A Rehabilitation Manual for Australian Streams

VOLUME 2

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Cooperative Research Centre for Catchment Hydrology

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We also want to know about your experiences in stream rehabilitation, so we can develop a data bank of case studies in stream work in Australia. Please use the space on the other side of this form to tell us what you have done or are doing.

Sharing your experiences will help. The stream rehabilitation industry is in its infancy, but it will grow and mature. We hope that this manual will foster this and will itself evolve as we learn from each other about the business of stream rehabilitation. By sharing, evaluating and recording the successes and failures of our stream rehabilitation efforts we will gain the confidence needed to begin roll back the many decades of degradation that our streams have suffered.

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PREAMBLE

This document forms the second part of A Rehabilitation Manual for Australian Streams. The manual is designed to help professional managers who are attempting to return some of the biological and physical values of Australia's streams. Volume 1 of the manual provides some rehabilitation concepts, and a summary of a rehabilitation planning procedure. Volume 2 provides more detailed information about the tools that can be used for rehabilitation. Volume 2 is divided into three sections:

1. Common stream problems

2. Planning tools

3. Intervention tools.

Our expectation is that managers would occasionally dip into Volume 2 if they need more detail than is provided in Volume 1. There are many cross-references from Volume 1 to the more detailed information in Volume 2. Please have a look through the table of contents to see what is included in Volume 2.

Please note that both volumes are available from the Land and Water Resources Research and Development Corporation website (www.rivers.gov.au).

It is important to emphasise that this is not a catchment or stream management manual. There are many reasons to intervene in streams and catchments that are not related to rehabilitation of the natural stream values. Thus, the manual will only touch on issues such as erosion control, water supply, flooding, and the sociology of management, in so far as they affect rehabilitation.

Also, this is not an engineering design manual. We provide some concepts, and guidance, but where detailed design information is required we will refer you to a better source.

This manual was only possible with the contribution of many managers and researchers across Australia. These contributions are acknowledged at the front of Volume 1 and often as footnotes to the text. We also acknowledge the generous support and vision of the Land and Water Resources Research and Development Corporation, and the Cooperative Research Centre for Catchment Hydrology that has brought this manual to fruition.

Please note:

a comprehensive glossary of terms is provided at the end of this manual.

FIGURE ACKNOWLEDGMENTS

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Land Victoria, Department of Natural Resources and Environment	Figure 38, Intervention Tools	Aerial photograph Latrobe Valley PHD 1908 Run 4 19/2/1987.

PART 1: COMMON STREAM PROBLEMS

PRESERVING VALUABLE REACHES

Please note:

The following pages are a cursory discussion of this important subject.

Dr Helen Dunn from the School of Geography and Environmental Studies at the University of Tasmania is presently (mid 1999) completing a LWRRDC project investigating the identification and protection of rivers with high ecological value. The results of this investigation will be incorporated into this section when they become available.

They will also be available on http://www.rivers.gov.au

- **Identifying valuable reaches**
- **Preserving a reach in good condition**
- **A summary and ranking of stream degradation issues**

IDENTIFYING VALUABLE REACHES

A reach can have high conservation value for two reasons.

1. It supports a rare species of plant or animal, or a rare community type.

2. The reach is in excellent overall condition. Such reaches are often chosen as reference or template reaches.

Briefly, the presence of rare species can be checked by contacting your State Herbarium and/or Department of Environment. These organisations should have records of the distribution of rare species of plants and animals, respectively. Also, if there have been biological surveys of your stream, you can check species lists against lists of known rare species. It is possible to search the Australian Heritage Commission's Register of the National Estate to check for sites of national significance that may be relevant to your stream (Skull *et al.,* 1996).

PRESERVING A REACH IN GOOD CONDITION

1.1. Introduction

In this manual we have emphasised the importance of preserving the natural assets of streams that remain in good condition. But how do you do this? We will assume here that the asset is a discrete reach of stream that may be valuable in its own right, or that supports animals or plants that are rare. We discuss three approaches to preserving such assets. These are: physical protection; planning controls; and identifying threats.

1.2. Physical protection

In some cases it may be necessary to physically protect the reach of stream from damage. This is most commonly done by fencing the stream (see *Managing stock access to streams*, in Intervention in the riparian zone, this Volume). However, there are other options. For example, the famous silt jetties of the Mitchell River, in Victoria, were being eroded where fishermen trampled the fringing phragmites reed that used to protect the banks from wave erosion. The solution was to build formal fishing platforms at a few points along the bank. These provide good access and so tend to concentrate the fishermen and protect the banks (see Figure 1). This is an example of concentrating impact so as to manage it.

Figure 1. A fishing platform on the Nicholson River, Victoria, built out of old tyres and logs.

