energy, small capacity channels, or where you have extremely large logs or whole trees. In most circumstances, arrays of logs constructed as discrete structures will be required to meet the engineering requirements at a site. In general, it is easier to construct a stable structure using multiple logs than just single logs. Depending on the size of the logs and the channel conditions, single logs will often be buried by mobile sediments, or will simply be of insufficient scale to address the magnitude of the problem (see Chapter 5). If, however, you want only to augment the structural woody habitat within the stream, then individual logs, or better still, whole trees with branches, may be appropriate.

Q. Do we need to artificially ballast or stabilise the logs?

A. In most medium to high energy coastal rivers along the Australian eastern seaboard or the upper reaches of most inland draining rivers — some form of ballasting or stabilisation will be required. Low gradient reaches of inland rivers and some coastal rivers may not require ballast, providing high density timbers are used in conditions where the timber is perennially saturated, and it can be demonstrated that the resisting forces on the log or structure are greater than the imposed drag forces. In mobile gravel bed rivers, artificial ballast, cable or other

Photo 32. Natural wood accumulations — Macintyre River, Queensland.

means of anchoring logs is generally unnecessary. Stable structures can be built using only the "native" gravel that is available on site as backfill to stabilise a structure, possibly with the additional stabilising effect of piles driven into the bed. If there is insufficient gravel, or you wish to design a permeable open structure for habitat purposes, it may be necessary to anchor the structure with piles, or where this is not possible ballast blocks may need to be attached to the structures.

In sand-bed rivers a different approach is required. Whilst similar structures to those in gravel-bed rivers can be built and some stability afforded by the reburial or partial backfilling of structures with sand — it is extremely difficult to design a structure so that the sand will remain on the structure (providing stability) during overtopping flows. In sand channels, driven piles present probably the best means of stabilising logs. This can be coupled with geo-textile within the structure to help retain sand in the structure, and extensive revegetation.

Q. How much will it cost?

A. In the wood reintroduction projects carried out to date in Australia (see Table 1) the biggest cost is the transportation of logs to the site. The log costings outlined in Table 1 are based on a standard log of around 8–10 m in length for the various size classes. The logs in this instance were made available at no cost, however, we had to provide machinery and trucks to load, transport and unload the logs on site. The figures are based on a 3–3.5 hour round trip per load, which generally comprised somewhere between 12–16 logs of varying sizes. A 22 tonne excavator was required at either end for loading and unloading, and a flatbed semitrailer with cradles was used for the transportation. The cost of logs in the Williams River project site represented about 50% of the total implementation cost (i.e. for machinery hire operators etc — but excluding design and supervision costs).

Q. Do we use green or weathered timber?

A. From an engineering perspective it is preferable to use green timber, as the specific gravity of most green timber is greater than that of water and, as a result, the logs will not float, and are less likely to move during a flood. Most timber that is naturally recruited to streams is green when it first falls in, so rivers are used to dealing with green timber. They may not, however, be used to coping with a massive input of green timber at one time in a confined reach, particularly tree boles still retaining their bark. Under these circumstances, a massive amount of carbon is introduced into the system in single pulse, which can deoxygenate the water and kill many of the organisms in the river. This can be a particular problem when the reintroduction occurs at a time of little or no flow — which is often the time that will be selected for undertaking in-stream works. It may be preferable in small streams, when you know that there will be little or no flow, to use timber that has been seasoned in a paddock for at least 6–12 months. In such cases, particular care must be taken to ensure that the structures are adequately anchored, given that specific gravity of seasoned timber will only be represented by its dry density until it becomes fully saturated (see Table 4, page 44).

Photo 33. Offloading logs at the project site — Williams River.

Table 1. Example of log costing from Williams River experimental project site.

Log class costing — based on costs of logs delivered to Munni experimental site (Year 2000 $)						
	Small	Sml/med	Medium	Med/large	Large	Total
Diameter at breast height (dbh) (cm)	<25	25–40cm	40–45	45–50	50–90	
Count	118	223	47	14	26	428
Volume (m^3)	38.4	174.5	65.7	22.4	75.8	376.7
Proportion of total by volume	0.10	0.46	0.17	0.06	0.20	1.00
Log class cost	$3,568	$16,208	$6,106	$2,080	$7,038	$35,000
Unit cost — $/log	$30.23	$72.68	$129.91	$148.58	$270.70	

Q. Isn't it a waste of timber to have a large portion of the timber buried?

Wood reintroduction sceptics often question why you would want to bury a significant proportion of the precious wood you have just acquired at great expense to put in the river.

A. As outlined in Chapter 7, one of the best techniques for stabilising log structures is to bury a significant proportion of the structure into the stream bed and banks, both to ensure the structure is adequately ballasted, but also to anticipate the scour that will occur around the structure, and ensure your structure foundations are deep enough so it doesn't get undercut and fail during a high magnitude event. If a log jam structure is buried into the bank, the structure can cope with being undercut to almost 50% of the total structure width without failing (Abbe 2005). A similar amount of undercutting on virtually any other kind of structure would almost certainly lead to failure. Buried logs will also decay more slowly than those subject to sub-aerial weathering processes. In this state they also form a long term slow release carbon source, something which is often a limiting ecosystem process in many heterotrophic Australian streams (Bolton & Brock 1999, Bunn et al. 2000).

Q. How long can I expect a log structure to last?

A. Some logs that are buried in channels or floodplains under anaerobic conditions can survive virtually unaltered for thousands of years or even up to 20,000 years or more (Nanson & Barbetti 1995). However, the design life of a particular structure will vary from site to site depending on a number of factors:

- The type of timber — generally the harder (or more dense) the timber the greater the longevity (see Table 4, page 44).
- Latitude — in terrestrial coarse wood decay studies it has been shown that timber decays much faster with higher temperature and humidity (Mackenson et al. 2003, Chambers et al. 2000). Similar studies do not appear to have been undertaken with in-channel wood, but it is reasonable to assume that a similar trend applies. Terrestrial wood decay studies show that many of the timbers that might typically be used in wood reintroduction programs have expected lifespans in the order of 20–30 years, however, these rates include the role of termites and it is likely that termites dominate the overall decay rate in these terrestrial systems. In most situations where wood is being used in riverine environments, the role of termites can most likely be excluded, although at the time of writing there is no research to back up such an assertion.
- Whether the logs are permanently wet or subject to seasonal wetting and drying cycles (i.e. the more wetting and drying, the faster the decay rate).
- Flood magnitude and frequency (physical breakdown will be greater where log structures are being pounded by a number of floods every year). Also, it is not generally possible or advisable to design a structure to structurally withstand the 1:100 year flood or greater. Depending on the site, this would require excessive over design, making the project prohibitively expensive.
- Stream energy (unit stream power). Wood in high energy streams is subject to greater physical abrasion.

Given these variables, it is difficult to give a categorical answer as to what the design life for a given structure will be. Some sense of 'structure life' can be gained from the life spans of timber bridges, which tended to be made out of high quality dense eucalypt timbers. Timber bridges tend to be subject to sub-aerial decay processes for the majority of the time and are also subject to extensive physical abrasion. It is not uncommon for timber bridges to have had effective working life spans of 100 years or more, albeit with considerable maintenance along the way. Hence, it is reasonable to expect a well designed structure in the right conditions to have an effective design life of 50 years or more.

Q. Are there any implications for fish passage regulations?

A. A number of states now have very strict guidelines regarding the management of in-stream structures for fish passage, so it is important that you familiarise yourself with the regulations in your region before you go about designing and constructing full channel spanning bed-control structures. It is important, however, to place such regulations in the context of your site specific circumstances, and to remember that before all the logs were removed from the rivers, fish had coped extremely well with natural log steps and, indeed, managed to negotiate complete channel spanning log jams! Even today in forested systems, it is not uncommon to find channel spanning log steps that are much larger than 300 mm high, and fish still occur upstream of such obstructions. We can assume the fish somehow negotiated the "obstruction" to be found in these parts of the river. In some states, the regulations regarding what constitutes a barrier to fish migration have become fairly stringent, given that they are targeted at mitigating the ecological effects of weirs and road culverts. There is a danger of such regulations being applied uniformly regardless of the local channel

Photo 34. A natural 1.5 m high log step on the upper Allyn River, NSW. Photo T. Abbe.

conditions, channel scale or whether there are other mitigating factors at play, for example, whether it is a rehabilitation strategy.

Taking the rehabilitation example further, if a stream has become incised, has a high sediment load and, as a consequence has lost all morphologic variability, plus it is subject to riparian water extraction during low flow periods, its value as fish habitat at periods of low, or no flow, is pretty well nil. The presence of a 400 mm high log step in these circumstances is immaterial to fish passage; other factors clearly dominate. In these circumstances, one might decide to build a series of channel spanning bed-control structures, both as a means of stabilising the bed and inducing some morphologic variability within the reach in an effort to recreate some permanent pool habitat in what would otherwise be an ephemeral channel. To suggest the constructed bed controls in these circumstances breaches fisheries regulations because they might exceed the threshold height for in-stream structures, is missing the point. River rehabilitation is always about getting the balance right between morphologic habitat, water quality, water quantity, flow regime, lateral and longitudinal connectivity. It is not possible to look at any one of these aspects in isolation and, consequently, “one size fits all” regulations should be avoided.

6.2 Preliminary investigations

6.2.1 Catchment context of river reach

It is now widely accepted that the design of an appropriate reach based rehabilitation strategy, irrespective of the techniques being applied, requires an understanding, not only of the past river dynamics within the reach, but also some sense of how the reach in question relates to the rest of the catchment, and the disturbance patterns operating at this broader scale (Brierley & Fryirs 2000, Brierley et al. 2002, Brierley & Fryirs 2005). Different river styles (sensu Brierley & Fryirs 2005) exist within different positions in catchments, and river style is suggested to be a strong indicator of likely adjustment patterns within a reach.

6.2.2 Reach dynamics

Delineating the river style can provide a sense of how the channel and floodplain within a reach has evolved, and the sort of natural channel adjustments that might be expected in the reach. It will also help predict how these might be exacerbated as a result of various disturbance scenarios (see Section 5.2). This sort of information provides important context for the more detailed analysis of historical and contemporary reach dynamics outlined in Section 5.4. One of the primary objectives of determining the historical reach dynamics is to better understand the adjustment trajectory of the reach and, therefore, how this might aid or compromise the rehabilitation strategy undertaken. For example, if there is a major sediment slug upstream of your intended rehabilitation reach, you would undertake a very different rehabilitation strategy to the situation where a sediment slug (or wave) had already moved through a similar reach.

Critical aspects of the reach geomorphology that are essential for the design process include:

- information about the location and extent of past bank erosion/ channel expansion,
- the location of any channel cutoffs or channel realignments (either natural or artificial) which can provide insight into local gradient changes and alterations to the channel cross section,
- the nature of past river management works and evidence of whether, how and why these works failed,
- a thalweg survey from which reach gradient and pool-riffle amplitude and wavelength can be determined,
- a survey of bed material characteristics,
- channel cross section surveys,
- a reach planform survey showing the location of the cross section and thalweg survey, and any other key geomorphic characteristics of the reach (for example the location and extent of bank erosion).

In addition to providing insight into the historical river changes, particularly where historical survey data is available (e.g. from old bridge crossing surveys), these data also provide the basis for the reach design process and hydraulic analysis.

6.2.3 Reach baseline data

Thalweg survey

An understanding of the reach gradient and the bed material characteristics is an essential component for both the design and subsequent monitoring of the rehabilitation strategy at each site. A reach thalweg profile (Figure 17), not only provides a measure of the reach gradient, but can also provide a minimum measure of the potential extent of bed scour likely to occur within the reach. Given that bed scour is notoriously difficult to predict, these empirical measures provide a lower bound of maximum scour in the absence of other information. When the elevation data is plotted as a deviation from the reach trend, the difference between the maximum positive and negative residuals (i.e. riffle crest to pool nadir) can provide some measure of the scouring potential of the reach (Figure 18). This is also known as the riffle/pool amplitude. Additional estimates of the depth of scour can also be derived using the empirical approach derived by Farraday and Charlton (see Rutherfurd et al. 2000, p. 148). It should be pointed out, however, that these empirical methods work best in gravel bed rivers. In sand bed rivers, scour pools that form at high stage are often in-filled in subsequent small events, or on the waning stage of floods, and so the surveyed bed profile may not represent the maximum scour depth. Bed surface texture data is also collected for the purposes of predicting scour depth, and as a baseline for measuring subsequent bed texture changes post rehabilitation.

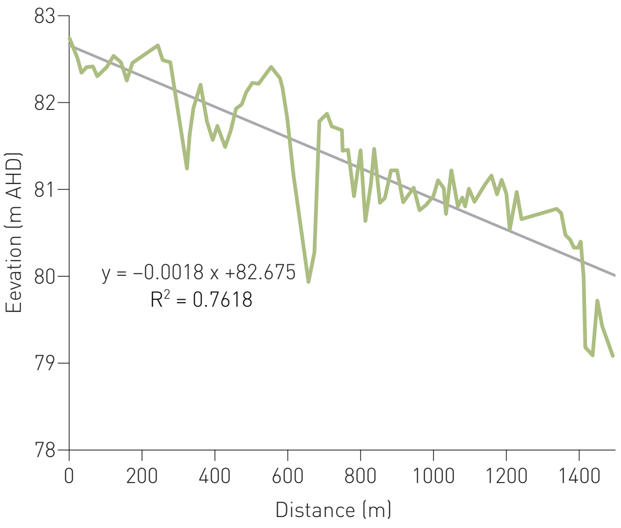


Figure 17. Example of a thalweg profile through a rehabilitation reach.

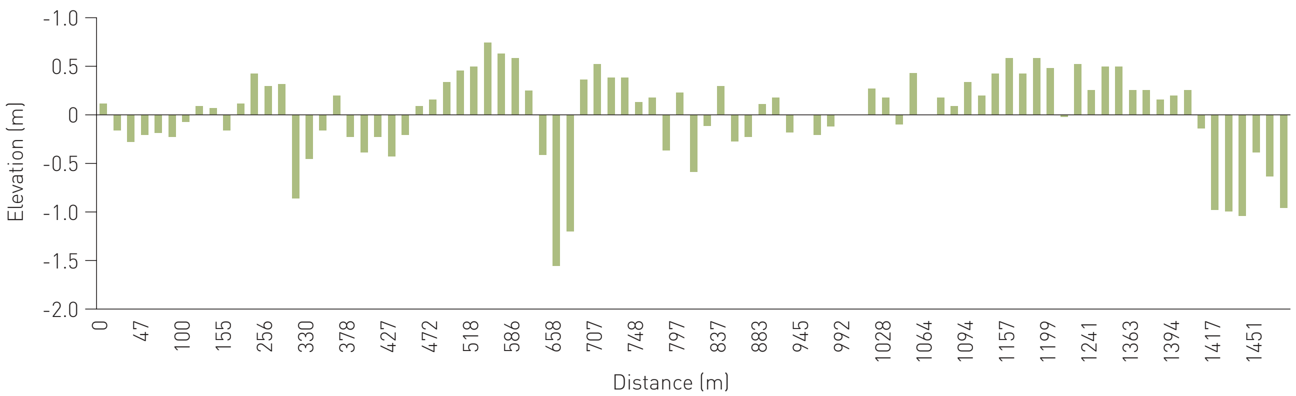


Figure 18. Example of a thalweg survey showing deviations from the thalweg profile trendline.

Table 2. Reach gradient and maximum scour predictions using two empirical methods.

Example of reach summary statistics	
Surveyed reach gradient for Williams River site 4 (11/2002)	0.0018
Max pool/riffle amplitude from Figure 19	2.3 m
Reach average scour depth for Q20 (Farraday and Charlton method)	2.3 m (below bed) +/- 0.96

6.2.4 Reach planform map

A reach planform map is best derived from the reach survey data, showing the locations of the key features within the reach as well as the locations of cross sections, the thalweg survey transect and all survey benchmarks. Once plotted up this map will form the base map onto which the reach rehabilitation strategy can be designed (e.g. Figure 20).

6.2.5 Bed material statistics

Bed material data is collected from each major geomorphic unit within the rehabilitation reach using the Wolman method (Wolman 1954) in gravel-bed systems (i.e. survey of the B axis of 100 randomly selected particles) or using a sediment particle size card in sand dominated systems. The particular size data is then plotted up as a particle size probability distribution, and the key particle size variables extracted as per Table 3. These data serve a dual purpose as a baseline dataset for monitoring purposes, as well as vital data for performing scour analysis.

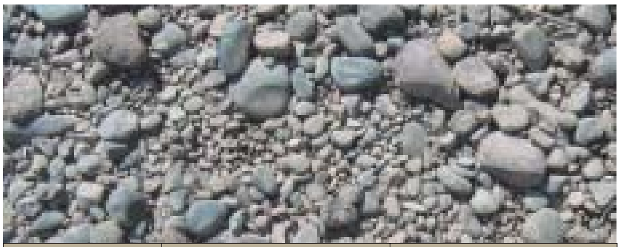


Photo Jo Hoyle.

	Site no. 10 (n = 800) reach average	Site no. 9 (n = 1100) reach average
D_5	39	3
D_{16}	56	60
D_{35}	74	81
D_{50}	90	94
D_{84}	136	144
D_{95}	171	193
D_{max}	342	462

Table 3. Examples of rehabilitation reach bed-material statistics derived from a Wolman survey (Wolman 1954). D_5, D_{95} etc. are shorthand notation for the diameter of the 5th or 95th percentile of the bed material particle size population, or in other words 5% of the population is finer than the D_5; 95% is finer than the D_{95}.

6.3 Standard ELJ design

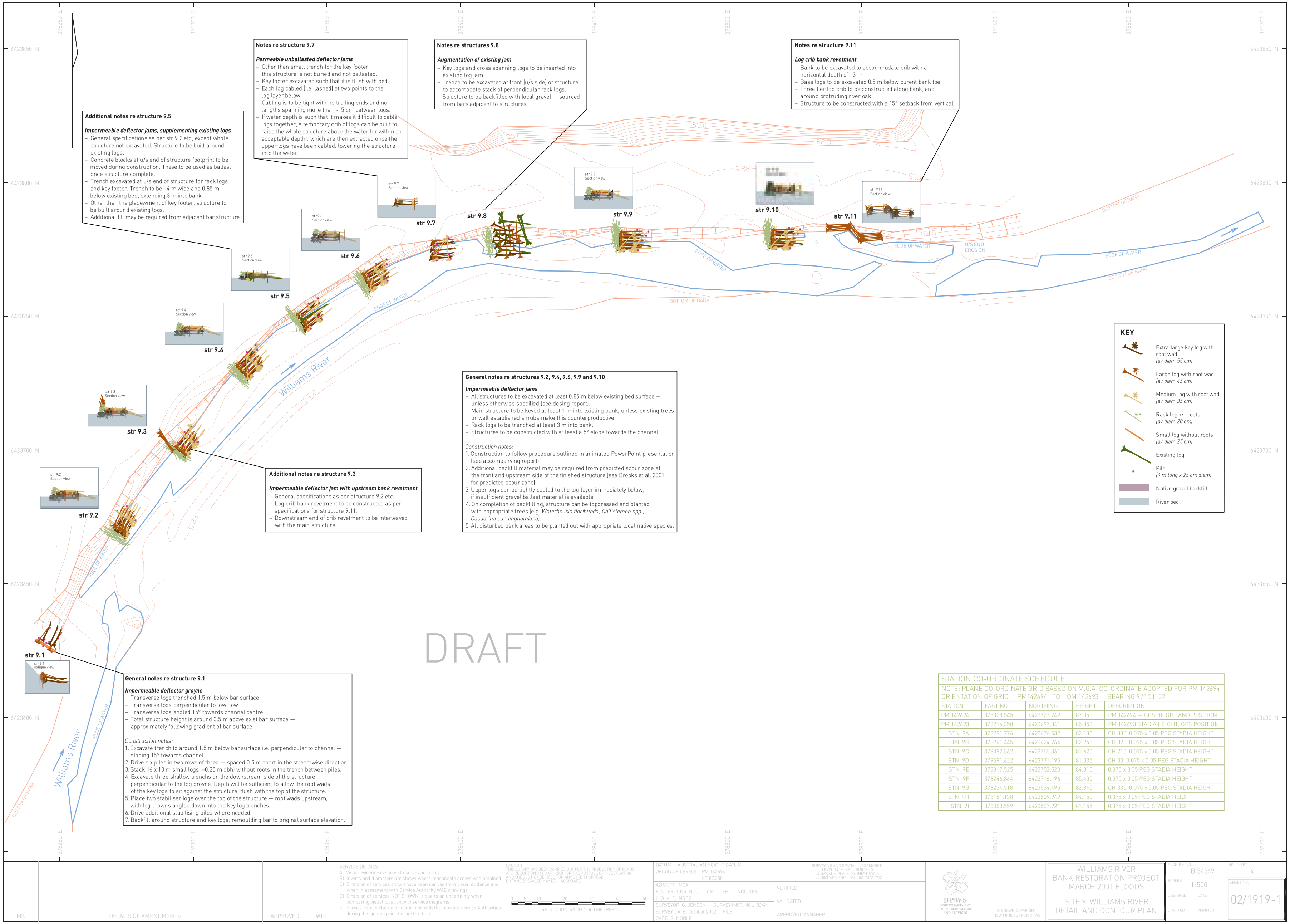
In this Section, an outline is given of the basic workhorse ELJ structure that has proved to be extremely effective as a bank erosion control device and fish habitat structure, particularly in moderate to high energy gravel bed river settings. It has also been used in sand-bed settings — but has yet to be fully proven in high energy flows, and we are therefore not able to make a blanket recommendation for their use in these settings. Nevertheless, there is no reason why it will not work in sand bed systems, provided additional anchorage is provided using driven piles or some alternative measure. A range of alternative structure types that have been employed at various locations around the country are also presented in Appendix A. Many of these alternative structures are not yet fully proven in the field, so some caution should be exercised in how and where they are used.