1.2.1. How wide should buffer strips be?

This question obviously depends upon what you are trying to buffer, and what sort of stream you have. The subject of buffers is much too substantial to cover here. The LWRRDC riparian zone guidelines provide direct guidance on this subject (see www.rivers.gov.au). Here are a few key points from those guidelines for protecting streams from polluted run-off.

- A grassed buffer of 4–6 m is very effective for buffering sediment and nutrients.
- Buffers are most effective in small streams in which hill slopes connect directly with the channel.
- A good buffer can be compromised by a single channelised flow passing through it.

You could also consider how tall a buffer strip of vegetation needs to be. A taller vegetated buffer will shade the stream more effectively.

In general, the more functions you want the buffer to perform, the wider it needs to be.

1.3. Planning controls

An obvious way to preserve stream assets is to give them a particular status at law. There are many examples of legislation that will limit the activities on particular streams. For example, the *Heritage Rivers Act (1994)* in Victoria controls all activities that would damage the special reaches of river identified by the Act. Also in Victoria, 'threatening actions' can be controlled under the *Flora and Fauna Guarantee Act (1988)*.

Stream frontages can be an area of overlapping jurisdiction. It is important that a reach is flagged as being important in any branches of government that could have some jurisdiction over the land. For example, different departments in Queensland manage the estuarine and freshwater parts of the stream system. One planning agency may be officially sanctioning damage to the natural assets of a stream reach, while another department is trying to preserve them.

It is often useful to publicise the special values of a stream reach. Around Victoria you often see the 'Land for Wildlife' signs that identify areas as being of special habitat value. It can be effective to let adjacent landholders know that a reach of stream is important, and get them on-side in managing the asset. Statistics can be helpful here: "This is part of the 5% of this stream that is still in good condition. Congratulations on preserving such an important piece of stream! Can we talk about how this reach could be managed?"

1.4. Identify and eliminate threats to the target reach

An obvious thing that one can do to protect reaches is to identify and eliminate existing and developing problems. A process for identifying, and prioritising, threats to high value reaches is built into *Step 5* of the Stream rehabilitation procedure, Volume 1. This procedure looks for threats to the target reach from:

- upstream (sediment, water quality, floods, major changes of course);
- downstream (erosion knickpoints, exotic fish, boats); and
- the riparian zone (stock access, fishermen, weeds, clearing, excess light).

Here is an obvious example of solving the damaging problem. The banks of the Gordon River have been eroded up to 10 m by waves from cruise boats (Bradbury *et al.,* 1995). This river is in a World Heritage Area and has obvious high value. The solution was to dramatically reduce boat speed.

A SUMMARY AND RANKING OF STREAM DEGRADATION ISSUES

Possibly the most common underlying vision that drives stream rehabilitation is to improve the health of stream, or to make the stream more biologically similar to an undisturbed pre-European condition. Because it is the plants and animals that we wish to encourage, it would be useful to know their perspective on stream problems. Any organism will have numerous requirements of its environment, and there are many processes which will degrade these requirements. Tables 1–3 list the main issues which contribute to the degradation or restoration of macroinvertebrates, fish and floodplains, and also indicate the likely importance of each issue.

In 1996, at the 1st Stream Management Conference, held at Merrijig near Mount Buller, Victoria, a group of conference delegates stood next to the beautiful Delatite River watching fish ecologists electrofish in the stream. The Delatite River appears to be a pristine mountain stream with perfect riparian vegetation, good water quality and original in stream structures. The delegates were looking forward to seeing a 'natural' range of native fish species from an undisturbed stream. Instead, they were shocked to find all that was caught was trout and more trout. These exotic fish appear to have completely displaced the native fish in the stream. This demonstrates that the viability of organisms can be threatened in numerous ways.

Table 1. Restoration and degradation issues important to macroinvertebrates in the Murray–Darling Basin. From Koehn *et al.* (1997b).

Restoration/degradation issue	Importance (high – low) comments
Riparian vegetation	**Very high** – not so much for itself, but most other degradation issues are affected by this.
Sedimentation	**High** – very widespread, changes fundamental habitat characteristics, essentially irreversible once having occurred (ie. needs natural cleaning).
Water flow, volume, seasonality	Probably **Low**, (except for zero flow, and some low flows – see *Temperature* and *Dissolved oxygen concentration*, below); flow for fish probably more important.
Water quality – temperature	**High** in places, especially below low release dams, small unshaded streams, possibly extremely low flows.
Water quality – nutrients	Possibly **Medium**, but definitely **High** in places, below sewage treatment plants, dairy, piggery outlets, some factories (dealt with by EPA).
Water quality – toxicants	**High** in places, below licensed discharges. Accidental pulse spills may be dramatic, but may not be important in the long term.
Water quality – pH, dissolved oxygen, salinity	**Medium** – streams with high salinity are **High**. In-stream habitat, bed structure **High** – particularly in rock streams subject to sedimentation.
In-stream habitat, including snags and fringing vegetation	**Medium** – not a major problem in upland sections, more important in lowland streams where snags and banks are possibly the only productive habitat.
Predation by exotic fish Competition by exotic invertebrates	**Low** – they probably can't eat enough. Overall **Low**, but **High** in specific places.