6.3.1 Basic bank erosion control structure — impermeable deflector jams (DFJs)

This is the basic, bank-attached erosion control structure, which has also been demonstrated to be highly effective for fish habitat (Section 3.3.2). This structure is a bank-attached, multi-layered, impermeable log jam with gravel back-fill for ballast (Figures 22 and 23). Basal key logs are buried to a depth greater than the predicted scour depth for the design flow. The magnitude of the log jam varies depending on the specific location, however, where the primary role is bank protection, it is recommended it should extend to at least half the height of the most effective flood stage (Abbe et al. 1997). The main uses of this structure are:

1. as an alternative to traditional rock revetment for protection from bank erosion,
2. as a mechanism for increasing sediment storage and inducing channel contraction, through direct modification of the channel cross section (with the structure) and via enhanced sedimentation on and around the structure, hence further constricting the cross section,
3. as a mechanism for inducing pool scour,
4. for flow re-direction and energy dissipation,
5. as high quality complex fish habitat,
6. as substrate for biofilms,

Figure 19. Example of reach survey plan onto which the reach rehabilitation strategy is overlaid.



Additional notes re structure 9.5

Impermeable deflector jams, supplementing existing logs
- General specifications as per str 9.2 etc, except whole structure not excavated. Structure to be built around existing logs.
- Concrete blocks at u/s end of structure footprint to be moved during construction. These to be used as ballast once structure complete.
- Trench excavated at u/s end of structure for rack logs and key footer. Trench to be ~4 m wide and 0.85 m below existing bed, extending 3 m into bank.
- Other than the placewment of key footer, structure to be built around existing logs.
- Additional fill may be required from adjacent bar structure.

Notes re structure 9.7

Permeable unballasted deflector jams
- Other than small trench for the key footer, this structure is not buried and not ballasted.
- Key footer excavated such that it is flush with bed.
- Each log cabled (i.e. lashed) at two points to the log layer below.
- Cabling is to be tight with no trailing ends and no lengths spanning more than ~15 cm between logs.
- If water depth is such that it makes it difficult to cable logs together, a temporary crib of logs can be built to raise the whole structure above the water (or within an acceptable depth), which are then extracted once the upper logs have been cabled, lowering the structure into the water.

Notes re structures 9.8

Augmentation of existing jam
- Key logs and cross spanning logs to be inserted into existing log jam.
- Trench to be excavated at front (u/s side) of structure to accomodate stack of perpendicular rack logs.
- Structure to be backfilled with local gravel — sourced from bars adjacent to structures.

Notes re structure 9.11

Log crib bank revetment
- Bank to be excavated to accommodate crib with a horizontal depth of ~3 m.
- Base logs to be excavated 0.5 m below curent bank toe.
- Three tier log crib to be constructed along bank, and around protruding river oak.
- Structure to be constructed with a 15° setback from vertical.

General notes re structures 9.2, 9.4, 9.6, 9.9 and 9.10

Impermeable deflector jams
- All structures to be excavated at least 0.85 m below existing bed surface — unless otherwise specified (see desing report).
- Main structure to be keyed at least 1 m into existing bank, unless existing trees or well established shrubs make this counterproductive.
- Rack logs to be trenched at least 3 m into bank.
- Structures to be constructed with at least a 5° slope towards the channel.

Construction notes:
1. Construction to follow procedure outlined in animated PowerPoint presentation (see accompanying report).
2. Additional backfill material may be required from predicted scour zone at the front and upstream side of the finished structure (see Brooks et al. 2001 for predicted scour zone).
3. Upper logs can be tightly cabled to the log layer immediately below, if insufficient gravel ballast material is available.
4. On completion of backfilling, structure can be topdressed and planted with appropriate trees (e.g. *Waterhousia floribunda*, *Callistemon spp.*, *Casuarina cunninghamiana*).
5. All disturbed bank areas to be planted out with appropriate local native species.

Additional notes re structure 9.3

Impermeable deflector jam with upstream bank revetment
- General specifications as per structure 9.2 etc.
- Log crib bank revetment to be constructed as per specifications for structure 9.11.
- Downstream end of crib revetment to be interleaved with the main structure.

General notes re structure 9.1

Impermeable deflector groyne
- Transverse logs trenched 1.5 m below bar surface
- Transverse logs perpendicular to low flow
- Transverse logs angled 15° towards channel centre
- Total structure height is around 0.5 m above exist bar surface — approximately following gradient of bar surface

Construction notes:
1. Excavate trench to around 1.5 m below bar surface i.e. perpendicular to channel — sloping 15° towards channel.
2. Drive six piles in two rows of three — spaced 0.5 m apart in the streamwise direction
3. Stack 16 x 10 m small logs (~0.25 m dbh) without roots in the trench between piles.
4. Excavate three shallow trenchs on the downstream side of the structure — perpendicular to the log groyne. Depth will be sufficient to allow the root wads of the key logs to sit against the structure, flush with the top of the structure.
5. Place two stabiliser logs over the top of the structure — root wads upstream, with log crowns angled down into the key log trenches.
6. Drive additional stabilising piles where needed.
7. Backfill around structure and key logs, remoulding bar to original surface elevation.

STATION CO-ORDINATE SCHEDULE

NOTE: PLANE CO-ORDINATE GRID BASED ON M.G.A. CO-ORDINATE ADOPTED FOR PM 142694
ORIENTATION OF GRID PM142694 TO OM 142693 BEARING 97° 51' 07"

STATION	EASTING	NORTHING	HEIGHT	DESCRIPTION
PM 142694	378028.545	6423723.742	87.350	PM 142694 — GPS HEIGHT AND POSITION
PM 142693	378216.358	6423697.841	85.850	PM 142693 STADIA HEIGHT, GPS POSITION
STN 9A	378291.776	6423676.532	82.130	CH 330 0.075 x 0.05 PEG STADIA HEIGHT
STN 9B	378261.445	6423624.764	82.265	CH 390 0.075 x 0.05 PEG STADIA HEIGHT
STN 9C	378382.562	6423755.361	81.620	CH 210 0.075 x 0.05 PEG STADIA HEIGHT
STN 9D	379591.622	6423771.195	81.035	CH 00 0.075 x 0.05 PEG STADIA HEIGHT
STN 9E	378317.525	6423752.520	84.310	0.075 x 0.05 PEG STADIA HEIGHT
STN 9F	378246.864	6423716.196	85.400	0.075 x 0.05 PEG STADIA HEIGHT
STN 9G	378234.518	6423534.495	82.845	CH 330 0.075 x 0.05 PEG STADIA HEIGHT
STN 9H	378181.138	6423509.949	84.150	0.075 x 0.05 PEG STADIA HEIGHT
STN 9I	378080.559	6423527.921	81.155	0.075 x 0.05 PEG STADIA HEIGHT

MK
DETAILS OF AMENDMENTS
APPROVED
DATE

SERVICE DETAILS
A) Visual evidence is shown to survey accuracy
B) Inverts and diameters are shown where reasonable access was obtained
C) Direction of services shown have been derived from visual evidence and when in agreement with Service Authority WAE drawings
D) Direction of services NOT SHOWN is due to an uncertainty when comparing visual location with service diagrams
E) Service details should be confirmed with the relevant Service Authorities during design and prior to construction

CAUTION
THIS SURVEY HAS BEEN CARRIED OUT FOR THE PRODUCTION OF PLANS AT A REDUCTION RATIO OF 1:500 FOR THE PURPOSE OF INVESTIGATION AND SHOULD NOT BE USED FOR ANY OTHER PURPOSE. DISTANCES SCALED MAY BE INACCURATE.

DATUM AUSTRALIAN HEIGHT DATUM
ORIGIN OF LEVELS PM 142694
HT 87.350
AZIMUTH MGA
FOLDER 1036 NCL LM FB NCL. 186
L. G. A. DUNGOG
SURVEYOR G. JENSEN SURVEY INST. NCL 02/44
SURVEY DATE October 2002 FILE
CADD S. NOBLE

SURVEYING AND SPATIAL INFORMATION
LEVEL 14, McKELL BUILDING
2-24 RAWSON PLACE, SYDNEY NSW 2000
TEL: (02) 9372 7907 FAX: (02) 9372 7922

VERIFIED
VALIDATED
APPROVED MANAGER

© CROWN COPYRIGHT
NSW MINISTER FOR DPWS

WILLIAMS RIVER
BANK RESTORATION PROJECT
MARCH 2001 FLOODS

SITE 9, WILLIAMS RIVER
DETAIL AND CONTOUR PLAN

PLAN RM NO. B 54349
NO. IN SET 4
SCALES 1:500
DESIGNED
DATE
DRAFTED
VERIFIED
SHEET NO. 02/1919-1

7. as a mechanism for increasing lateral hyporheic zone exchange (Findlay 1995, Mika et al. 2004, Section 2.2) in the scallops scoured into the bars opposite the structures (Boulton et al. 2003).

To achieve the first objective the structures are normally located on concave eroding banks where they actively deflect the channel thalweg away from the bank, thereby reducing the force driving the erosion. Deflector jams also provide toe-revetment aiding in the geotechnical stabilisation of the bank.

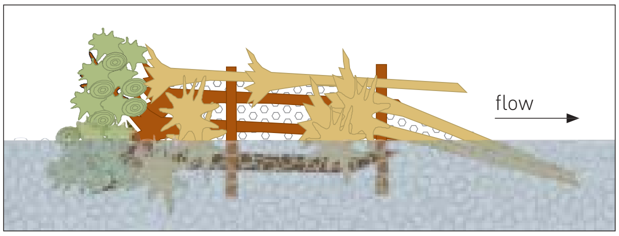


Figure 20. Standard ELJ — section view, towards bank.

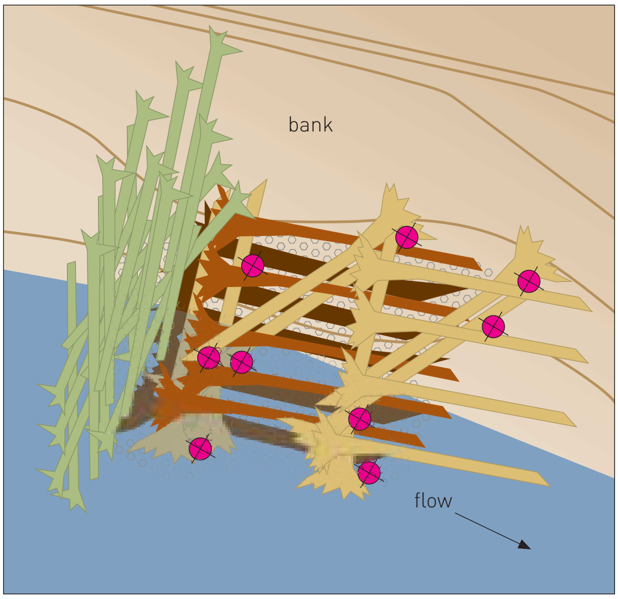


Figure 21. Standard bank attached deflector jam — plan view.

Figure 22. Construction sequence for a standard deflector jam. (A) Excavated pad ready to begin construction of a large deflector jam. (B and C) Upper layers of the longitudinal logs being arranged on structure. (D) Completed structure. Photos T. Abbe.

chapter 7

Designing log structures

7.1 Data requirements to perform force-balance stability analysis and design of a wood reintroduction strategy

To undertake the design of a wood reintroduction strategy, the following data is regarded as being the minimum to adequately complete a full reach design.

- Channel cross section surveys to morphological bankfull height and onto the floodplain. Representative sections spaced at no more than one channel widths separation, ideally located at the site of each structure location, with a minimum of 10 per site to try to encapsulate more than one complete riffle-pool sequence (if they exist).
- Channel long profile survey (at least three riffle pool sequences or 15–20 channel widths long). This is for determining the reach bed slope — i.e. as a regression from riffle to riffle (if riffles exist).
- Bed material samples: one per cross section.
- Some flow discharge magnitude/frequency data from which a design discharge can be selected (e.g. 10 year ARI discharge). If gauging data is not available, a regional catchment area/discharge relation can be used. As a minimum, the morphological bankfull discharge can be estimated using the Manning equation from the slope and cross section area data.
- Volume of wood being reintroduced can be estimated based on assumed log diameter at breast height (dbh) and lengths.
- Wood dry density (use 900 kg m^{-3} if a eucalypt, and species not known).

See Table 4 overleaf.

7.2 Selecting a design flood

There is no hard and fast rule for the selection of a design discharge. Different engineers will have their own design discharges that they use in different circumstances, but by and large it is a question of the risk (of structure failure) that you are prepared to accept. The primary reason for selecting a design flood is that you want your structure to withstand, with high probability, a flood of this magnitude. As a result, you will design your structures to withstand the forces imposed by a flood of this magnitude within standard factors of safety (to account for sources of error in the calculations and an additional comfort margin). Typical (minimum) factors of safety that most engineers are prepared to live with are in the order of 1.5 to 2. Ideally, once a design discharge is selected, a sensitivity analysis will also be undertaken to assess the performance of the structures under conditions that are more extreme than the design flood.

Factors that must be taken into account when selecting a design flood are as follows:

- The index of flow variability (Iv) of your stream (see Finlayson & McMahon 1988, Rutherfurd et al. 2000). The higher the Iv, the greater the difference between the frequent small floods and rare large floods. In the situation where you have a high Iv it will be prohibitively expensive to design structures that will withstand the rare extreme events. To design something capable of withstanding the 1:100 year event would require structures to be massively over-designed for the circumstances likely to be encountered for the majority of the time. Conversely, in streams with a low Iv, there will be little difference

Table 4. Wood density characteristics for common Eucalypt species (Bootle 1983).

Common name	Species name	State	Green density ($kg\ m^{-3}$)	Dry density ($kg\ m^{-3}$)
Rough bark apple	*Angophera floribunda*	NSW, Qld	1180	850
Smooth bark apple	*A. costata*	NSW	1240	990
Alpine ash	*Eucalyptus delegatensis*	Tas, NSW, Vic	1050	620
Mountain ash	*E. regnans*	Tas Vic	1030	680
Silvertop ash	*E. sieberi*	NSW, Vic	1200	820
Blackbutt	*E. pilularis*	NSW, Qld	1100	900
WA blackbutt	*E. patens*	WA	1120	850
Red bloodwood	*E. gummifera*	NSW, Vic, Qld	1150	900
Mountain grey gum	*E. cypellocarpa*	NSW, Vic	1100	880
Forest red gum	*E. tereticornis*	Vic, NSW, Qld	1200	1050
River red gum	*E. camaldulensis*	Vic, NSW, Qld	1130	900
Sydney blue gum	*E. saligna*	NSW	1070	850
Spotted gum	*E. maculata*	NSW, Vic, Qld	1150	950
Karri	*E. diversicolour*	WA	1200	900
Jarrah	*E. marginata*	WA	1170	820
Grey ironbark	*E. paniculata*	NSW	1210	1120
White stringybark	*E. globoidia*	NSW, Vic, Qld	1100	880
River sheoak	*Casuarina cunninghamiana*	NSW, Qld	970	770
Southern mahogany	*E. botryoides*	NSW, Vic	1180	920
Silky oak	*Grevillia robusta*	NSW, Qld	1100	620

in design specifications for a structure that can withstand the 1:10 year event and the 1:50 or the 1:100 year event.

- Consequences of structure failure. The extent to which you may over-design a structure and hence increase costs and material requirements, will in part be a function of the consequence that would result from the structure's failure. If, for example, you are undertaking a rehabilitation program within a semi-urban environment in a stream immediately upstream of a sequence of bridges or culverts adjacent to a floodplain housing development, then the consequences of the failure of your rehabilitation strategy are potentially quite extreme. Under these circumstances you might select a higher magnitude design flood, and possibly higher factors of safety to ensure that risk of structure failure is minimised. This will of course result in higher construction costs, and possibly mean that a significant portion of the structure is functionally redundant for the majority of the time. In the majority of cases, however, where rehabilitation programs are undertaken in rural streams where there is very little risk of damaging critical infrastructure, smaller design discharges can be used and/or less conservative (lower) factors of safety. As outlined in Section 3.3, when using good quality eucalypt hardwoods, even if some structures partially fail it is unlikely the logs will move far beyond the structure from which they originate. In the Williams River study approximately 14 logs became dislodged from various structures and none moved beyond the study reach.
- Expected or desired longevity of the structure. The design flood selected should bear some relationship to the expected, or desired, life of the structures.

In streams that are ungauged and there is no flow rating curve available from which to select your design discharge (as per Figure 23), a regional flow rating curve (i.e. catchment area/discharge curve) will need to be derived from the available river gauge data in your region, from catchments having similar rainfall-runoff characteristics. Most state governments have a HydSys database of flow gauge data from which rating curves can be extracted. In most cases the standard Log-Pearson III (LP3) curve that has been fitted to the annual series curve, can be used to determine the annual

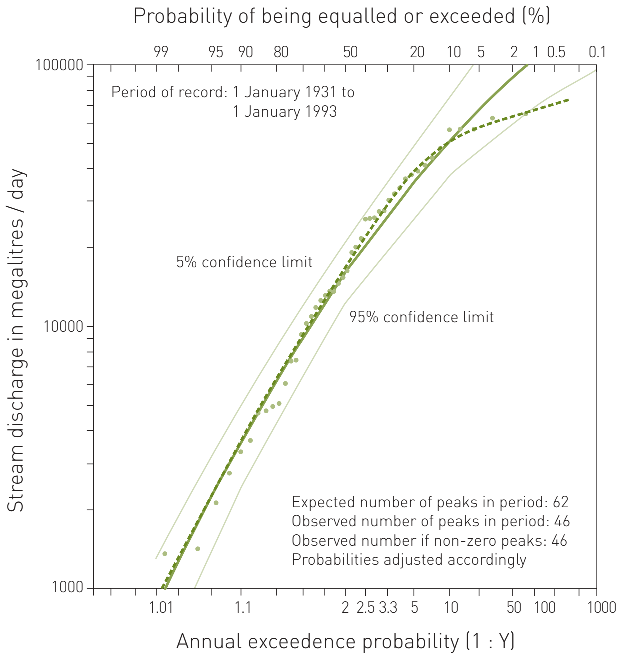


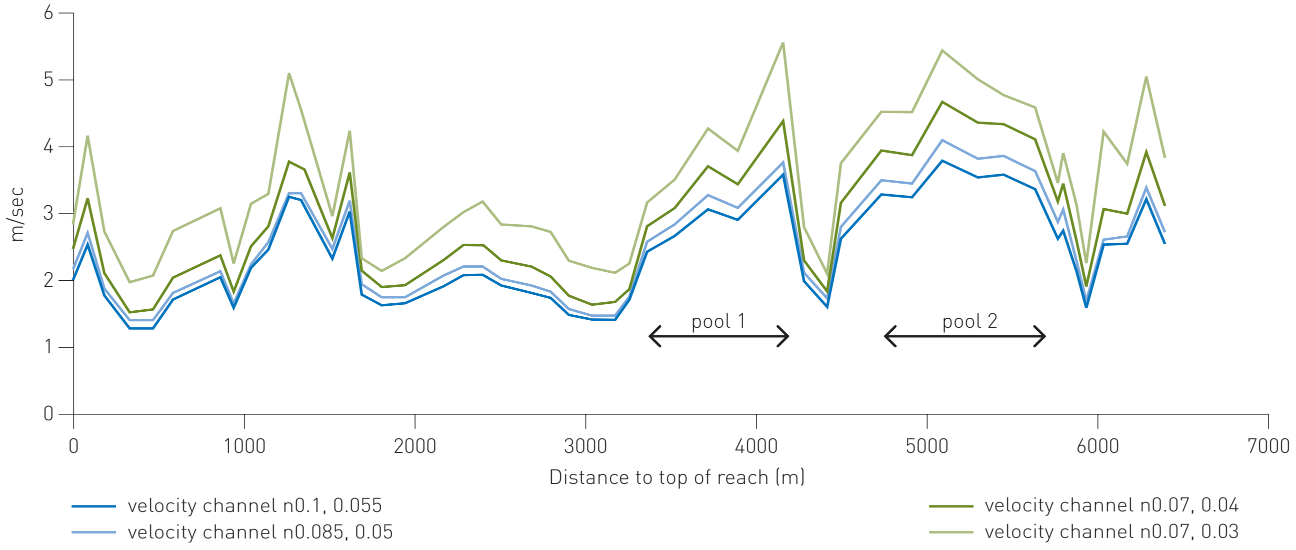
Figure 23. Annual exceedence probability curves for the Tillegra gauge (station 210011). Solid line is the Log Pearson (III) curve, dashed line fitted by eye.

exceedance probability. It should be pointed out, however, that in some cases the Log-Pearson III curve does not fit the data very well at the upper end of the curve, and it may be better to fit a curve by eye. In the example shown in Figure 23 there is a very poor fit at discharges greater than a 10 year ARI using the LP3 curve fit. If selecting a 20 year ARI design discharge based on the LP3 curve from the Tillegra gauge, a discharge would be derived that is greater than any flood recorded within the 70 years of gauging represented by this plot. This means that selecting the 20 year discharge based on LP3 would result in significant over design of the structures.

Figure 24. Example of HecRas model output for determining design velocities for structure emplacement locations.

7.3 Hydraulic modelling

Having now collected your field survey cross sectional and long profile data and selected your design discharge, the next stage in the design process is to set up a 1D hydraulic model of your rehabilitation reach. The industry standard, and most accessible (i.e. free), hydraulic modelling software for undertaking this task is the HecRas model developed by the US Army Corp of Engineers (see http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html). It is beyond the scope of this Guideline to outline the process required to undertake a HecRas modelling analysis, however, free tutorials are available for download on the web, and it is not particularly difficult to teach yourself how to do rudimentary 1D hydraulic modelling (see http://www.ce.utexas.edu/prof/maidment/grad/tate/research/RASExercise/webfiles/hecras.html). The primary output we are interested in from this exercise is the cross sectional depth averaged velocity at the intended locations of the structures. It must be remembered that HecRas is not a dynamic model and does not take into account bed scour (and hence increased cross sectional area) during high stage flows. On balance, this is likely to lead to an over prediction of peak flood stage. Figure 24 provides an example of a typical output from a HecRas model run, showing the within-reach variability in velocity down a 6 km reach of the Hunter River, as well as the sensitivity of the output to variations in hydraulic roughness. Similar model runs to this would ideally be undertaken using different discharge inputs. Note how velocities are higher in the pools at flood stage due to the greater hydraulic mean depth of the pool cross sections compared with the riffles. Depending on the scale of structures being designed, and if the rehabilitation reach is in an area where there are sensitivities to any increases in flood stage, it may be advisable to undertake model runs that include the projected cross sectional obstruction posed by the structures.



7.4 Prediction of scour at LWD

As outlined in Section 6.2, scour depth prediction in streams with a mobile alluvial bed is notoriously difficult. In the absence of anything else, the two empirical approaches outlined in Section 6.2 (i.e. thalweg residuals and the Faraday and Charlton method) can provide a first order approximation of maximum scour depth. However, these approaches tend to work best in gravel bed rivers, where scoured pools are less likely to infill under moderate or low flow conditions or on the waning stage of the hydrograph. Sand bed rivers pose a particular problem because pools can form and disappear during the course of a single flood, particularly when sediment supply is high. Thus, predicting scour on the basis of observed reach geomorphology is likely to grossly under predict maximum scour depth. Conversely, the empirical approach of Faraday and Charlton tends to overestimate scour in sand bed channels.

Maximum scour occurs where maximum turbulence is induced, and this will tend to be at sites where obstructions such as log structures protrude into the high velocity flow thread. Figure 25 shows the zone of maximum scour around a bar apex jam (sensu Abbe et al. 1996) in the Queets River, in Washington state, USA, which behaves as a mid-channel bluff body obstruction. From this example, it can be seen that there is major scour at the front of the structure associated with downwelling flow separation, and a more linear pool along each flank of the log jam associated with the vortex street shed off either side of the structure. Bank attached structures show a very similar pattern of scour, albeit only on the streamward side of the structure, as this example of the measured scour at the Williams River site demonstrates (Figure 26). Maximum depth of scour in this case was in the order of 2 m.

7.4.1 2D hydrodynamic modelling

In some circumstances, where your budget allows it, and where detailed insights into the predicted response to rehabilitation works are required, it may be justified to undertake 2D hydrodynamic modelling to predict scour and deposition likely to result from the proposed treatment. This is an expensive option and in most cases is probably not justified. It is also subject to the vagaries of any modelling exercise in that the output is only as good as the input data and assumptions. Model parameterisation and calibration may indeed present more of a problem than the rehabilitation exercise itself. Nevertheless, in some high profile projects, such as the one undertaken by Tim Abbe (Figure 27) to construct large log jams to halt erosion of an interstate highway, 2D modelling can provide convincing evidence of the

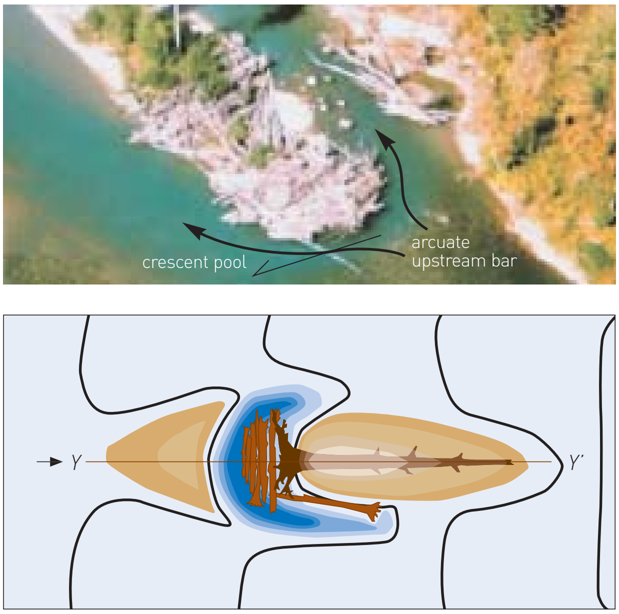


Figure 25. Scour associated with a bar apex jam — Queets River, USA. Courtesy T. Abbe.

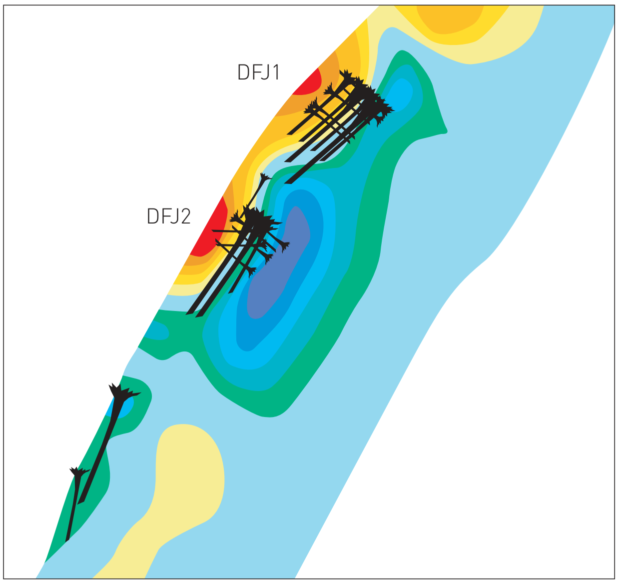
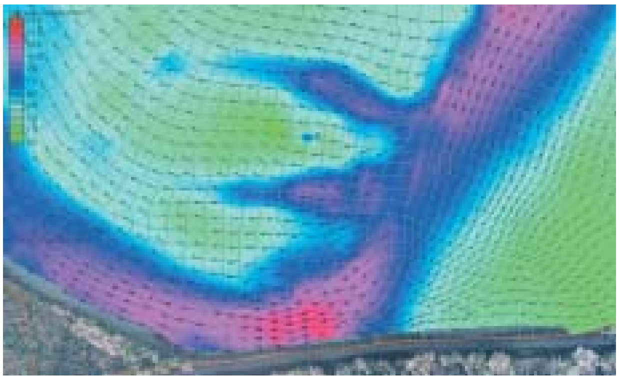


Figure 26. Scour (blues and greens) associated with bank attached jams — Williams River.

Figure 27 (below and right). Example output of 2D hydrodynamic modelling from the Hoh River ELJ project WA, USA. Courtesy T. Abbe. **27a** (below) shows the situation before construction, **27b** (right) illustrates the predicted changes after structure emplacement.



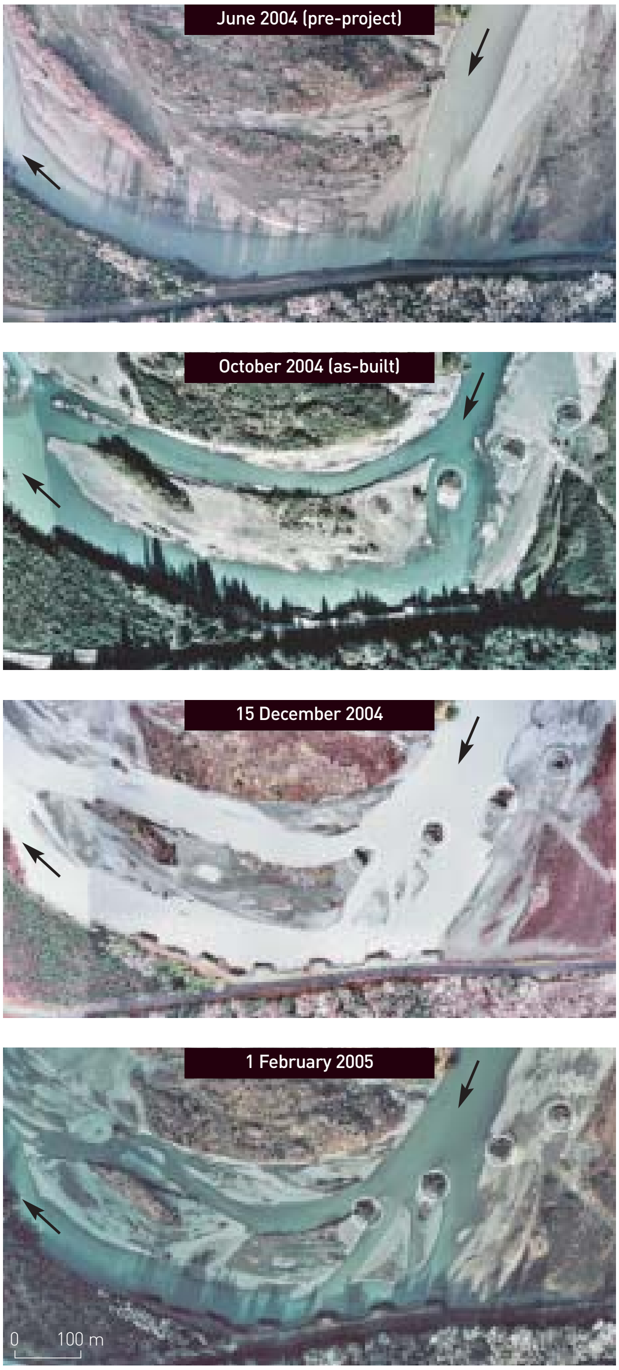
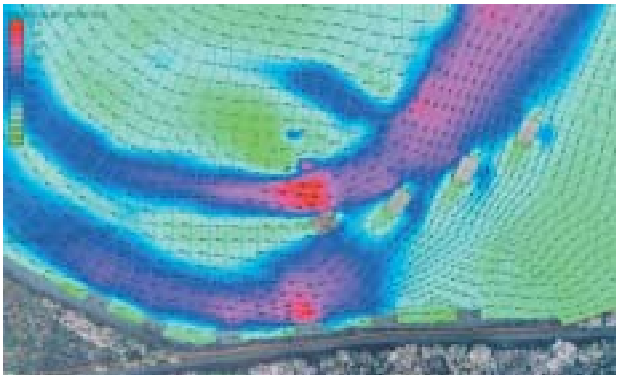


Figure 28 (above). Observed response of Hoh River project site to ELJ emplacement. Scale applies to all images. Courtesy T. Abbe.

Figure 27b.



viability of the proposed solution. In this case the model predictions appear to have predicted the actual stream response reasonably well (Figure 28).

7.4.2 Scour in sand-bed creeks — insights from the Granite Creeks sand-bed pool scour experiments

As mentioned previously, accurately predicting scour in sand-bed streams is fraught with difficulty. The problem is best illustrated with some results from experimental work carried by Nick Marsh, Dan Borg, Ian Rutherfurd, Mike Stewardson and others in the Granite Creeks (northern Victoria) and the lower Snowy River (east Gippsland, Victoria). The following are summaries and excerpts from the various reports of this work (see Marsh et al. 2001, Borg et al. 2004).

The Granite Creeks experiment

A study was conducted into the potential for creating persistent scour holes for their habitat value in a series of sand-bed streams in the Granite Creeks System of north-east Victoria. Large volumes of sand have been eroded from the granitic upper reaches of the system, infilling pools and burying woody debris in a classical sand slug stream (Davis & Finlayson 2000). As is typical of sand slugged streams, this system had been transformed from a physically diverse, heterogeneous environment, to a flat, homogeneous sand bed.

The experiment aimed to create pool habitat using a simple model of an elevated cross spanning log. The structures consisted of river red gum sleepers bolted together (cross section 200 mm x 200 mm) elevated just above the average height of the streambed, placed perpendicularly to flow and spanning the full width of the stream (Figure 29, A and B). The structures were keyed into the banks using steel-pickets. Flume studies suggested these structures should produce a relatively large amount of scour (Beschta 1983, Marsh et al. 2001) (Figure 30), and the maximum scour depth could be predicted for a given flow for this type of structure (Marsh 2001).

The results of the experiment showed that the model significantly over-predicted the resultant scour pool dimensions, which is not to say that this extent of scour did not occur during peak discharge. Repeat observations revealed that pools generally formed during a flood, and subsequently infilled during the waning stage of the hydrograph. In this mobile sand bed stream it was found that snapshot sampling of flow and scour depths failed to record the maximum scour depth (and pool dimension achieved). This highlighted two things: firstly that this strategy was ineffective at producing persistent pool habitat; and, secondly, that to record maximum scour depth required real time monitoring.

Figure 29. Artificial habitat structures in the Granite Creeks. (Left) One structure reach. (Right) Four structure reach.

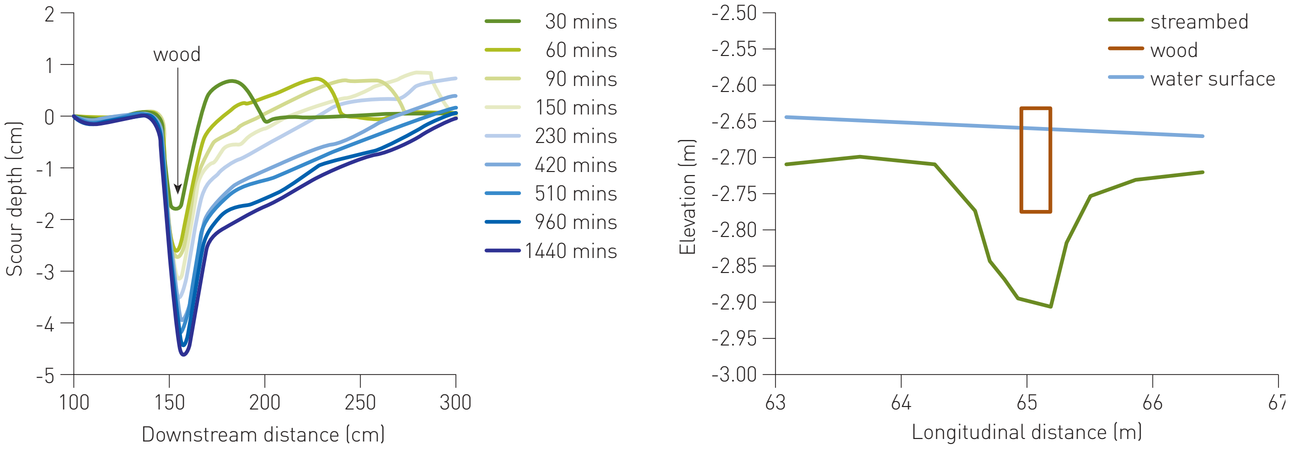


Figure 30. Anticipated and observed scour pool geometries. (Left) Laboratory study of temporal evolution of a scour pool (Marsh 2001). Note the exaggeration of the vertical axis. Position of the structure is marked with an arrow. (Right) Scour pool geometry for a log structure in the Granite Creeks system. The artificial scour pool is shallower, and does not extend as far downstream, as the model would predict.

Real-time monitoring

To overcome the inadequacies of observing maximum scour depths based on snapshot surveys, Borg et al. (2004) developed a technique for continuously monitoring scour around log structures. The technique used buried pressure transducers to measure changes in pressure of above-lying sand, which was then related to a depth of sand. Continuous scour pool depth data from the Granite Creeks, and also from investigations of natural scour pools in the lower Snowy River, (eastern Victoria), provided further evidence that the flow-scour relationship is not as simple as initially anticipated.

Data from a natural scour pool in the lower Snowy River indicates both scour and infilling can occur following flow events, in addition to infilling as flow levels recede (Figure 31). As the stage rises 0.2 m, the pool progressively infills by 0.9 m (late January). Following this infilling, the pool then progressively scours following a 0.54 m increase in stage (early February). The pool then gradually infills throughout February and March as the stage recedes.

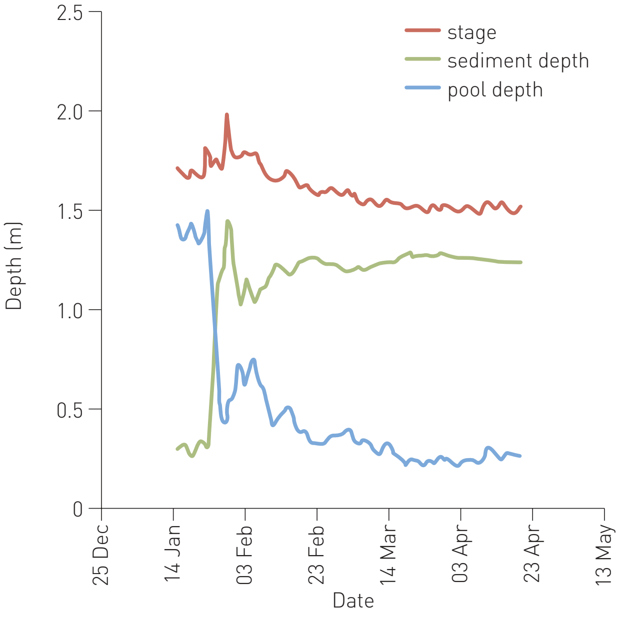


Figure 31. Scour pool data for a pool in the lower Snowy River. Sediment depth refers to the depth of sand above the sensor and pool depth is the difference between the stage and the sediment depth.

Study outcomes

The flow-scour relationship has been investigated in a number of flume studies (Beschta 1983, Cherry & Beschta 1989, Marsh et al. 2001), and these studies suggest that maximum scour can be predicted around instream wood structures (Marsh 2001, Wallerstein 2003). Results from the Granite Creeks revealed that the scour-flow relationship was not as simple as these flume modelling exercises predict. Long, deep meso-habitat scale features did not form, and the pools that did form were much more variable than expected (in space, and time). This variation was driven by the influence of geomorphic features and debris build up on local hydraulics, as well as a complex streamflow-scour relationship. These results are in marked contrast to the results obtained from gravel-bed streams in which large structures with appreciable blockage ratios were introduced, resulting in the formation of persistent meso-habitat features (Brooks et al. 2006, and Section 3.3). The question still remains as to whether large structures in sand bed systems can induce more persistent scour pools.

Scour pools in the Granite Creeks experiment were shown to infill and re-scour with different magnitude flows. Similar patterns of scour and deposition with time have been reported in other sand-bed stream restoration trials (Shields et al. 1995). Real-time monitoring in the Granite Creeks and lower Snowy River, provided further evidence that flow-scour model predictions were far too simplistic for predicting resultant scour pools, but were probably realistic for predicting maximum scour. It was demonstrated that pools sometimes scoured as flows increased, while other times they filled, and vice versa. These dynamics were further complicated by orientation of debris and reach geomorphic conditions.

It was concluded that such dynamics are not well represented by engineering theory. Much of the theory predicting scour around instream structure is concerned with peak flows, maximum scour depths, and structural failure. This type of information was found to be of little use to ecologists and in habitat applications. Rather, it was suggested that the full range of pool scour and fill needed to be known for key points in an organism's life cycle. It was thought that the probability of wood structures providing habitat at key times is increased with the installation of multiple structures.

7.5 Anchoring strategies

7.5.1 ELJs in a gravel-bed river

The standard approach for anchoring ELJs in gravel bed rivers is the excavation of the whole structure into the bed, and the partial burial of the structure once completed. The stability for the ELJ is predicated on the whole structure acting as a discrete cohesive entity, in which the frictional resistance afforded by the total mass of the structure exceeds the drag force imposed by the flow acting on the structure cross section exposed to the flow. A full explanation of the force balance analysis is outlined in Section 7.7.