Table 2. Restoration and degradation issues important to fish populations in the Murray–Darling Basin. From Koehn *et al.* (1997b).

Restoration/degradation issue	Importance (high – low) comments
Flows	**High**
Minimum flows	Habitat area covered.
Reduced flooding (frequency, amplitude and extent)	System cues (eg. spawning); floodplain habitats; organic inputs; system resetting; flushing; habitat creation (inputs, scouring).
Altered seasonality	Spawning.
Constant flows	No movement cues; favours 'constant species'.
Flow rate	Velocities and depths eg. weir pools, changes below hydro power stations.
Riparian vegetation	**High** Has widespread importance to the river system: includes shading, organic inputs, snag input, filtering of run-off, bank stability.
Sedimentation	**Medium** The problem is settling out of suspended sediment or too much bedload movement. Smothers spawning sites, small fish habitats and invertebrate food supply, fills holes and contributes to a uniform substrate.
Habitat removal	**High**
Substrate	Small fish habitat, upland food source, substrate undulations (pools).
Snags	Key habitat areas. Increased importance in lowland systems; preferred spawning sites and habitats for many species. Provides food supply and causes habitat diversity.
Channelisation	Removes most habitat; the job can be well completed by the addition of concrete channelling.
Floodplain habitats (swamp, billabong and wetland areas)	Removed by drainage, levee banks, damage or reduced flooding.
Aquatic plants	Food supply, juvenile fish habitat.
Channel/bank form	Contains water and morphology provides habitat (such as undercuts).
Water quality	**Medium**. Can be critical.
Toxic substances	Generally in urban areas and isolated spills.
Temperature	Increases or decreases can affect spawning, productivity and metabolism.
Salinity	Important in some areas, saline pools and stratification.
Suspended sediment	Decreases light penetration and productivity, affects sight feeding.
Eutrophication	Usually seasonal, high levels cause decreases in dissolved oxygen.
Dissolved oxygen	Can be low in stratified pools.
Barriers	**High**. More important in coastal drainages where up to 70% of species have a marine life phase and need to move back upstream. Loss of over 50% of species in south-eastern Australia. The importance of general movement has been underestimated for many species.
Introduced species	**Medium/High**
Harvesting (commercial and recreational)	**Medium**. Previously more of a problem, only for some species and in some areas/circumstances.
Diseases	**Low**. Will increase with increased movement of fishes outside their natural range.

Table 3. Restoration and degradation issues important to floodplains in the Murray–Darling Basin. From Koehn *et al.* (1997b).

Restoration / degradation issue	Importance (high – low) comments
Levees: Isolation from main stream floods	**High**. Some land uses too highly valued for protection to be removed (eg. urban areas, dairies in lower Murray). Others should have levee protection removedóland use restricted to flood-compatible types.
Terrestrial vegetation/habitat diversity	**High**. If flood-induced changes result in disappearance of one component (eg. Moira grass). **Medium** if changes stop at a shift in relative representation of components.
Carbon inputs: organic detritus from terrestrial floodplain	**High**. Probably the major source of carbon in lowland river pre-development.
Nutrient dynamics between floodplain and stream	**Medium**. Deposition of nutrients on floodplain—re-suspension by floods and bank erosion.
Biotic transfer between billabong and main stream	**Medium–High**. Suspected of being significant in supplying larval fish food during high flows. May supply key zooplankton and microbial inputs to stream on declining hydrograph.
Material transfer between billabong and main stream	**Low–Medium**. Probably less significant quantitatively. Possibility of significant qualitative difference in carbon inputs from billabong versus terrestrial floodplain.
Anabranch function	**Low–High** Significance reach-specific and dependent on relative condition of main channel and land management effects on anabranches. Effectiveness further modified by flow management. Could offer fish passage–habitat–food resources alternative.

1. Implications

Every species has a long list of requirements of its environment, many of which are essential for survival. Unfortunately, for many species, these requirements are basically unknown, which makes it difficult to design a rehabilitation program to suit one animal or plant. Even for those species where some environmental requirements are known, we seldom, if ever, have the complete picture. Basing a rehabilitation project on such incomplete information risks damaging one important aspect of habitat while trying to fix another. For this reason, we recommend a more basic approach of working out rehabilitation goals by copying the characteristics of a stream which does manage to support a diverse aquatic community. Ideally, these characteristics would be based on the original condition of the stream in question. Alternatively, you could use a 'template' reach—a stream section which currently supports the organisms you wish to encourage. When 'copying' either the original condition, or a template reach, you should examine:

- the structure and form of the channel bed, including adjacent benches and banks;
- the riparian zone, including flow connection with the floodplain;
- free passage between different habitat areas;
- the flow regime, including variability over many years;
- the water quality; and
- the natural complement of indigenous animals and plants.