For situations in which channel degradation has created conditions which are more inhospitable for wood stability than had naturally existed, such as incised channels or where large trees are no longer available, artificial means of stabilisation may be necessary. A quantitative assessment of site conditions and a force balance analysis can provide the means to evaluate the stability of a proposed wood placement and help determine where artificial ballast is appropriate (Abbe et al. 1997, D'Aoust & Millar 1999, 2000; Castro & Sampson 2000, Shields et al. 2000).

To cable or not to cable?

In gravel bed rivers, experience has shown that stable structures can be built without any cable at all. For piece of mind, however, some cable can be used to help secure the top layer of logs in place. When cable is used it should only be used to secure logs tightly to one another, or directly to rock ballast so that all the components act as one unified structure (D'Aoust & Millar 2000). It is only necessary to secure the top layer to the layer below as it would be virtually impossible to remove the upper two layers from the structure.

Cable anchoring (e.g. dead-man or duck-billed anchors) have been used in wood placements (Fischenich & Morrow 1999) in the USA, however they pose significant risks that should be considered. A flexible medium such as a cable will not prevent wood from moving up and down, or side to side, with fluctuating stage or turbulence. Movement of the wood will move the cable, and an oscillating or vibrating cable will tend to cut away the material within which it is set. The cable can become exposed to create an entanglement hazard, or simply fails and liberates the log that it was intended to secure. Stable wood structures can be designed without the use of any cable (Abbe et al. 1997, 2003; Brooks et al. 2001, Brooks et al. 2004).

Experience with duck-bill anchors has not found them to be particularly successful. An example where this approach was trialled was an experimental project conducted by the United States National Sediment Laboratory on Little Topashaw Creek (Shields et al. 2003). In this study, large wood was anchored by cable stretched over wood piles and attached to soil anchors. After several years and numerous floods, 21% of the structures anchored using soil anchors were destroyed because the soil anchors failed, compared with a 33% failure rate for those structures not anchored. The reason for failure of the soil anchors is not clear, although it is likely to be because the soil anchors are rated for a static load rather than dynamic loads. When attached to a flexible cable in fast flowing water, the cable would tend to vibrate, allowing the anchor to work its way to the surface in unconsolidated sediment (see http://ars.usda.gov/Research/docs.htm?docid=5533).

7.6 Stabilisation using piles

Piles are commonly used for securing structures in riverine and marine projects. Piles are very effective at supporting a vertically applied load, however, they can also be used for securing wood where the applied load is largely lateral. Design specifications for pile depths are somewhat arbitrary because in practice the size of piles and pile driving depth is often determined by the available machinery, piles and depth of sediment to bedrock. To determine the ideal depth that piles should be driven, the first step is to determine the maximum depth of scour predicted at the design discharge. Once this is established, the problem becomes one of determining the depth required to prevent rotational displacement of the pile under a given lateral load.

A freeware program called LLP99 created by Arnold Verruijt from the Delft University of Technology (http://geo.verruijt.net/), can then be used to determine the minimum pile depth required for a given lateral load. The lateral load can be determined for the whole structure as outlined in Section 7.7, and the load distributed between the number of piles used to secure the structure. A worked example of the LLP99 calculations is shown in Appendix B.

7.7 Structure stability analysis

7.7.1 Overview

The great efforts river engineers and others took to remove wood from rivers is testament to the natural stability of logs in rivers. Anecdotal and documentary evidence from people who have been involved with the removal of ‘snags’ attests to the fact that once logs become wholly or partially buried within the bed substrate they are extremely difficult to remove (e.g. Ruffner 1886, Russell 1909, McCall 1984). Nevertheless, logs can and do move within rivers, particularly in the period immediately following their recruitment to the channel. Methods are now well established for assessing the stability of logs and log jams (or multiple log structures) in alluvial river channels (D’Aoust & Millar 1999, 2000; Abbe 2000, Shields et al. 2000, Brauderick & Grant, 2000), and the designs included within this report incorporate aspects of each of these approaches in both the design conceptualisation and the stability analysis.

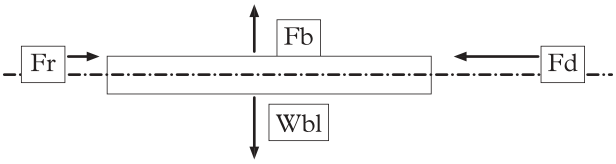


Figure 32. Conceptual model of forces applied to a cohesive structure within a river channel.

The key consideration when designing a stable log structure is to consider the circumstances under which the structure will fail within an alluvial river. It will fail when:

- buoyant force of the logs exceeds ballast weight,
- the net imposing forces on a structure exceed the net resisting forces,
- scour undercuts the structure and it disaggregates.

The forces acting on a log or structure within a channel can be represented by the simple conceptual model (Figure 32) where flow is from right to left.

Where Fb = buoyant force; Wbl = weight of ballast material; Fd = total drag force; Fr = friction between the total structure and the river bed. (Note: ballast material includes the weight of overburden associated with burial — assuming the material remains in place during a flood.) In this, no additional consideration is given to the anchoring effect of the key log root wads and, as such, it is a very conservative model, as the root wads add considerable frictional resistance. The anchoring effect of root wads is considered in the single log stability model.

According to model above, if Fb > Wbl the log is buoyant and therefore there is nothing to resist the imposing drag force. Even if a log has a large root wad, if the log is buoyant, then any additional frictional resistance offered by the root wad in the bed is negated. Thus, buoyancy is a major concern for log stability.

It is often assumed that Australian timbers are denser than water and, therefore, log buoyancy is not an issue in Australia rivers. This is a fallacy. Many Australian hardwoods, including species like river red gum (*Eucalyptus camaldulensis*) have dry densities that are less than the density of water (1000 kg m^{-3}) and can float when fully desiccated. From an engineering perspective, log structures must be designed for the worst case scenario. The worst case scenario from a log stability perspective is the situation, which commonly occurs in Australia, where a river dries out completely for an extended period of time, therefore, allowing the logs to fully desiccate. Under these circumstances wood density is represented by the dry density alone. If drought breaking floods then overtop the logs/structures before they have time to re-hydrate, also a common occurrence, the timber at this point may very well be buoyant. This is why log jams do (or did) form in many Australian rivers. Unless it can be assumed with complete certainty that a log structure is never going to dry out, the dry density should be used in any stability calculations.

It must also be remembered that many Australian timbers are subject to termite and borer attack, and timbers sourced for use in rehabilitation projects might be partially hollow or have significant portions of their total mass that is partially decayed and, as a result, of lower density than the reported density data for the species. Timber will also decay through time because of microbial attack and become less dense. For both these reasons, it is best to adopt a fairly conservative approach to structure design, and use conservative (i.e. low) density values in the stability analysis.

Of the three failure mechanisms identified above, the first and second mechanism are analysed as part of the overall force-balance analysis. The prediction of failure due to scour is the most difficult, due to the poorly developed theoretical basis of scour prediction around complex obstructions. The prediction of maximum scour depth is determined from one of the methods outlined in Section 6.2.3. It should be remembered, however, that because most of the structures are attached to the bank it is highly unlikely that they will scour uniformly around or under the entire structure. Indeed, it is most likely that deposition will occur within the distal (bank side) and downstream portions of the structure, while scour will occur upstream and around the streamward edge of the structure. Experience to date shows that it is highly unlikely that scour will occur under more than a third of the total width of the structure during a large flood that overtops a structure by several metres (pers obs, and Tim Abbe, pers comm.).

7.7.2 Computational procedure for force-balance analysis

Two types of analysis can be performed when assessing the stability of wood reintroduced into streams: multiple log structures or log jams, and single logs. Single log stability analysis is the most appropriate method for assessing the stability of single logs used as toe revetments (see Appendix B).

Multiple log stability assessment

In this assessment the log jam is treated as a single coherent entity and a force-balance analysis is performed according to the following assumptions:

- The imposing force is due to the drag force associated with the cross sectional area of the structure obstructing the flow. The worst case scenario is assumed in which the full height of the structure is exposed to the flow, including the buried portion, where the structure is completely scoured. The full structure width is generally not used, as it is assumed that the portion buried within the bank will remain so.
- In the simplest analysis, the resisting force is a result of the net downward force associated with the weight of the ballasting gravel that is used to backfill the structure less the timber buoyancy times the bed material friction angle. It is assumed that the structure is roughly rectangular in shape, one log wide and one log long of whatever width is deemed appropriate for the structure in question.
  The buoyant force is a function of the total timber volume contained within the structure. The volume of each log can be determined from the length and mean diameter of the logs (note: it is not necessary to use a taper model for calculating the wood volume for Australian hardwoods, as most tree boles of Australian eucalypts — the timbers used in these structures — have relatively little taper in the main part of the trunk).
- Structure height is a function of the number of layers of logs used, and is essentially the sum of the log diameters with some extra at the top for the protruding root wads. A fairly conservative ratio of root wad diameter has been assumed — this being 1.5 x mean log diameter.
- The volume of the structure — and hence the volume of gravel ballast in the force balance analysis, is equal to the width x length of the whole structure x the structure height, but not including the extra height associated with the protruding root wads as it is assumed that the structure will only be back filled to the level of the upper horizontal logs.
- To account for that fact that most structures are going to be located on concave banks, and that in most cases only the mean one dimensional velocity will be available, velocity is increased by a factor of 1.5 times to account for the higher velocities encountered in the outer portion of a channel bend (after Shields et al. 2000).

Computational procedure (after Shields et al. 2000, D'Aoust & Millar 1999, 2000)

In light of the general description of structure design provided, the following is a description of the computational procedure for undertaking the force balance analysis of a multiple log structure. The drag force on the structure is equal to:

EQUATION 1

$$F_D = 0.5V^2 A\rho C_D$$

where: F_D = drag force in N; V = approach velocity of the design discharge $m\ sec^{-1}$; A = the cross sectional area (m^2) of the structure projected into the flow; ρ = fluid density (1000 $kg\ m^{-3}$); C_D = drag coefficient, which is assumed to be 1.2 — which is at the upper end of a range of values quoted in Gippel et al. (1996), Shields et al. (2000), D'Aoust & Millar (1999).

The buoyant force associated with the total volume of wood in the structure is represented by:

EQUATION 2

$$F_B = \left(\sum{}^{n}K\right)\rho g(1-S_L)$$

where F_B is the buoyant force N; K is the total volume of n logs; ρ = fluid density (1000 $kg\ m^{-3}$); g is gravitational acceleration (9.81 m $\sec^{-2}$); S_L is the dry density of the logs (g cm^{-3}). This relationship doesn't account for the volume of wood contained within the root wad portion of the tree, as this is assumed to be neutrally buoyant due to the sediment contained within the roots — a conservative assumption as the root wad is most likely to have a net negative density.

The volume of each log (K) can be calculated simply according to:

EQUATION 3

$$K = \pi l\left(\frac{d}{2}\right)^2$$

where l is the log length (m) and d is the diameter of the log measured in the log centre. This relationship assumes that log taper is negligible, which is a reasonable assumption for the majority of Australian eucalypt tree boles.

The overall immersed weight of the ballast material within the structure is a function of the total structure volume less the volume of wood. It can be calculated by:

EQUATION 4

$$W_{BL} = \rho g\,(S_S-1)\left(\psi - \left(\sum{}^{n}K\right)\right)$$

where W_{BL} is the ballast weight (N); ψ is the structure volume (m^3); and S_S is the specific gravity of the gravel ($g\ cm^{-3}$) — which in this case is conservatively assumed to equal 2.0 ($g\ cm^{-3}$) to account for the void space between the clasts.

The effect of friction between the total structure and the river bed is a significant component of the force resisting structure movement. The critical frictional force to initiate sliding of the whole structure can be estimated by:

EQUATION 5

$$F_{FS} = (W_{BL} - F_B)\tan\phi$$

where ϕ is the friction angle of coarse gravel and is estimated to be 40° (after D'Aoust & Millar 2000).

To determine whether a structure will be stable two conditions must be met.

First, the structure must be shown to have a net negative buoyancy, and this can be assessed using a factor of safety analysis. A factor of safety (FS) is defined as the ratio of resisting forces to imposing forces. Hence values of FS > 1 indicate the structure will be stable, while values < 1 indicate the structure may fail. The FS with respect to buoyancy can be represented by:

EQUATION 6

$$FS_B = \frac{W_{BL}}{F_B}$$

If $FS_B > 1$ then the factor of safety with respect to sliding can be represented by:

EQUATION 7

$$FS_S = \frac{F_{FS}}{F_D}$$

Permeable, non-embedded structures

The forces acting on a non-embedded structure are the same as those acting on the impermeable ELJ, except in this case the analysis aims to determine the mass of ballast required to be attached to the structure (i.e. as blocks of rock or concrete), for a given factor of safety, under given design discharge conditions. For the purposes of the analysis a worst case scenario is assumed whereby the upstream side of the structure becomes clogged with transported debris, making the structure impermeable. As with the previous analysis, the drag force Fd imposed on the structure is simply a function of the structure cross sectional area (equation 1). Fb is calculated in the same way (equation 2) and W_{bl} can be calculated using an iterative procedure to determine the F_{FS} for a desired FS_S. The analysis assumes that the ballast is firmly attached to the structure and that they are a coherent unit. Structure failure (i.e. sliding failure), requires the movement of the combined mass of all ballast blocks plus the structure.

Single log force/balance analysis

The forces acting on a single log with a root wad, where the log is perpendicular to flow with root wad facing upstream, can be calculated as follows (after D'Aoust & Millar 2000).

Assuming that the root wad portion of the log can be represented by the volume of a cone, the buoyant force acting on this log can be represented by:

EQUATION 8

$$F_{BL} = \left(\frac{\pi D_L{}^2 D}{4} + 0.33\pi\,\frac{D_{RW}{}^2 L_{RW}}{4}\,(1-\rho)\right)\rho g(1-S_L)$$

where F_{BL} is the buoyant force on the single log (N); D_L is the diameter of the log measured at the centre (m); L is the log length (m); D_{RW} is the average diameter of the root wad (m); L_{RW} is the length of the root wad (m) and S_L is the specific gravity of the log ($g\ cm^{-3}$); ρ is the porosity of the root wad.

Assuming the surface area of the root wad subject to drag is represented by a disk of diameter D_{RW}, the drag force acting on this disk can be written as:

EQUATION 9

$$F_{DRW} = C_{DRW}\,\frac{\pi D_{RW}{}^2}{4}\,\frac{V^2}{2}\,\rho\sin(\beta)$$

where V is the average flow velocity (m $\sec^{-2}$), β is the angle of the rootwad with respect to the direction of flow in either the horizontal or vertical plane (assumed by default to be 90°); C_{DRW} is the drag coefficient for the root wad.

Single log partially buried

The buoyant force and the drag force on a single log can both be counteracted if the log and root wad is buried.

In the case where the root wad is partially buried the passive earth pressures exerted on an idealised root wad can be defined as:

EQUATION 10

$$P_P = K_P \frac{\gamma h^2}{2}$$

where P_P is the force per unit width of root wad; K_P is the coefficient of lateral passive earth pressures i.e.

EQUATION 11

$$KP = \frac{1 + \sin\phi}{1 - \sin\phi}$$

; γ is submerged weight of the substrate (Nm^{-3}), and h is the depth of the buried portion of the root wad (m), ϕ = substrate friction angle.

If it is assumed that the end area of the root wad is embedded in the substrate and subdivided into a number of wedges of height h (which will be a series of arcs across the buried root disk < the maximum burial depth at the centre of the disk) and width w, the magnitude of the added resisting force is equal to:

EQUATION 12

$$F_P = \sum P_P w_{(i+1)}$$

In the situation where a log is rotated into the bed at an angle θ so that it is buried within the substrate — we can assume that the sediment burying the log is ballasting it to an extent equivalent to the weight of the overlying sediment (in fact it will be greater than this due to the friction between the particles). The ballast effect of log burial can be represented as:

EQUATION 13

$$W_{BL} = \frac{DL^2 Sin\,\theta \rho g (S_S - 1)}{2}$$

In a similar fashion to the situation with the log jam, the stability characteristics of a single buried log can be represented as a Factor of Safety:

EQUATION 14

$$F_S = \frac{W_{BL} - F_{BL}}{F_{DRW} - F_P}$$

Clearly a single log with a specific gravity <1 can only be regarded as being stable within a river channel if it is partially buried, or the log is of such dimensions that it is not fully inundated. For the purposes of this analysis we will assume that the log is fully submerged and that the log is at least partially buried, otherwise, the analysis is similar to the multi log jam analysis, with the exception that the effect of the root wad burial is included here. In reality this should also be included in the log jam assessment as the basal logs have root wads that are buried within the river bed.

EQUATION 15

$$FS_{SB} = \frac{W_{BL}}{F_B}$$

If $FS_B > 1$ meets then the factor of safety with respect to sliding can be represented by:

EQUATION 16

$$FS_{SS} = \frac{F_{FS} + F_P}{F_D}$$

7.7.3 Example of spreadsheet computation procedure

Explanatory notes

Refer to Section 7.7 for detailed description of the variables and computational processes. The following is an explanation of the spreadsheet shown in Table 5 (overleaf) that detail the specifications for each structure. Each spreadsheet is arranged in two parts:

1. The upper section details the log specifications for each structure — layer by layer. **These specifications, coupled with the reach plans and the generic structure models, provide all the necessary details to construct each structure.**
2. The lower section provides the details of the structure stability analysis.

   The upper section is relatively self explanatory, however, the following assumptions have been made:
   - root wad diameter (D_{RW}) has been assumed to equal 2.5 x average log diameter,
   - root wad length (L_{RW}) has been assumed to be 2 x average log diameter,
   - cumulative height does not include the height of the protruding root wad — it is the cumulative height of the log diameters — as such total structure height will be slightly higher than that reported here,
   - cumulative width is the sum of the root wad diameters of the key logs x 1.2 — to allow for some space between logs
   - the structure dimensions (i.e. cross sectional area of the structure projected into the flow) are ~0.75 x the cumulative width x total structure height. This assumes that around 25% of the structure is buried into the bank and is not exposed to the flow. Note that the proportion of the structure projected into the flow varies slightly from structure to structure, depending on local site conditions.

Computational procedures for each of the parameters presented in the lower part of the spreadsheet are detailed in Section 7.7.2.

Rack log numbers are calculated on the assumption that the logs have a mean diameter of 0.25 m and that to allow for a stack of logs to be arranged in a stable configuration, there will need to be more logs at the bottom, tapering up to the top of the stack. Rack log numbers are calculated according to the relationship:

no. of rack logs = (structure height (m)/0.6)^2 x 2

Table 5. Example of spreadsheet used for undertaking a force balance analysis.

Structure 9.2 — Budget cost									
Layer	Type	Log length (m)	Av. diameter (m)	No. of logs/layer	Log volume (m^3)	D_{RW}	L_{RW}	Cumulative height	Cumulative width
1	Key footer	9	0.35	1	0.87	0.875	0.7	0.35	
2	Key logs	10	0.55	4	9.50	1.375	1.1	0.90	6.6
3	Cross spaners	9	0.35	2	1.73	0.875	0.7	1.25	
4a	Longitudinal logs (row 1)	10	0.45	4	6.36	1.125	0.9	1.70	
4b	Longitudinal logs (row 2)	10	0.35	3	2.89	0.875	0.7	1.70	
5	Cross spaners	9	0.35	4	3.46	0.875	0.7	2.05	
6a	Longitudinal logs (row 1)	10	0.45	4	6.36	1.125	0.9	2.50	
6b	Longitudinal logs (row 2)	10	0.35	3	2.89	0.875	0.7	2.85	
7	Diagonal logs	10	0.35	2	1.92	0.875	0.7	2.85	
	Total logs			27	35.98 Total wood volume				
Structure dimensions		Width (m)	Height (m)	Length (m)	XS area (m^2)	Volume (m^3)			
		7	2.85	10	19.95	199.5			

Shields Method for determining stability of whole structure. (Design of Structure 9.2 is for an impermeable deflector structure protruding ~2 m above bed, i.e. structure excavated into bed)									
Backfill volume required (m^3)		148.7							
Immersed weight of backfill (Nm^{-3})		W_{BL}	−1458257	(= a specific gravity for gravel of 2.0)					
S_{wood}	Fb	Fb_{net}	Velocity*	Structure area (m^3)	C_D	Fd	Friction angle (degrees)	Friction angle (RADS)	F_{FS}
0.9	35301	-1422955	6.51	19.95	1.2	507290	40	0.7	-1194001
Factor of safety (buoyancy)		41.31							
Factor of safety (sliding)		2.35							
Rack log requirements		Structure height (m)	Mean rack log diameter (cm)	Number layers required	Stack taper allowance				
		2.85	0.25	11.40	45 (total rack logs)				
Rack log requirements (continued)		Log length (m)	Diameter (cm)	Diameter (m)	Log volume (m^3)	D_{RW}	L_{RW}		
		9	20	0.20	0.28	0.400	0.4		
					12.76 Total rack log volume				

* Velocity based on modelled mean discharge for a 20 year ARI event x 1.5 to account for higher velocity in channel thalweg (after Shields et al. 2000).

chapter

8

Monitoring and evaluation

The extent and type of monitoring you choose to undertake at your rehabilitation site will very much depend on your project objectives, the evaluation methods, the scale of the project, the budget and the commitment of people involved with the project who are prepared to undertake monitoring on an ongoing basis. Some level of monitoring and reporting will be required for every project, especially where public funding is used. The type and length of monitoring required to fully evaluate a wood reintroduction project (for example that undertaken for the Williams River project), is time consuming, quite expensive and may need to continue for several years until the structure(s) have been tested by flood flows. This level of monitoring and evaluation may be justifiable only for larger (more expensive) projects costing $100,000 or more, and it is essential that the process be built into the project planning and budget from its commencement. This type of evaluation, made publicly available, will be vital for continued improvement in the design and construction of ELJs, as well as for building confidence in their value and use.

If you are setting out to scientifically "prove" that your strategy has had a measurable ecological and/or geomorphic benefit, you will need to set your project up as a standard Before After Control Impact design experiment (see Downes et al. 2002), ideally with multiple controls. If you are wanting to measure changes to meso- or micro-habitat complexity, you will probably need to consider undertaking a fully 3D reach survey as this is the most effective method for demonstrating changing complexity (see Brooks et al. 2006). In most cases this level of detail will not be possible, but there are a range of things that can be done that will provide some means for evaluating whether or not your project has achieved its objectives, providing valuable information for funding bodies in the future about the efficacy of different approaches to river rehabilitation.

Photo 35. Bank deflector jam that appears to have failed, but in fact is still there — only buried. This is a case of the structure being over designed and too effective — to the extent that it initiated so much deposition that the whole structure was buried and the channel shifted laterally by ~20 m. In this case the structure is still performing its primary engineering role — even while buried. It provides woody substrate in the hyporheic zone, and a source of slow release carbon to the system. In this instance we may need to reconsider what is meant by "failure".

1. Ensure that you produce some sort of written report in which you state very clearly what it is you are trying to achieve. This report would ideally include your baseline survey data, plans and reach maps, as well as a series of photographs. The data you have collected for undertaking your project designs can serve as the basis for your monitoring strategy.

2. To ensure that your reach survey can be repeated, make sure that you establish some permanent bench marks that are out of the channel (and hence are not likely to be destroyed by a flood or buried, nor affected by grazing stock or other land uses). Each of your cross sections should have permanent benchmarks set up with GPS coordinates — so they can be relocated. Steel pickets or buried metal plates are good as they can be relocated with a metal detector — but make sure your star pickets are well labelled so they are not recycled for fencing materials!
3. Establish georeferenced (and documented) photo points (i.e. points that you can return to repeatedly to take "after" photos in the future). If you have access to a GPS record, the GPS coordinates of your photo points — and other information that might help people in the future interpret the photos — e.g. date and time and flow stage (if known).
4. If you are undertaking ecological monitoring of any sort, a "multiple lines of evidence" approach should be adopted (Downes et al. 2002, Howell et al. 2004). Expert advice will need to be sought if you wish to assess the impacts of the rehabilitation on fish or macroinvertebrates.

Photo 36. "Failed" cross-spanning log bed control structure on the Williams River. This structure failed when one of the key abutting logs in the centre of the channel was removed in a flood. Note, the abutting log jam in the foreground is still functioning and most of the logs in the channel centre are still providing good habitat value. This structure has, therefore, only failed in an engineering sense.

8.1 Dealing with "failure"

It is inevitable that some of the structures you build will "fail" in one form or another, even if it is only losing some of their logs. Do not despair. This is inevitable, as it is not possible to design and build structures on the budgets that most river managers have to work with that will withstand everything that the river can throw at it. Depending on what your overall objectives are, in many cases this may not matter too much either, particularly if the logs that have moved are still within the channel and forming some sort of in-stream woody habitat. Even structures that are designed with a purely engineering purpose in mind (e.g. bank erosion control) can withstand a certain amount of disintegration and still perform the primary function for which they were designed. It is important to remember that in most degraded agricultural streams, any wood in the stream is good wood from an ecological point of view. What you will always need to weigh are the risks associated with that wood moving and causing problems to infrastructure or human safety.

chapter 9

Building log structures

By the time you get to this point in the process you will now have a concept plan, some structure designs and are no doubt rearing to go. One of the first things to come to terms with when you begin the construction process is that there is no tidy way of implementing a major in-stream rehabilitation project. Doing river rehabilitation is a bit like performing open heart surgery — it's a messy business — but you have to make a mess to treat the patient. Once you start driving 22 tonne excavators around in the river bed, significant amounts of fine sediment are going to be liberated into the water column. Nevertheless, there are things that can be done to lessen the impact and minimise the disturbance. In the following Chapter an outline is provided of some of the practical and logistical issues that will need to be considered in planning and carrying out the construction phase of your project. Where appropriate we outline some of lessons learnt and practical tips from the construction of over 70 structures of varying shapes and sizes across a range of sites.

Photo 37. DFJ construction in full swing — Williams River, NSW.

9.1 Construction phase planning

Having made it this far through the process you will already have undertaken a considerable amount of project planning, given that you will have selected a site, undertaken site surveys and developed a rehabilitation plan. The following Chapter should serve as a checklist of things relevant to the construction phase that need to be considered fairly early on in the planning process. It is too late to start thinking about these issues on construction day.

9.1.1 Professional indemnity insurance

Before you even think about doing anything in a stream, you need to ensure that you are adequately covered by your own, or your employer's, professional indemnity and liability insurance. This also applies to the persons or organisation developing the designs for the rehabilitation strategy. If you are unsure whether you are covered by your employer's insurance seek legal advice.

9.1.2 Landholder approvals and maintenance agreements

Having already completed the initial site selection work and undertaken preliminary surveys, it is assumed you will have had considerable discussions with the landholder(s) about the proposed rehabilitation strategy, and ideally engaged them in the whole project from its beginning. Experience tells that the most successful rehabilitation projects are those initiated by, or at least significantly involving the landholders on whose land the rehabilitation will be carried out. A range of issues will need to be sorted out with the landholder before the construction process can go ahead.

- *Vehicular access tracks*. Consideration should be given to accessibility if wet weather occurs during construction. It may even be necessary to lay road base in certain areas to ensure that trucks delivering logs do not become bogged. Bear in mind that what may look like firm ground under normal circumstances may be a different story once it has been driven over by a fully laden semi-trailer a few times. You may also need to consider the issue of overhanging trees and branches — as most truck drivers will not want to have their trucks scratched by protruding branches. On the site itself, it is a good idea to restrict vehicle movement to certain areas (i.e. by cordoning off the site) to prevent the entire area being completely churned up by unnecessary vehicle movement. Small trees or shrubs that you want protected, or infrastructure such as pumps and pipes, should be clearly marked.

- *Log storage area* (depending on the size of your project this can take up considerable space). The ideal situation is to have a large area where your logs are stored so that during construction they can be spread out and sorted into size classes ready for construction. When you are building log structures you will need to be able to access logs of different sizes and with different characteristics throughout the process.
- *Stock management during and after the construction phase.* Given that revegetation is an integral part of a wood reintroduction program, it is critical that stock are excluded from the river channel and adjacent riparian area beyond the construction phase if plantings are to succeed.
- *A maintenance agreement* should be signed with the landholder (unless someone else is making a commitment to carry out the necessary maintenance) to ensure that fences are maintained — particularly in the event of floods; and that during periods of drought, trees are watered. If funding is going to the landholder or to a land/rivercare group, the funding should be contingent on such an agreement being formalised.

9.1.3 Permit requirements

- All states and territories require permits for doing in-stream works and, in some cases, you may need to complete an environmental impacts statement. You will need to check with your local state, territory or catchment agency for details. Bear in mind the processing of such permits may take a considerable amount of time, so allow plenty of lead time to sort this out.

9.1.4 Log sourcing

- As mentioned previously, a supply of logs will be one of the major constraints on your project. Indeed, it may be such a constraint as to necessitate the complete reappraisal of your project objectives and your structure designs. So while it is great to develop an ideal plan and undertake designs and stability assessments based on these plans, if you cannot then source the logs as specified in your plan, you may have to go back to the drawing board and start the process again, based on what you can get. It is a good idea to develop an initial draft concept plan with approximate log specifications, then see if you can source these logs. Inevitably, you will end up taking what you can get, within some broad specifications, and design the structures and the reach strategy based on what is available (within your budget). With a bit of luck you might be able to source logs where you are not required to pay for the timber, and will therefore only have to bear the cost of transport and handling. Bear in mind that this will still be a considerable cost. The handling costs at either end will often be the biggest component of the total project cost as you will often need an excavator at either end. The distance the timber has to be transported may not be the major cost, except that it increases the waiting time for your excavator at either end. If possible, a good way to transport the timber is in a semi-trailer tipper, because this way you will not need an excavator for off loading.
- From experience to date, we have generally been able to source timber from within 2 hours (each way) travel time of the project site. In some cases where we were desperate, we have transported timber from up to 4 hours away.
- Logs should be sourced from sites where tree clearing has been approved. Given that there is still plenty of land clearance occurring for roads, urban and other development in Australia, this should not be a major problem in most regions — although securing large trees will be a problem in some inland regions. The key in many instances is securing the logs before they are burnt or turned into woodchips. In the future, securing logs from land clearance sites will (hopefully) become more of a problem, and it may well be wise to begin planning for this eventuality by establishing plantations earmarked as future log sources.
- In an ideal world you would attempt to use timber species that were representative of the primary riparian tree species in the region. However, given that very little riparian forest remains in some areas, and the few areas that do remain will often be rare or threatened remnant communities, it is not advisable to attempt to source timber from these sites. This means that you will inevitably be required to use dryland eucalypt species (i.e. non riparian/floodplain species), and you probably won't be able to be too selective about the species, given that you will probably have to take whatever you can get. There is

Photo 38. A universally rotating log grab makes log placement a much easier and more efficient process.

no evidence that the species used in projects thus far have presented problems from an ecological point of view. If you have the option of choosing between species, the choice should be based on wood density — i.e. use the hardest and heaviest wood you can find (see Table 4) providing it is a good quality native hardwood. The use of exotic species such as willow or camphor laurel must be avoided on engineering grounds as both are extremely light and of little use in log structures as they are difficult to stabilise. Both are also invasive exotics that are capable of resprouting when buried. There are also concerns about the toxicity of camphor laurel timber to aquatic biota. In the case of willow, this wood also decays extremely rapidly, turning to useless pulp within as little as five years. Much the same can be said for the native river oak (*Casuarina cunninghamiana*), which has a low density and a high decay rate; so at best this should be used only for structure augmentation, or for structures with a relatively short design life.

- Given that you want the timber with good quality root wads still intact, the best approach is to identify areas earmarked for clearance before the clearance begins, and to see whether you can have some influence over the way the trees are cleared. Forest cleared rapidly with large bulldozers often tends to shear the trees off at the base (particularly the smaller trees), not leaving you with much of a root wad. Trees cleared with smaller dozers or excavators seem to end up with a more intact root wad — but obviously this is a function of the size of the trees, the soils they are growing in, and the area of land being cleared. Careful handling after clearance is also important.
- Typical sources of good quality logs can be found at:
  - highway diversions or widening sites,
  - suburban sub-divisions,
  - clearings for power line easements,
  - clearing for fence line easements, and
  - clearance for new open-cut mining operations.

  In many of these cases it should be possible to negotiate favourable deals with the parties undertaking these clearance operations, particularly if you make it known what they are being used for. Most people are happy for the timber to be put to a good use like river rehabilitation.

Photo 39. A 4WD tractor/loader like this one is an essential piece of equipment at a log structure construction site. It can be used for moving logs around on site, backfilling structures and regrading the site.

- To ensure you get first dibs on logs at new clearance sites (and hopefully to get wind of clearance before it takes place), the best people to get to know are the tree clearance contractors in your region. They will be tendering for any clearance in your area, and can even build in the "public good" end use into their tender. In most states and territories, clearance of more than a couple of hectares will require a permit, so making friends with your local tree clearance permitting officer is another good way to find out about prospective tree clearance sites before they happen.

9.1.5 Site preparation

- *In-stream access* for heavy machinery is something that needs to be considered very early in the project planning process, as lack of access may well limit what you can do at the site. Keep in mind that at the very least you are going to need a 20 tonne (or larger) excavator to use for the construction process.
- *Access tracks*. Depending on your site, it may be necessary to prepare access tracks to allow machinery to gain access down into your river channel. If tracks have to be cut down the bank, ensure they are cut on the inside bend, oriented down stream to minimise the potential for initiating new bank erosion. Bear in mind that the most efficient way to move logs is for an excavator or front-end loader to pick the logs up in the middle and carry them sideways. As the average log length is around 10 m, you need a fair bit of space — although it is not recommended that you clear riparian vegetation just for this purpose — there are ways of manoeuvring logs in restricted areas.
- *Log storage areas* will need to be organised as close as possible to the sites where you are constructing your log structures, but not so close that they get in the way. Remember to have enough space in your log staging area to sort logs and ideally have them laid out so that you can pick and choose individual logs as they are needed. Given that you are always going to be working with a motley array of log shapes and sizes, when you are constructing a log jam it is an exercise in selecting specific logs for specific locations in your structure, depending on what you have available. To ensure the construction process is as efficient as possible, it is good to be able to pick and choose between your logs without having to dismantle a whole pile to get to the one you want.
- *Construction of machinery work platform*. When building in-streams structures, by necessity one has to get the machinery as close to the site as possible — which will generally mean getting right down into the bed of the river. Depending on whether you have permanent water in the channel at your site and depending on its depth, it may be necessary to construct a platform into the water that will allow your excavator to be located within reach of the structure site. If you are building a bank erosion control structure at a steep cut bank it is usually fairly easy to build a platform out from the point bar on the inside of the bend. It is generally not a good idea to attempt to do any work with heavy machinery from the top of a cut bank due to the risk of bank collapse — and risk to the machine and driver. When working in-stream with heavy equipment, beware of unconsolidated sediment!! (Photo 41)

Photo 40. Log staging and sorting area in a paddock adjacent to the rehabilitation site on the Williams River, NSW.

Photo 41. Check the substrate stability before you enter!
Photo courtesy Ian Dixon.

9.1.6 Machinery and site logistics

The key for a smooth construction process and keeping your project on budget, is having the right equipment to do the job, and having everyone working on the site suitably briefed or supervised to ensure the process progresses as efficiently as possible. For a standard sized project where you may be building half a dozen structures comprising several hundred logs, the following is a basic equipment list:

- 1 x 20–25 tonne excavator with various attachments including a log grab, a bucket and a hydraulic pile driving hammer,
- 1 x 4WD tractor/loader with a winch and a grab bucket,
- 1 x chainsaw,
- 1 x power auger (for drilling holes on logs to thread cable through — if required),
- miscellaneous fencing and tree planting equipment,
- two-way radio communication between all machinery and on-ground supervisors.

Experience has shown that at the very least you will need a 20–25 tonne excavator with a log grab, as well as a medium and/or a large bucket for excavation and backfilling. A fully rotating log grab (if you can get one) will make the process of placing the logs much easier and more efficient than a fixed grab. The downside of a

Photo 42. A 22 tonne excavator with a non-rotating grab offloading logs (without root wads) for use in bed-control structures.

rotating grab is they generally can't lift as much weight as a standard fixed log grab. The 4WD tractor/loader will do most of the log moving — supplying the excavator in the channel with the logs as needed. One thing you do not want is the excavator driving back and forth out of the channel to pick up logs. This creates too much disturbance of the bed and banks, is too slow, and is an inefficient use of the excavator's time.

On a larger job a second excavator can be justified to speed things up but only of you have enough supervision to keep both machines busy for the majority of the time — as it becomes uneconomic. If you do have a second excavator you will probably also need a second loader for moving logs around. It is important to consider carefully whether you can justify having, what amounts to, two construction crews on site at the one time. In general, a second crew would only be needed on a particularly large job.

Two-way radio communication is essential to keep the construction process moving as efficiently as possible as well as for occupational health and safety (OH&S) reasons. The ideal way to build each structure is to have a supervisor on ground, in the river, albeit at a safe distance from machinery and with a clear view of the construction site. The supervisor will be in radio contact with the excavator driver, who will be in position next to the construction site, and the loader driver, who will be bringing the logs down to the site. The supervisor will essentially be directing the operators in building the structure according to plan. They will select the logs for each layer, and will help guide the operator placing individual logs, checking they have been placed correctly. If the site is in the water, it might be a good idea for this person to be in waders, so they can feel around with their feet in the water to ensure the logs below the water are sitting correctly. (This is only when the machinery has backed away, and there is no danger of logs falling on the person in the water.)

A chainsaw will be required for cutting piles to length, putting points on them, and trimming them off to the correct length once put in place.

9.1.7 OH&S considerations

Building ELJs can be an extremely dangerous business, particularly if you, and/or the machinery operators, are doing it for the first time. As with any construction site all standard OH&S procedures appropriate to your region will need to be adhered to. You will most likely need to develop an OH&S plan for the site, and all personnel coming onto the site will need to be inducted onto the site. Particular things to consider as part of your site plan include:

- *Spectator management*. Spectators need to be kept well away from the construction area. If onlookers are likely to be present during construction the construction area should be cordoned off with safety tape.
- *Power lines*. Beware of overhead power lines. If there are any in the vicinity, have tiger tails put on them prior to the construction phase or cordon areas off near the power lines.

Photo 43. Warning signs should be erected at your project site to indicate the boundaries of the project area.

- *Personal safety equipment*. Safety vests, hard hats and appropriate foot ware must be worn on site at all times.
- *Two-way radio* contact should be maintained between all drivers and people on ground who are working anywhere near machinery in a supervisory capacity.
- *Accredited operators*. All machinery on site should only be driven/used by properly accredited staff. In particular, chainsaw should only be used by suitably qualified personnel.

9.1.8 Construction procedure — standard ELJ

The following set of schematic diagrams provides a step by step outline of the procedure for constructing a standard bank attached deflector jam with the approximate log dimensions shown in Table 6. Rack log dimensions are not shown in the table. These can be made up of any sizes you have available in abundance, which is usually the smaller logs with dbh of around 20 cm or less.

Table 6. Typical log dimensions for standard ELJ construction.

Layer		Log length (m)	Average diameter (m)	Number of logs/layer	Log volume (m^3)	Effective log volume	Cumulative height
1	Key footer	8	0.35	1	0.77	0.94	0.35
2	Key logs	10	0.65	5	16.59	16.59	1.00
3	Cross spanners	8	0.45	4	5.09	6.20	1.45
4	Longitudinal logs (row 1)	10	0.45	4	6.36	6.36	1.90
4	Longitudinal logs (row 2)	10	0.40	5	6.28	6.28	2.30
5	Longitudinal logs (row 3)	10	0.35	5	4.81	4.81	2.65
5	Cross spanners	8	0.35	3	2.31	2.81	2.65
			Total logs	27	42.22	44.00	Total wood volume

Figure 33. Schematic step by step diagrams of deflector jam (DFJ) construction.

Step 1. Excavate pad and construct check dam to isolate pad from river channel.

Step 2. Place key footer log — with root wad towards the channel.

Figure 33. continued.

Step 3. Place key member logs parallel to the flow, root wads upstream.

Step 4. Place first cross spanning log.

Step 5. Place a row of longitudinal logs angled down between the key logs.

Step 6. Place a second cross spanning log.

Step 7. Place a second row of longitudinal logs.

Step 8. Place a pair of cross spanning logs at the downstream end of the structure.

Figure 33. continued.

Step 9. Place two small longitudinal logs over the two cross spanning logs, angled fairly acutely into the bed at the tail end of the structure. Place a diagonal log butting against the root wads of the outer most logs on the second and third rows of longitudinal logs.

Step 10. Arrange a stack of small rack logs against the upstream end of the structure.

Step 11. Drive a series of piles into the structure to locate all the cross spanning (at least three to four piles should be used per row, driven at least 2 m below the base of the structure). Place one or more locator logs over the rack logs, angled into the bed, underneath all existing logs.

Step 12. Back fill the entire structure with the gravel excavated from the initial pad — leaving the upstream rack logs exposed and the streamward edge logs. Additional gravel can be used from the area immediately in front and to the upstream outer edge of the structure (i.e. the area that will be scoured in the first flood). Regrade the channel back to something similar to the pre-existing morphology). Note the extent of backfill shown in the diagram is slightly exaggerated.

Step 13. Top-dress the backfilled part of the structure and plant with appropriate indigenous species.

9.1.9 Revegetation and stock exclusion

Revegetation and riparian stock exclusion should be an integral part of any in-stream works. As a general rule, at least 10% of the total project budget should be set aside for revegetation and rehabilitation of the site after construction. Some areas that have experienced high levels of traffic, and hence compaction during the construction phase may need to be ripped and replanted at the end of the project. As outlined previously, a maintenance agreement for fences and plantings is essential at any rehabilitation site (learnt through bitter experience — having lost all trees planted at the Williams River site when fences were not repaired quickly enough following a flood). Where large, bank-attached jams are constructed, the actual structure should be planted with appropriate in-channel species (such as *Casuarina cunninghamiana*).

9.1.10 Legal liability issues

In addition to the OH&S issues covered previously, and ensuring you have adequate professional indemnity insurance, there are a number of other major considerations outlined here to help minimise your exposure to a claim of professional negligence:

- *Hazard to river users*. If you are rehabilitating a stream or river that is used by recreational canoeists, rafters or waterskiers, you will need to provide some notification or warning that can be read in-stream, by river users, notifying them of the changed conditions associated with the log structures. Legal advice should be sought regarding the wording of such signage to ensure that you are not accepting liability for any misadventure associated with the structures — but instead are simply warning users of the changed conditions.
- *Flooding*. This is the perennial concern that landholders in particular have with anything in a river, be it vegetation, logs or car bodies. Gippel et al. (1996), however, found that unless you are adding sufficient timber to block the channel cross section by more than 10%, there will be very little measurable change to flood stage. This can be fairly easily tested when you do your Hec-Ras modelling as part of the project design. It should be remembered that your Hec-Ras model assumes a stable bed and, as such, takes no account of the fact that in an alluvial channel if you build a structure that only partially blocks the channel cross section, the channel is likely to scour the unblocked portion to re-establish the channel capacity. Hence, there may be no resultant flow afflux.

  There are two approaches you can take in dealing with the perceptions about flow afflux associated with wood reintroduction into rivers. The first approach, which should suffice in 99% of cases, is to demonstrate in a rational manner, the possible maximum flow afflux associated with your rehabilitation strategy, and to show the small impact this may have on the frequency and duration of flows above a given threshold. In a very small minority of cases, however, nothing you can do or say will convince some people that putting a single log in the river is not going to induce catastrophic flooding and the ruination of all riparian landholders. It is probably wise to avoid undertaking rehabilitation works adjacent to such landholders, unless there are pressing ecological or engineering reasons. If it is essential on management grounds to go ahead at such a site, as long as you adhere to the guidelines outlined in Gippel et al. (1996) and undertake due diligence in the design phase, the onus would be on someone claiming damages for flooding to prove that the structures you have built have increased flood stage over and above normal flood levels to such an extent that they caused damage which would otherwise not have occurred had your structures not been in place. Due to hydrologic measurement errors this would be very difficult to demonstrate, unless you had built a large log weir across the channel.
- *Structure failure and subsequent damage to infrastructure*. While this is highly unlikely to occur, refer to Section 7.2 on selecting a design flood for a full discussion on how the risk associated with structure failure can be minimised. The best way of protecting yourself against legal action associated with property damage caused by structure failure is to ensure you can demonstrate due diligence in fully evaluating the stability of your structures and the risk of failure, and ensuring they are well built.

Photo 44. Example of sign warning river users of changed conditions ahead at the Williams River site.

appendix
A

Alternative log structures

Additional disclaimer

Many of the structures shown here have not been fully evaluated under a range of flow conditions and the examples shown here are offered as a guide only of structure styles that may be suitable for your site. Care should be taken to ensure appropriate design standards are applied in the application of any of the structures shown here or derivates thereof.

Natural wood accumulation — Meander River, Tasmania. Photo T. Cohen.

STRUCTURE TYPE

Log sill +/- abutment jams (gravel bed version)

Description

- Multi log structure complex comprising a buried, multi-log sill, and two small abutment jams
- Generally built as a full channel spanning structure, or between the bank and a mid-channel bar

Purpose

- Bed stabilisation
- Initiation of pool downstream of structure
- Creation of hydraulic gradient to drive hyporheic exchange

Location trialled

Williams and Hunter Rivers, NSW (see photos)

River characteristics

- Medium to high energy gravel rivers
- Catchment area ~200 and 4000 km^2
- Mean annual flood ~170 and ~500 cumecs
- Channel full discharge ~800 and 4000 cumecs
- Gradient 0.0019 and 0.001

Pros or cons

In highly active gravel bed rivers, log sill structures are highly prone to failure by scour undercutting the structure or by outflanking of the structure. Abutment jams appear to reduce outflanking failure, and reduce the risk of losing the whole structure from scour beneath the logs.

Performance to date

Of the seven log sill structures built in the Williams and Hunter Rivers, the structures with abutment jams are generally still performing as designed, while those without abutment structures tended to fail through under cutting or outflanking. This is similar to the experience on the Nambucca River (northern NSW) in the mid 1990s where a series of log sill structures were built, virtually all of which failed via under-scour or outflanking within a couple of years (A. Raine, pers comm.).

Captions, top to bottom

1. As-built small log sill complex — Williams River, October 2004. Note log sill between the abutment jams consists of a stack of six logs buried ~1 m below the bed, arranged as a pyramid and secured with piles and abutment jams.
2. Same structure as (1) 12 months later.
3. Cross channel spanning structure under construction — Hunter River, NSW. Photo S. Mika.
4. Same structure as (3) 12 months later.

1

2

3

4

STRUCTURE TYPE

Bar apex jam

Description

- Multiple log structure — variation of the standard bank attached deflector jam
- Located on an existing mid-channel feature

Purpose

- Stabilising existing bar (transforming to stable island), with a view to creating hydraulic diversity within a reach
- Initiating stable mid-channel bar/island
- Replacing stabilising influence of exotic vegetation on existing vegetated island/bar, i.e. to allow for removal of the vegetation without losing the bar

Location trialled

Williams River, NSW (see photos)

River characteristics

- Med-high energy gravel river
- Catchment area ~200 km^2
- Mean annual flood ~170 cumecs
- Channel full discharge ~800 cumecs
- Gradient 0.0019

Pros or cons

If using on a existing vegetated bar as the core — significantly fewer logs are required than if you were building an equivalent sized structure from scratch. This is because less excavation is required to help stabilise the structure with deeply buried key logs and, as a result, less logs are required overall for an equivalent sized structure above the bed.

Performance to date

To date, only two structures like this have been built in Australia (to our knowledge). Both are performing well after five years.

Captions, top to bottom

1. Willow induced bar/island with riffle to right.
2. Constructing log structure around existing vegetated bar.
3. Constructed bar apex jam.
4. Same structure as (3) after series of flows.

1


2


3


4


STRUCTURE TYPE

Bank revetment structure

Description

- Small, single or multi log structure for application as bank toe protection and habitat
- Located along the bank toe, parallel to the bank at sites with low banks, i.e. not subject to mass failure

Purpose

- Stabilisation of the toe of low banks or inset benches
- Recreation of bank overhang habitat
- Initiation of small scour holes adjacent to the bank overhang, in association with the protruding root wads

Location trialled

Williams River, NSW (see photos)

River characteristics

- Med-high energy gravel river
- Catchment area ~200 km^2
- Mean annual flood ~170 cumecs
- Channel full discharge ~800 cumecs
- Gradient 0.0019

Pros or cons

Primarily a habitat augmentation structure — although can potentially be an effective erosion control structure in small streams. Undercut banks are extremely valuable fish habitat and due to stock trampling and vegetation removal of this type of habitat is common along degraded agricultural/urban streams. This is a cheap and effective way of recreating this critical habitat.

Performance to date

To date only a small number of these structures have been built in the gravel bed Williams River site. In general they appear to be performing well, although they have lost some of their habitat value due to excess sedimentation adjacent to the structure.

Captions, top to bottom

1. Revetment structure on the Williams River. Note how the upstream logs overlap on the inside the downstream logs along the toe of this inset bench.
2. Same structure as (1) after a series of floods.
3. Revetment structure under construction — Williams River.
4. Same structure as (3) after completion.

1


2


3


4


STRUCTURE TYPE

Log sill +/- abutment jams (sand bed type — version 1)

Description

- Multi log structure complex comprising a buried, multi-log sill, using logs without rootwads for the cross spanning logs to ensure a snug fit, keyed well into both banks. Geo-fabric used in sub surface portion of log sill to reduce undercutting risk
- Generally built as a full channel spanning structure across small sand-bed streams

Purpose

- Bed stabilisation
- Initiation of pool downstream of structure
- Sediment retention

Location trialled

Stockyard Creek, Hunter Valley, NSW (see photos)

River characteristics

- Low–medium energy sand-bed streams
- Catchment area ~50 km^2
- Mean annual flood ~10 cumecs
- Channel full discharge ~300 cumecs
- Gradient 0.001–0.002

Pros or cons

Any bed control structure is prone to under-cutting failure in a mobile sand-bed stream, particularly in streams like Stockyard Creek with a high index of flow variability (Iv). Outflanking failure is also a real risk, and it is necessary to excavate the structures well into the bed and banks to reduce the risk of failure. This means large numbers of logs are required, and that the structures are relatively expensive. It would also be difficult to build structures like this in larger streams with a substantial base-flow, because of the need to excavate the bed to a depth of 1.5 m or more and construct the structures before the hole in-filled. These structures also require substantial disturbance of the bed during construction which may not always be desirable.

Performance to date

To date, six of these structures have been built, however, as yet they have not been subjected to a substantial flows due to ongoing drought in this area since construction. It is too early to provide a definitive answer as to the efficacy of the structures.

1

2

Captions, top to bottom

1. Log sill under construction on Stockyard Creek. Cross-spanning logs are stacked between driven piles.
2. Cross-spanning logs do not have roots to enable tight packing. Note also how the geo-fabric has been woven through the stacked logs.

3

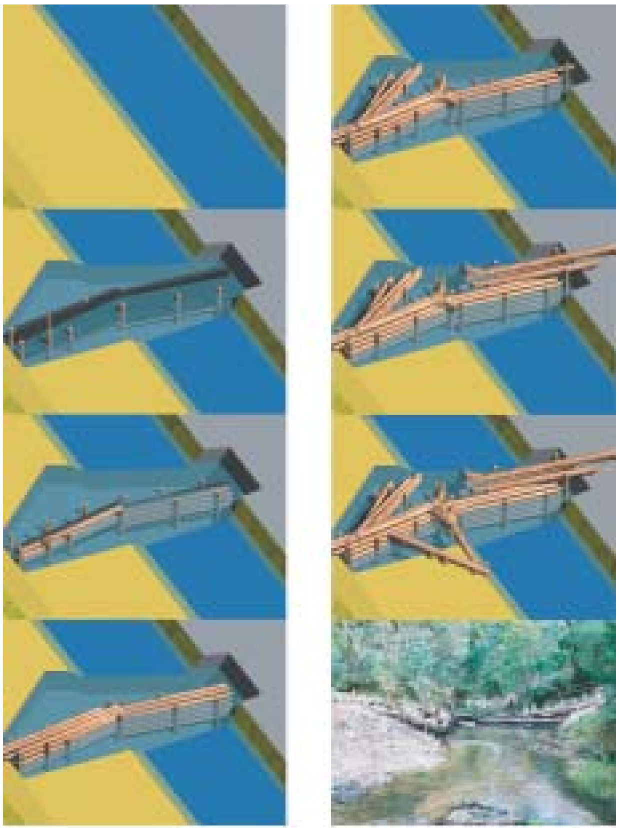
3. Cross channel spanning structure with bank abutments nearing completion.

4

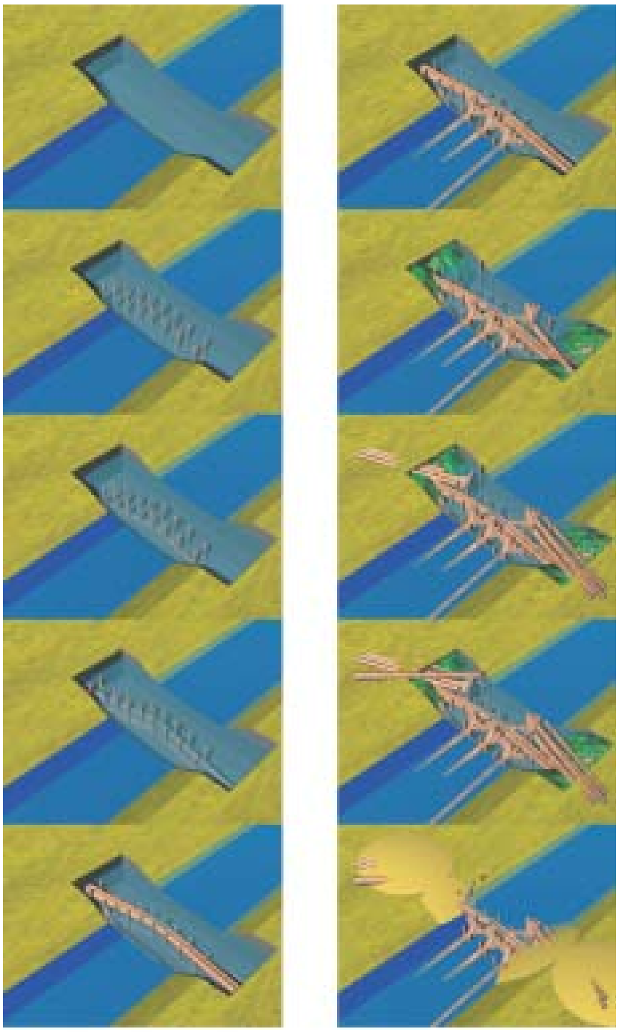
4. Completed structure looking upstream.

Schematic diagrams showing sequential construction procedure for sand-bed stream cross spanning log sill structures. The second variant uses green acacia foliage within the abutment structure instead of geo-fabric.

Sand-bed channel log bed-control structure, type 1.



Sand-bed channel log bed-control structure, type 2.



STRUCTURE TYPE

Pre-fabricated deep water fish habitat structures (fish hotels)

Description

- Pre-fabricated, coherent log structures consisting of small logs (regrowth timber) bolted together to form a rectangular log stack. These can be made more complex by the addition of branches and other small timber pieces to the centre of the structure
- Requires additional ballast where the structures can't be fixed to the bed with piles. Structure also required to be sufficiently sturdy to be picked up by crane and lowered into the water in one go

Purpose

- Fish habitat — where large logs not available, and where steep banks and deep water prevent in-stream access for construction
- Useful method of making functional habitat structures from small regrowth timber

Location trialled

Hunter River, NSW near Muswellbrook

River characteristics

- Low–medium energy gravel-bed river
- Catchment area ~4000 km^2
- Mean annual flood ~110 cumecs
- Channel full discharge ~1800 cumecs
- Gradient 0.0005

Pros or cons

On the downside, these structures are not particularly aesthetically pleasing, and they go against the philosophy of using nature as a guide for designing log structures. While the log structures themselves can be constructed fairly cheaply and easily, the size of crane required to lower a structure of this size into the river makes them very expensive. In this trial we also had to lower ballast blocks into the river, which added even more to the cost (in addition to the making of the ballast blocks themselves). In most cases it should be possible to use other means of securing the structures (either with driven piles or some sort of dual tether). On the upside, in many locations where large timber is scarce, this may be the only option available. Initial results also indicate they are very effective fish habitat, particularly when made more complex with added branches etc.

1

2

3

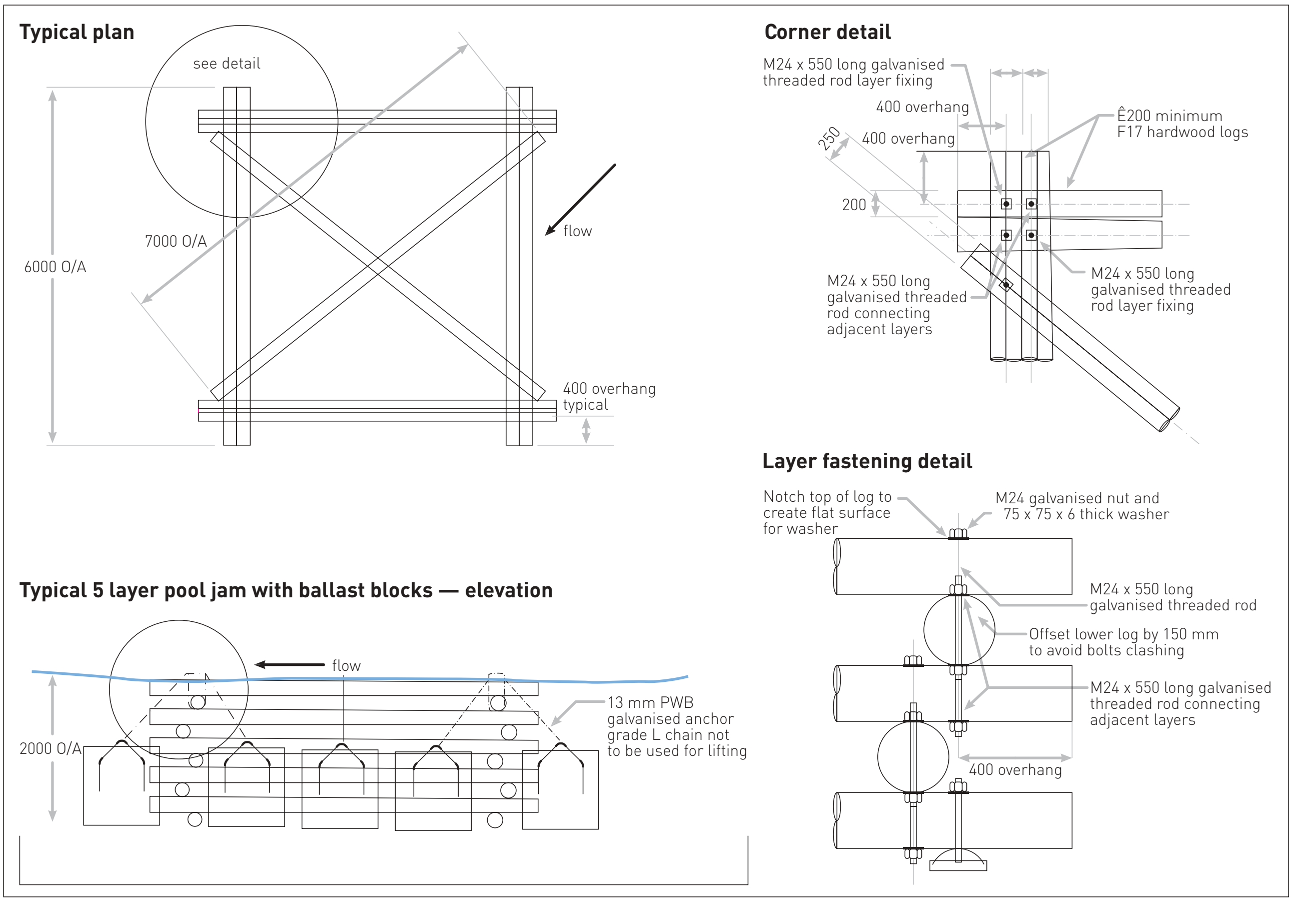
Captions, top to bottom

1. Completed fish hotel ready for deployment to river. Note the log offset between layers to allow for high tensile bolts between layers.
2. Logs being bolted together.
3. Completed structure ready for lifting into river.

4. Fish hotel being lowered into pool 1.

5. Fish hotel being positioned in pool 1.

Design for 5 m square fish hotel structure


Typical plan

Corner detail

Layer fastening detail

Typical 5 layer pool jam with ballast blocks — elevation

STRUCTURE TYPE

Elevated log sill with log pin abutments (gravel bed rivers)

Tony Broderick and Peter Menzies, NSW Northern Rivers CMA

Background and description

Trees often fall across channels following bed incision. These can play an important role in raising upstream water levels during flood events, thereby decreasing hydraulic gradient upstream and promoting deposition. Observation of this natural process initiated the concept of the Elevated Log Sill (ELS).

- Cross spanning logs elevated above bed level with timber pins radiating either side to protect abutments.

Purpose

- Decrease upstream hydraulic gradient
- Upstream riffle stabilisation/aggradation
- Localised energy dissipation

Locations trialled

Bonville Creek (2), Orara (4) and Urumbilum (1) Rivers, northern NSW (see photos)

River characteristics

- Medium to high energy gravel rivers
- Catchment area ~55–135 km^2
- Mean annual flood ~25–42 cumecs
- Channel full discharge ~148 cumecs
- Gradient 0.004–0.0065

Pros or cons

ELS are cheap, do not require trenching into the bed, are effective in upstream riffle stabilisation and localised energy dissipation. Whilst water flows beneath the structure, downstream scour is minimised and low flow fish passage provided. Over time gravel aggradation behind and under the ELS can increase scour depth and reduce fish passage. Outflanking is a risk and needs to be considered in design.

ELS provide an alternative to LWD realignment; i.e. trees naturally fallen perpendicular to flow the low flow channel can be lowered to an appropriate height and anchored in situ.

Performance to date

Seven ELS structures have been constructed over the last seven years. Six have successfully influenced upstream hydraulic gradient and deposition. Bed level monitoring and flood observation has indicated the importance of design location and height. Radial pins have been successful in stabilising abutments in these gravel bed rivers.

1

2

3

Captions, top to bottom

1. Site One — Orara River. Left view of elevated log sill (ELS) with log pin radials to protect abutment.
2. Site One — Orara River right view during a fresh. Note the localised step in hydraulic gradient and energy dissipation immediately downstream of ELS.
3. Site Two — Orara River post March 2006 bankfull event (note height of debris). ELS constructed in meander cutoff with pin rows (in background) to reduce upstream hydraulic gradient.

4. Site Two — view from upstream. Elevation of upstream water levels has promoted gravel deposition and riffle formation upstream of ELS.

5. Site One — under low flow conditions.

STRUCTURE TYPE

Elevated log sills with log pin abutments

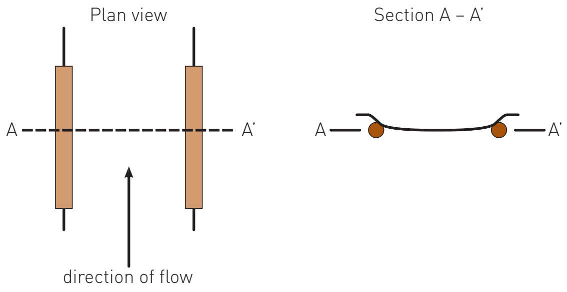
Tony Broderick and Peter Menzies, NSW Northern Rivers CMA

Generic ELS structure design and construction notes

- ELS are constructed between riffles.
- Objectives relating to hydraulic gradient and depositional patterns upstream of structure determine the exact height (<600 mm) and construction location.
- The higher the structure the greater the risk of trapping flood debris and outflanking due to flow deflection. Poorly armoured substrates may require more substantial abutments than timber pin radials detailed in this design.

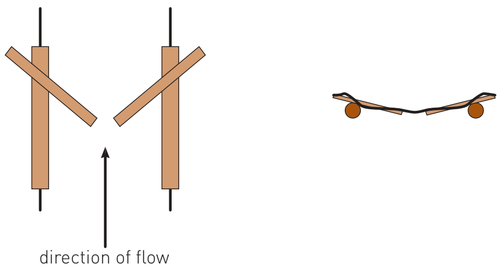
Step 1

Trench bed log into both sides of low flow channel. Depth determined by height of structure and diameter of bed and cross-spanning logs. Top of bed logs to be level.



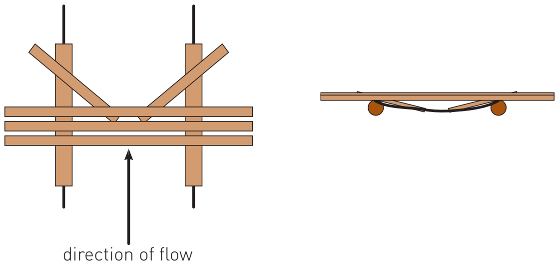
Step 2

Position diagonal logs over bed logs at appropriate angle, pointing upstream (i.e. into direction of flow). One end of diagonal log to key into bank, opposite end to key into bed.



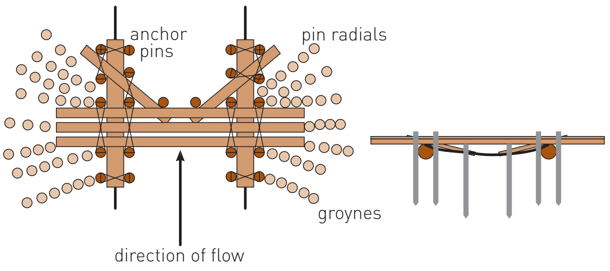
Step 3

If necessary, cut billets out of cross-spanning logs to enable these to sit over diagonal logs. Position three cross-spanning logs on top of bed logs and over diagonal logs. Cross-spanning logs to be placed perpendicular to direction of flow, overlapping bed logs by at least 1.5 m to key into bank. Largest diameter log to be placed in middle, to raise sill to desired height.



Step 4

Place and drive anchoring pins with cable to suitably anchor structure to bed. Proceed to place and drive pin radials around flanks of structure and pin groynes on upstream side.



STRUCTURE TYPE

Bed control constriction structure

Tony Broderick and Peter Menzies, NSW Northern Rivers CMA

Description

- Log and rock channel constriction with complementary downstream groyne arrangement

Purpose

- Slowing flows upstream promoting deposition and raising bed levels
- Control bed incision
- Locally dissipate energy
- Increase diversity of geomorphic units (pools, riffles, bars) and habitat features

Location trialled

Blaxland Creek (3) Northern NSW (see photos)

River characteristics

- Medium energy sand and small gravel bed
- Catchment area ~125 km^2
- Mean annual flood ~35 cumecs
- Mid bank channel discharge ~53 cumecs
- Gradient 0.001–0.0017

Pros or cons

Relatively cheap and effective bed control structure which significantly increases upstream water levels with only a relatively minor change (100 mm single step) in bed gradient. A variety of flow velocities across the single step constriction combined with downstream eddying currents facilitates fish passage. These eddying currents, which are enhanced by downstream groynes to ensure hydraulic jump development, may cause bank erosion. Designs need to cater for these erosive forces.

Riffles are not disturbed as the structures are located in shallow pools. They are effective in upstream deposition, localised energy dissipation and scour pool development. Depth of scouring needs to be linked to girdle depth.

Performance to date

Constriction has elevated upstream water levels by an average of 0.3 m at each structure, depositing sands and small gravels. Scour pool development of >2 m has exceeded that predicted (1.5 m). Structures have created a diverse range of velocity profiles and habitats throughout the reach.

1

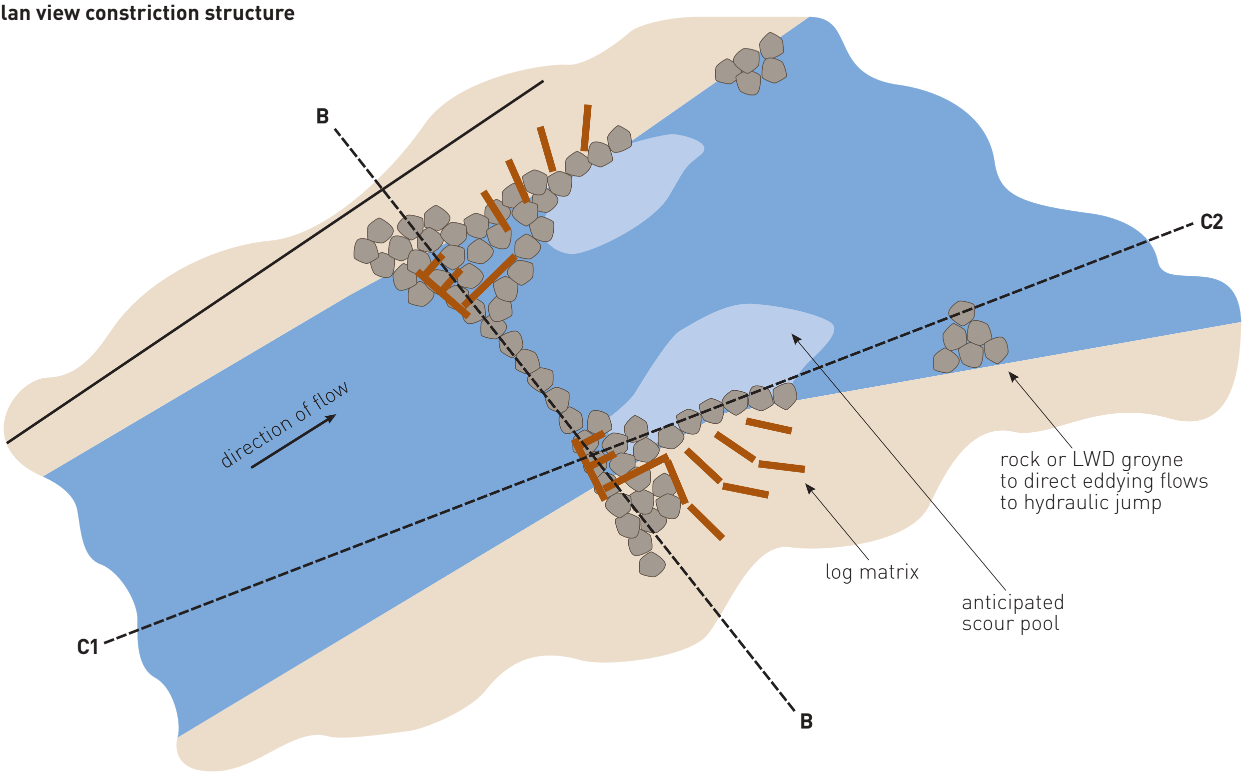

2


3

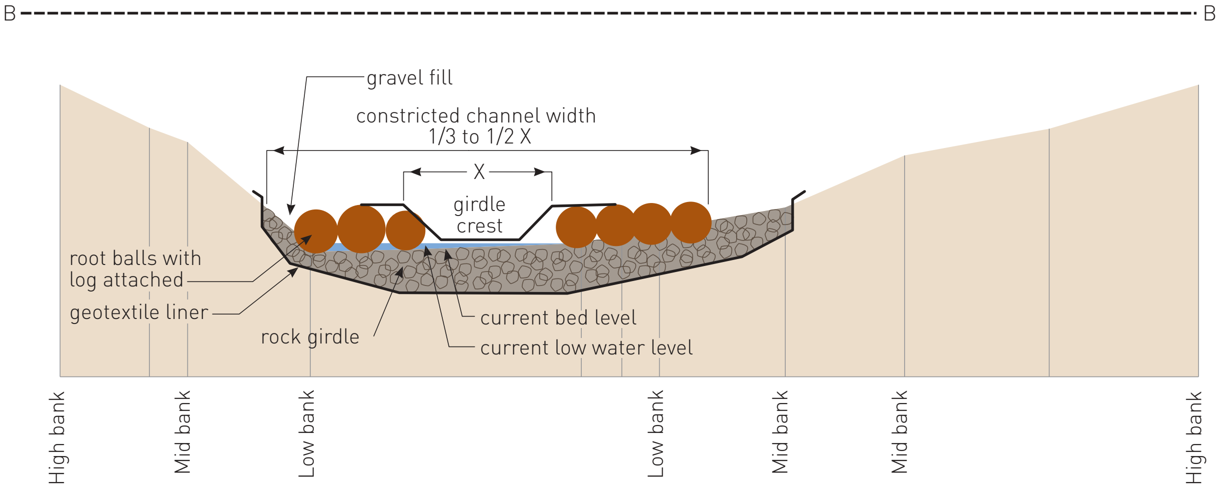

Captions, top to bottom

1. Site One — Blaxland Creek. One of three bed control constriction structures within a 500 m reach. LWD is anchored to the rock girdle beneath structure.
2. Site Two — Blaxland Creek, September 2005. Prior to works pools >0.3 m depth were almost absent throughout reach.
3. Site Two — Blaxland Creek, November 2006. Post works with approx. 8 cumecs of flow released from hydro power station. Groynes downstream of constriction direct eddying flows back upstream to enhance hydraulic jump. >2 m scour pool downstream and upstream water levels elevated by 0.37 m promoting deposition and raising bed levels.

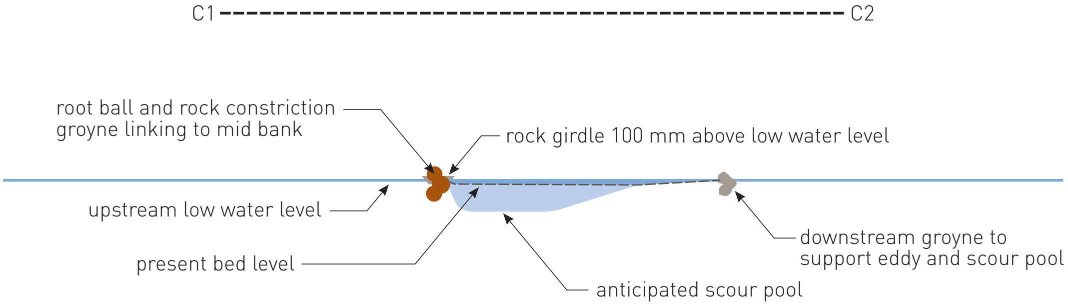
Plan view constriction structure



Long section B to B through constriction



Long section C1 to C2 through girdle crest



Designs by T. Boderick and P. Menzies. Redrawn from drawings by P. Menzies, NSW Northern Rivers CMA.

appendix B

Worked example of pile stability analysis

An example of the model parameters used to predict stable pile depth in the Snowy River study (SKM 2005) is outlined.

The inputs used in the run of the LLP99 model were:

- single soil layer,
- very high flexural stiffness of pile (1,000,000 kN/m^2).
- pile width = 0.3 m (i.e. wooden pile),
- shear strength in the absence of lateral stress (for unconsolidated sand 150 kN/m^2 was used),
- effective unit weight of soil (15 kN/m^3),
- active lateral effective stress coefficient (used 0.426 based on coefficient of earth pressure at rest for sand with θ = 35°),
- neutral lateral effective shear stress coefficient (used default – 1),
- passive lateral effective stress coefficient (= 1/ active lateral stress coefficient = 2.35), and
- stroke displacement between active and passive stress (used default 0.02 m).

Loading steps of 1 kN were applied at 1 m above the pile interception with the pre-scour bed level. The moment for each loading step is based on a maximum scour hole depth of 3.5 m, hence the moment arm is 4.5 m (i.e. moment = 4.5 kNm for each loading step). The depth of pile was varied in order to determine an effective pile depth for securing LWD.

The pile deflection was limited for all pile depths considered (Table 7). For piles constructed 1 m below the maximum scour depth, the piles should not deflect more than 1 cm under the bankfull flow. In practice we would recommend that piles be driven an extra metre to account for any underestimation in maximum scour depth. The recommended pile depth is, therefore, the maximum depth of scour (3.5 m) plus 2 m, or 5.5 m from the pre-scour bed level for securing in-stream wood.

Table 7. Pile displacement under alternative loads.

Pile depth below scour (m)	Deflection (m)	
	3 kN load	6 kN load
1	0.003956	0.008011
2	0.000926	0.002067
3	0.000385	0.000852
4	0.000220	0.000490

Bibliography

For all Land & Water Australia and earlier LWRRDC publications, see the webite **www.rivers.gov.au**

Abbe, T.B. 2000, *Patterns, mechanics and geomorphic effects of wood debris accumulations in a forest river system*, Ph.D. dissertation, University of Washington, Seattle, WA. 219 pp.

Abbe, T.B. & Montgomery, D.R. 1996, 'Large woody debris jams, channel hydraulics and habitat formation in large rivers', *Regulated Rivers: Research and Management*, vol. 12, pp. 201–21.

Abbe, T.B. & Montgomery, D.R. 2003, 'Patterns and processes of wood debris accumulation in the Queets river basin, Washington', *Geomorphology*, vol. 51, pp. 81–107.

Abbe, T.B., Montgomery, D.R. & Petroff, C. 1997, 'Design of stable in-channel wood debris structures for bank protection and habitat restoration: an example from the Cowlitz River, WA', in S.S.Y. Wang, E.J. Langendoen & F.D. Shields Jr (eds), *Proceedings of the conference on management of landscapes disturbed by channel incision*, University of Mississippi, pp. 809–16.

Abernethy, B., Dando, T. & Shirley, M. 2005. *Trials of structures — lower Snowy River*, Report to the Victorian Department of Sustainability and Environment.

Bartley, R. & Rutherfurd, I. 2001, 'Statistics, snags and sand: measuring the geomorphic recovery of streams disturbed by sediment slugs', in I.D. Rutherfurd, F. Sheldon, G. Brierley & C. Kenyon (eds), *Proceedings of the 3rd Australian Stream Management Conference*, Brisbane, August 2001, Cooperative Research Centre for Catchment Hydrology, pp. 15–21.

Bartley, R. & Rutherfurd, I. 2005, 'Measuring the reach-scale geomorphic diversity of streams: application to a stream disturbed by a sediment slug', *River Research and Applications*, vol. 21, no. 1, pp. 39–59.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S. et al. 2005, 'Ecology — Synthesizing US river restoration efforts', *Science*, vol. 308(5722), pp. 636–37.

Bird, J.F. 2000, 'The impact of mining waste on the rivers draining into Georges Bay, northeast Tasmania', *River Management: The Australasian Experience*, S.O. Brizga & B.L. Finlayson, London, John Wiley & Sons, pp. 151–72.

Bisson, P.A., Wondzell, S.M., Reeves, G.H. & Gregory, S.V. 2003, 'Trends in using wood to restore aquatic habitats and fish communities in western North American rivers', in S.V. Gregory, K.L. Boyer & A. Gurnell (eds), *The ecology and management of wood in world rivers*, Bethesda, Maryland, American Fisheries Society, pp. 391–406.

Borg, D., Rutherfurd, I. & Stewardson, M. 2004, 'Merging the fish, the wood and the engineer: the complex physical response to additions of woody debris', in I. Rutherfurd, I. Wiszniewski, M. Askey-Doran & R. Glazik (eds), *Proceedings of the 4th Australian Stream Management Conference*, County Club Casino, Launceston, Tasmania, Department Primary Industries, Hobart, pp. 95–102.

Boulton, A.J. 1993, 'Stream ecology and surface-hyporheic exchange: implications, techniques and limitations', *Australian Journal of Marine and Freshwater Research*, vol. 44, pp. 553–64.

Boulton, A.J. 2000a, 'The functional role of the hyporheos', *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie*, vol. 27, pp. 51–63.

Boulton, A.J. 2000b, 'River ecosystem health down under: assessing ecological condition in riverine groundwater zones in Australia', *Ecosystem Health*, vol. 6, pp. 108–18.

Boulton, A.J. & Brock, M.A. 1999, *Australian freshwater ecology processes and management*, Glen Osmond, Gleneagles Publishing.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H. & Valett, H.M. 1998, 'The functional significance of the hyporheic zone in streams and rivers', *Annual Review of Ecological Systems*, vol. 29, pp. 59–81.

Boulton, A.J., Mika, S., Ryder, D.S. & Wolfenden, B. 2004, 'Raising the dead: can we restore the health of subsurface aquatic ecosystems by recovering geomorphic complexity using conventional river rehabilitation techniques?', in G. Albrecht (ed.), *Airs, Waters, Places — Transdisciplinary Research in Ecosystem Health*, University of Newcastle, Callaghan, NSW, pp. 41–61.

Boulton, A.J., Sheldon, F., Thoms, M.C. & Stanley, E.H. 2000, 'Problems and constraints in managing rivers with variable flow regimes', in P.J. Boon, B.R. Davies & G.E. Petts (eds), *Global perspectives on river conservation: science, policy and practice*, John Wiley and Sons, London, pp. 411–26.

Bootle, K.R. 1983, *Wood in Australia: types, properties, uses*, Sydney, McGraw Hill.

Braudrick, C.A. & Grant, G.E. 2000, 'When do logs move in rivers?', *Water Resources Research*, vol. 36, pp. 571–83.

Brierley, G.J. & Fryirs, K. 2000, 'River styles, a geomorphic approach to catchment characterisation: implications for river rehabilitation in Bega catchment, New South Wales, Australia', *Environmental Management*, vol. 25, no. 6, pp. 661–79.

Brierley, G.J., Fryirs, K. et al. 2002, 'Application of the river styles framework as a basis for river management in New South Wales', *Applied Geography*, vol. 22, pp. 91–122.

Brierley, G.J. & Fryirs, K.A. 2005, *Geomorphology and river management: applications of the river styles framework*, Blackwell Publishing, Oxford, p. 398.

Brooks, A.P. & Brierley, G.J. 1997, 'Geomorphic responses of lower Bega River to catchment disturbance, 1851–1926', *Geomorphology*, vol. 18, no.s 3–4, pp. 291–304.

Brooks, A. & Brierley, G.J. 2002, 'Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river', *Earth Surface Processes and Landforms*, vol. 27, pp. 343–367.

Brooks, A.P., Abbe, T.B., Jansen, J.D., Taylor, M. Gippel, C.J. 2001, 'Putting the wood back into our rivers: an experiment in river rehabilitation', in I. Rutherfurd, F. Sheldon, G. Brierley & C. Kenyon (eds), *Proceedings of the 3rd Australian Stream Management Conference*, Brisbane, Australia, pp. 73–80.

Brooks, A.P. & Brierley, G.J. 2004, 'Framing realistic river rehabilitation targets in light of altered sediment supply and transport relationships: lessons from East Gippsland, Australia', *Geomorphology*, vol. 58, nos 1–4, pp. 107–23.

Brooks, A.P., Brierley, G.J., Millar, R.J. 2003, 'The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia', *Geomorphology*, vol. 51, nos 1–3, pp. 7–29.

Brooks, A.P., Gehrke, P.C., Jansen, J.D. & Abbe, T.B. 2004, 'Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses', *River Research and Applications*, vol. 20, no. 5, pp. 513–36.

Brooks, A. 1999a, 'Lessons for river managers from the fluvial tardis', in I. Rutherfurd & R. Bartley (eds), *Second Australian Stream Management Conference*, Adelaide, South Australia, Cooperative Research Centre for Catchment Hydrology, pp. 121–27.

Brooks, A. 1999b, 'Large woody debris and the geomorphology of a perennial river in southeast Australia', in I. Rutherfurd & R. Bartley (eds), *Second Australian Stream Management Conference*, Adelaide, South Australia. Cooperative Research Centre for Catchment Hydrology, pp. 129–36.

Brooks, A.P. 2004, 'Geomorphic changes to catchments and water courses in eastern Australia over the last 200 years: causes, implications and prospects', in G. Albrecht (ed.), *Airs, Waters, Places — Transdisciplinary Research in Ecosystem Health*, University of Newcastle, Callaghan, NSW, pp. 62–89.

Brooks, A.P., Abbe, T.B., Howell, T. & Arthington, A.H. 2006, 'Confronting hysteresis: river rehabilitation in highly altered riverine landscapes of southeastern Australia', *Geomorphology*, vol. 79, pp. 395–422.

Brunke, M. & Gonser, T. 1997, 'The ecological significance of exchange processes between rivers and groundwater', *Freshwater Biology*, vol. 37, pp. 1–33.

Castro, J. & Sampson, R. 2001, 'Incorporation of large wood into engineering structures', *Natural Resource Conservation Service Engineering Technical Note no. 15*, U.S. Department of Agriculture, Boise, ID, 14 pp.

Chambers, J.Q., Higuchi, N. et al. 2000, 'Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon', *Oecologia*, vol. 122, no. 3, pp. 380–88.

Cherry, J. & Beschta, R.L. 1989, 'Coarse woody debris and channel morphology: a flume study', *Water Resources Bulletin*, vol. 25, no. 5, pp. 1031–36.

Cohen, T.J. & Brierley, G.J. 2000, 'Channel instability in a forested catchment: a case study from Jones Creek, East Gippsland, Australia', *Geomorphology*, vol. 32, pp. 109–28.

Coleman, R.L. & Dahm, C.N. 1990, 'Stream geomorphology: effects on periphyton standing crop and primary production', *Journal of the North American Benthological Society*, vol. 9, pp. 293–302.

Cottingham, P., Bunn, S., Price, P. & Lovett, S. (eds) 2003, 'Managing wood in streams', *River and Riparian Land Management Technical Guideline*, no. 3, Land & Water Australia, Canberra.

D'Aoust, S.G.D. & Millar, R.G. 1999, *Large woody debris fish habitat structure performance and ballasting requirements*, British Columbia, Watershed Restoration Program, BC Ministry of Environment, Lands & Parks and Ministry of Forests, p. 119.

D'Aoust, S.G. & Millar, R.G. 2000, 'Stability of ballasted woody debris habitat structures', *Journal of Hydraulic Engineering*, vol. 126, pp. 810–17.

Davis, J. & Finlayson, B.L. 2000, 'Sand slugs and stream degradation: the case of the Granite Creeks, north-east Victoria', *Cooperative Research Centre for Freshwater Ecology Technical Report 7/2000*, p. 108.

Dent, C.L., Schade, J.D., Grimm, N.B. & Fisher, S.G. 2000, 'Subsurface influences on surface biology', in J.B. Jones & P.J. Mulholland (eds), *Streams and ground waters*, Academic Press, San Diego, pp. 381–402.

Downes, B.J., Barmuta, L.A., Fairwether, P.G., Faith, D.P., Keough, M.J., Lake, P.S., Mapstone, B.D. & Quinn, G.P. 2002, *Monitoring ecological impacts: concepts and practice in flowing waters,* Cambridge University Press, p. 434.

Dudley, S.J., Fischenich, J.C. & Abt, S.R. 1998, 'Effect of woody debris entrapment on flow resistance', *Journal of the American Water Resources Association*, vol. 34, no. 5, pp. 1189–97.

Dyer, B.G., Western, A.W. & Grayson, R.B. 1996, 'Hydraulic characteristics of retards', in I.D. Rutherfurd & M. Walker (eds), *First National Conference on Stream Management in Australia*, Merrijig, Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 87–92.

Erskine, W.D. & White, L.J. 1996, 'Historical river metamorphosis of the Cann River, East Gippsland, Victoria', in I.D. Rutherfurd & M. Walker (eds), *First National Conference on Stream Management in Australia*, Merrijig, Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 277–82.

Fetherston, K.L., Naiman, R.J. & Bilby, R.E. 1995, 'Large woody debris, physical process and riparian forest development in Montane river networks of the pacific northwest', *Geomorphology*, vol. 13, pp. 133–44.

Findlay, S. 1995, 'Importance of surface-subsurface exchange in stream ecosystems: the hyporheic zone', *Limnology and Oceanography*, vol. 40, no. 1, pp. 159–64.

Fischenich, C. & Morrow, J. Jr 1999, 'Streambank habitat enhancement with large woody debris', *EMRRP Technical Notes Collection, ERDC TN-EMRRP-SR-13*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Frissel, C.A. & Nawa, R.K. 1992, 'Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington', *North American Journal of Fisheries Management*, vol. 12, pp. 182–97.

Garde, R., Subramanya, K. & Nambudripad, K. 1961, 'Study of scour around spur-dikes', *Journal of the Hydraulics Division*, ASCE, vol. 87, no. HY6, pp. 23–37.

Gippel, C.J. 1995, 'Environmental hydraulics of large woody debris in streams and rivers', *Journal of Environmental Engineering*, vol. 121, no. 5, pp. 338–95.

Gippel, C.J., Finlayson, B.L. & O'Neill, I.C. 1996a, 'Distribution and hydraulic significance of large woody debris in a lowland Australian river', *Hydrobiologia*, vol. 318, pp. 179–94.

Gippel, C.J., O'Neill, I.C., Finlayson, B.L. & Schnatz, I. 1996b, 'Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers', *Regulated Rivers: Research and Management*, vol. 12, pp. 223–36.

Gregory, K., Gurnell, A. & Hill, C. 1985, 'The permanence of debris dams related to river channel processes', *Hydrological Sciences*, vol. 30, no. 3, pp. 371–81.

Gregory, K., Davis, R. & Tooth, S. 1993, 'Spatial distribution of coarse woody debris dams in the Lyminton Basin, Hampshire, UK', *Geomorphology*, vol. 6, pp. 207–24.

Hancock, P.J. & Boulton, A.J. 2005, 'The effects of an environmental flow release on water quality in the hyporheic zone of the Hunter River, Australia', *Hydrobiologia*, in press.

Hancock, P.J. 2002, 'Human impacts on the stream-groundwater exchange zone', *Environmental Management*, vol. 29, pp. 763–81.

Heede, B. 1981, 'Dynamics of selected mountain streams in the western United States of America', *Zeitschrift fur geomorphology N.F.*, vol. 25, no. 1, pp. 17–32.

Hilderbrand, R., Lemly, A., Dollof, C. & Harpster, K. 1997, 'Effects of large woody debris placement on stream channels and benthic macroinvertebrates', *Canadian Journal of Fisheries and Aquatic Science*, vol. 54, pp. 931–39.

Hilderbrand, R., Lemly, A., Dolloff, C. & Harpster, K. 1998, 'Design considerations for large woody debris placement in stream enhancement projects', *North American Journal of Fisheries Management*, vol. 18, pp. 161–67.

Hillman, M. & Brierley, G. 2005, 'A critical review of catchment-scale stream rehabilitation programmes', *Progress in Physical Geography*, vol. 29, no. 1, pp. 50–76.

House, R.A. & Boehne, P.L. 1985, 'Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream', *North American Journal of Fisheries Management*, vol. 5, pp. 283–95.

House, R.A. & Boehne, P.L. 1986, 'Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon', *North American Journal of Fisheries Management*, vol. 6, pp. 38–46.

Howell, T., Arthington, A., Pusey, B., Brooks, A.P., Creese, R. & Downes, B. 2005, 'Measuring the effect of river rehabilitation for fish: logistical constraints on experimental design', in I.D. Rutherfurd et al. (eds), *Proceedings of the 4th Australian Stream Management Conference: Linking Rivers to Landscapes*, 19–22 October 2004, Country Club Casino, Launceston, Tasmania, pp. 299–305 .

Jeffrey, K.A., Beamish, F.W., Ferguson, S.C., Kolton, R.J. & MacMahon, P.D. 1986, 'Effects of the lampricide, 3-trifluoromethyl-4-nitrophenol (TFM) on the macroinvertebrates within the hyporheic region of a small stream', *Hydrobiologia*, vol. 134, pp. 43–51.

Keller, E. & Tally, T. 1979, 'Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment', in *Adjustments of the Fluvial System: Annual Geomorphology Symposium, Binghampton*, NY, Kendall Hunt Publications.

Keller, E.A. & Macdonald, A. 1995, 'River channel change: the role of large woody debris', in A. Gurnell & G. Petts (eds), *Changing River Channels*, John Wiley & Sons Ltd, pp. 217–35.

Keller, E.A. & Swanson, F.J. 1979, 'Effects of large organic material on channel form and fluvial processes', *Earth Surface Processes*, vol. 4, pp. 361–80.

Knighton, A.D. 1989, 'River adjustment to changes in sediment load: the effects of tin mining on the Ringarooma River, Tasmania, 1875–1984', *Earth Surface Processes and Landforms*, vol. 14, pp. 333–59.

Knighton, A.D. 1991, 'Channel bed adjustment along mine-affected rivers of northeast Tasmania', *Geomorphology*, vol. 4, pp. 205–19.

Koehn, J.D. & O'Connor, W.G. 1990, *Biological information for management of native freshwater fish in Victoria*, Heidelberg, Arthur Rylah Institute for Environmental Research.

Lane, E.W. 1955, 'Design of stable channels', *Transactions*, ASCE, vol. 120, pp. 1234–79.

Lisle, T.E. 1986, 'Stabilisation of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California', *Geological Society of America Bulletin*, vol. 97, pp. 999–1011.

Lovett, S. & Price, P. (eds) 1999, *Riparian Land Management Technical Guidelines*, volumes 1 and 2, LWRRDC, Canberra.

Lovett, S. & Price, P. (eds) 2007, *Principles for Riparian Lands Management*, Land & Water Australia, Canberra.

Mackensen, J. & Bauhus, J. 1999, 'The decay of coarse woody debris', *National carbon accounting system, technical report no. 6*, Australian Greenhouse Office, Canberra, p. 40.

Mackensen, J., Bauhus, J. et al. 2003, 'Decomposition rates of coarse woody debris — A review with particular emphasis on Australian tree species', *Australian Journal of Botany*, vol. 51, no. 1, pp. 27–37.

Malard, F., Tockner, K., Dole-Olivier, M.-J. & Ward, J.V. 2002, 'A landscape perspective of surface-subsurface hydrological exchanges in river corridors', *Freshwater Biology*, vol. 47, pp. 621–40.

Marmonier, P., Fontvieille, D., Gibert, J. & Vanek, V. 1995, 'Distribution of dissolved organic carbon and bacteria at the interface between the Rhône River and its alluvial aquifer', *Journal of the North American Benthological Society*, vol. 14, pp. 382–92.

Marsh, N. 2001, 'Large woody debris loading, distribution and scour hole formation in lowland streams', Ph.D. thesis, Civil Engineering, The University of Melbourne, Melbourne.

Marsh, N., Rutherfurd, I. & Jerie, K. 1999, 'Large woody debris in some Australian streams: natural loading, distribution and morphological effects', in I.D. Rutherfurd & R. Bartley (eds), *Proceedings of the Second Australian Stream Management Conference*, Adelaide, pp. 427–32.

McCall, E. 1984, *Conquering the Rivers: Henry Mill Shreve and the Navigation of America's Inland Waterways*, Louisiana State University Press, Baton Rouge, LA.

McMahon, T.A., Finlayson, B.L. Haines, A.T. & Srikantham, R. 1992, *Global runoff: continental comparisons of annual flows and peak discharges*, Cremlingen-Destedt, Germany.

Melville, B. & Sutherland, A. 1988, 'Design methods for local scour at bridge piers', *Journal of Hydraulic Engineering*, vol. 114, no. 10, pp. 1210–26.

Melville, B. 1997, 'Pier and abutment scour: integrated approach', *Journal of Hydraulic Engineering*, vol. 123, no. 2, pp. 125–36.

Murphy, M. & Koski, K. 1989, 'Input and depletion of woody debris in Alaska streams and implications for streamside management', *North American Journal of Fisheries Management*, vol. 9, pp. 427–36.

Mutz, M. 2000, 'Influences of woody debris on flow patterns and channel morphology in a low energy, sand-bed stream reach', *International Review of Hydrobiology*, vol. 85, no. 1, pp. 107–21.

Nakamura, F. & Swanson, F.J. 1993, 'Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon', *Earth Surface Processes and Landforms*, vol. 18, pp. 43–61.

Nanson, G.C. 1983, 'Channel migration and incision on the Beatton River', *Proceedings of the Journal of Hydraulic Engineering*, vol. 109, pp. 327–37.

Nanson, G.C. & Doyle, C. 1999, 'Landscape stability, Quaternary climate change and European degradation of coastal rivers in southeastern Australia', in I. Rutherfurd & R. Bartley (eds), *Proceedings of the Second Australian Stream Management Conference*, Adelaide.

Nanson, G.C., Barbetti, M. et al. 1995, 'River stabilisation due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia', *Geomorphology*, vol. 13, pp. 145–58.

Nichols, R.A. & Sprague, S.G. 2003, 'Use of long-line cabled logs for stream bank rehabilitation', in D.R. Montgomery, S. Bolton, D.B. Booth & L. Wall (eds), *Restoration of Puget Sound Rivers*, University of Washington Press, Seattle, WA, pp. 422–42.

O'Connor, N.A. 1992, 'Quantification of submerged wood in a lowland Australian stream system', *Freshwater Biology*, vol. 27, pp. 387–95.

Olley, J.M. & Wasson, R.J. 2003, 'Changes in the flux of sediment in the Upper Murrumbidgee catchment, southeastern Australia, since European settlement', *Hydrological Processes*, vol. 17, no. 16, pp. 3307–20.

Packman, A.I. & Bencala, K.E. 2000, 'Modeling surface-subsurface hydrological interactions', in J.B. Jones & P.J. Mulholland (eds), *Streams and ground waters*, Academic Press, San Diego, pp. 45–80.

Piegay, H. & Gurnell, A. 1997, 'Large woody debris and river geomorphological pattern: examples from south east France and south England', *Geomorphology*, vol. 19, pp. 99–116.

Piegay, H., Thevenet, A. & Citterio, A. 1999, 'Input, storage and distribution of large woody debris along a mountain river continuum, the Drome River, France', *Catena*, vol. 35, pp. 19–39.

Pilgrim, D.H. 1987, *Australian Rainfall and Runoff*, The Institution of Engineers, Australia, Canberra.

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

Pusey, B.J., Kennard, M.J. & Arthington, A.H. 2004, *Freshwater Fishes of North-Eastern Australia*, CSIRO Publishing, Collingwood, 684 pp.

Ralph, S., Poole, G., Conquest, L. & Naiman, R. 1994, 'Stream channel morphology and woody debris in logged and unlogged basins of western Washington', *Canadian Journal of Fisheries and Aquatic Science*, vol. 51, pp. 37–51.

Richards, K.S. 1982, *Rivers, Form and Process in Alluvial Channels*, Methuen, London.

Richmond, A.D. & Fausch, K.D. 1994, 'Characteristics and function of large woody debris in subalpine Rocky Mountain streams in Northern Colorado', *Canadian Journal of Fisheries and Aquatic Science*, vol. 52, pp. 1789–802.

Robison, E. & Beschta, R. 1990, 'Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA', *Earth Surface Processes and Landforms*, vol. 15, pp. 149–56.

Robison, E., 1988, 'Large woody debris and channel morphology of undisturbed streams in southeast Alaska', Master of Science thesis, Oregon State University.

Ruffner, E.H. 1886, *The practice of the improvement of the non-tidal rivers of the United States, with an examination of the results thereof*, John Wiley & Sons, New York.

Russell, I.C. 1909, *Rivers of North America*, G.P. Putnam's Sons. New York.

Rutherfurd, I.D. 1996, 'Sand-slugs in south-east Australian streams: origins, distribution and management', in I.D. Rutherfurd & M. Walker (eds), *Proceedings of First National Conference on Stream Management in Australia*, Merrijig, pp. 29–34.

Rutherfurd, I., Jerie, K. & Marsh, N., 2000, *A Rehabilitation Manual for Australian Streams*, volumes 1 and 2, LWRRDC, Canberra.

Schälchli, U. 1992, 'The clogging of coarse gravel river beds by fine sediment', *Hydrobiologia*, vols 235/236, pp. 189–97.

Shields, F.D.J. & Gippel, C. 1995, 'Prediction of effects of woody debris removal on flow resistance', *Journal of Hydraulic Engineering*, vol. 121, no. 4, pp. 341–54.

Shields, F.D.J., Knight, S.S. et al. 2000, *Large woody debris structures for incised channel rehabilitation*, Proceedings of ASCE 2000 joint conference on water resources engineering and water resources planning and management, Reston VA, ASCE.

Shields, F.D. & Gippel, C.J. 1995, 'Prediction of effects of woody debris removal on flow resistance', *Journal of Hydraulic Engineering*, vol. 121, no. 4, pp. 341–54.

Shields, F.D. & Nunnally, N.R. 1984, 'Environmental aspects of clearing and snagging', *Journal of Environmental Engineering, vol. 110, no. 1, pp. 152–65.*

Shields, F.D., Knight, S.S. & Cooper, C.M. 1998, 'Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi', *Hydrobiologia*, vol. 382, pp. 63–86.

Shields, F.D., Knight, S.S., Morin, N. & Blank, J. 2003, 'Response of fishes and aquatic habitats to sand-bed stream restoration using large woody debris', *Hydrobiologia*, vol. 494, no.s 1–3, pp. 251–57.

Smith, R., Sidle, R. & Porter, P. 1993a, 'Effects on bedload transport of experimental removal of woody debris from a forest gravel-bed stream', *Earth Surface Processes and Landforms*, vol. 18, pp. 455–68.

Smith, R.D., Sidle, R.C., Porter P.E. & Noel, J.R. 1993b, 'Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream', *Journal of Hydrology*, vol. 152, pp. 153–78.

Smith, R.D. & Beschta, R.L. 1994, 'A mechanism of pool formation and maintenance in forest streams', *Hydraulic Engineering*, Buffalo, ASCE.

Spanhoff, B., Alecke, C. et al. 2001, 'Simple method for rating the decay stages of submerged woody debris', *Journal of the North American Benthological Society*, vol. 20, no. 3, pp. 385–94.

Stanford J.A. & Ward J.V. 1988, 'The hyporheic habitat of river ecosystem', *Nature*, vol. 335, pp. 64–66.

Sukhodolov, A., Uijttewaal, W.S. & Wngelhardt, C. 2002, 'On the correspondence between morphological and hydrodynamical patterns of groyne fields', *Earth Surface Processes and Landforms,* vol. 27, pp. 289–305.

Swanson, F., Bryant, M., Lienkaemper, G. & Sedell, J. 1984, 'Organic debris in small streams, Prince of Wales Island, southeast Alaska', *General Technical Report PNW-166*, USDA.

Thexton, E. 1999, 'Rehabilitation of the lower Genoa River, far east Gippsland, Victoria with assisted regeneration', in I. Rutherfurd & R. Bartley (eds), *Second Australian Stream Management Conference*, Adelaide, South Australia. Cooperative Research Centre for Catchment Hydrology, pp. 623–28.

Thibodeaux, L.J. & Boyle, J.D. 1987, 'Bed form generated convective transport in bottom sediment', *Nature*, vol. 325, pp. 341–43.

Trotter, E. 1990, 'Woody debris, forest-stream succession, and catchment geomorphology', *Journal of the North American Benthological Society*, vol. 9, no. 2, pp. 141–56.

Valett, H.M., Fisher, S.G. & Stanley, E.H. 1990, 'Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream', *Journal of the North American Benthological Society*, vol. 9, pp. 201–15.

Valett, H.M., Fisher, S.G., Grimm, N.B. & Camill, P. 1994, 'Vertical hydrologic exchange and ecological stability of a desert stream ecosystem', *Ecology*, vol. 75, pp. 548–60.

Vaux, W.G. 1962, 'Interchange of stream and intergravel water in a salmon spawning riffle', *United States Fisheries and Wildlife Service Research Reports Fisheries*, vol. 405, pp. 1–11.

Wallerstein, N.P. 2003, 'Dynamic model for constriction scour caused by large woody debris', *Earth Surface Processes and Landforms*, vol. 28, no. 1, pp. 49–68.

Wallerstein, N.P., Alonso, C.V., Bennett, S.J. & Thorne, C.R. 2001, 'Distorted froude-scaled flume analysis of large woody debris', *Earth Surface Processes and Landforms*, vol. 26, pp. 1265–83.

Wallerstein, N.P., Alonso, C.V. S. J. Bennett, S.J. & Thorne, C.R. 2002, 'Surface wave forces acting on submerged logs', *Journal of Hydraulic Engineering*, vol. 128, pp. 349–53.

Wallerstein, N., Thorne, C.R. & Doyle, M.W. 1997, 'Spatial distribution and impact of large woody debris in Northern Mississippi' in S.S.Y. Wang, E.J. Langendoen, & F.D. Shields, Jr (eds), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision,* University of Mississippi, MS, pp. 145–50.

White, D.S. 1993, Perspectives on defining and delineating hyporheic zones, *Journal of the North American Benthological Society*, vol. 12, pp. 61–69.

Wood, P.J. & Armitage, P.D. 1997, Biological effects of fine sediment in the lotic environment, *Environmental Management*, vol. 21, pp. 203–17.

Wood-Smith, R.D. & F.J. Swanson 1997, 'The influence of large woody debris on forest stream geomorphology', in S.S.Y. Wang, E.J. Langendoen & F.D. Shields (eds), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, pp. 133–39.

www.Rivers.gov.au

WOOD

RiverLandscapes