In the absence of evidence to the contrary, stream rehabilitators should see these six characteristics of the stream as their target for management. As the example on page 15 demonstrates, it is important to consider the role that all of these play in the condition of any stream.

GEOMORPHIC PROBLEMS

- Geomorphic problems: an introduction
- Chains-of-ponds: description and rehabilitation
- Gullies
- Valley floor incised streams (also, incised channelised streams)
- Larger over-widened streams
- Typical small, enlarged rural streams
- Sediment slugs

GEOMORPHIC PROBLEMS: AN INTRODUCTION

Many rehabilitation projects in streams focus on the geomorphic condition of the channel and floodplain. This might be because treating the geomorphic problems (whether erosion or sedimentation) is sometimes the best way to treat water quality problems (such as turbidity), and is often a prerequisite for successful rehabilitation of the stream ecology. Some geomorphic problems can be classified into similar types that require similar treatment. Further discussion on these geomorphic problems can be found in Rutherfurd (in press). Here we briefly discuss:

- chains-of-ponds;
- gullies;
- valley-floor incised streams (including channelised streams);
- larger over-widened streams;
- small, enlarged rural channels; and
- sediment slugs.

CHAINS-OF-PONDS: DESCRIPTION AND REHABILITATION

Written with the assistance of Scott Wilkinson and Barry Starr

1. Description

Much international work in stream rehabilitation assumes that the natural state of small streams was to have pools and riffles. As a result, returning pools and riffles is the focus of much rehabilitation design. By contrast, at first settlement, numerous streams throughout south-eastern Australia (including South Australia and Tasmania) had a quite different morphology consisting of chains-of-ponds, or the related swampy meadows (Prosser, 1991).

Swampy meadows are poorly drained, confined valley floors in which sediments and organic matter gradually build-up (Prosser *et al.,* 1994). Chains-of-ponds consist of deep, permanent pools, separated by bars of sediment stabilised with vegetation (Eyles, 1977b). They are typically found on smaller streams, with non-perennial flow regimes. There is no regularity to the spacing of the ponds down the drainage line. Unlike pool-and-riffle sequences, the ponds are not always associated with stream bends, although there will generally be a pool located where a tributary enters the main channel.

Figure 2. A remnant chain-of-ponds in the Goulburn River catchment, Victoria.

Chains-of-ponds appear to be more common in Australia than elsewhere, perhaps due to climatic variability producing infrequent high flows that form ponds, interspersed with long periods of low stream flow that allow vegetation to become established between the ponds (eg. Figure 2). Before and during European settlement, chains-of-ponds were reported to exist in many streams, both coastal and inland, from Western Australia to Queensland (Eyles, 1977b; Gaydon *et al.,* 1996).

Two types were categorised by Bannerman in Herron (1993) according to the dominant process that forms the ponds:

1. Scour chains-of-ponds are formed where sheet flow over a gradual slope of varying erodibility leads to depressions that are deepened by scour. This form is more likely to occur on duplex soils. In this situation, a resistant topsoil stabilised by vegetation overlays a dispersible clay. If a scour hole penetrates through a weak point in the surface layer, the clay gradually erodes by dispersion. Yabbies may contribute to this erosion. The ponds grow in size until an equilibrium is established between erosion and sedimentation in reeds at the pond edges. The impermeability of the clay maintains water in the pool during long dry periods. This form generally exists on alluvial plains, above the limit of a well-defined channel. Scour ponds have been known to remain in equilibrium for 140 years (Eyles, 1977b).

2. Depositional chains-of-ponds on channelised reaches form by the deposition of fixed bars which block the channel, producing long pools. This is different to a pool-and-riffle sequence by virtue of the irregularity in pond spacing and the large amount of vegetation

stabilising the inter-pond bars. They are semi-permanent, occupying constant positions for at least 20 years (Eyles, 1977a).

Most chains-of-ponds will exhibit characteristics of both types, but identifying the dominant process can assist management.

Typical vegetation stabilising the bars would be rushes, reeds, sedges, grasses, paperbarks, and tea-trees.

1.1. Ecological significance

Chains-of-ponds were often the only source of stock water for early pastoralists, but equally they provided permanent water for wildlife. Chains-of-ponds, and related swampy valley-fills, are of great ecological significance because they were the natural state of so many of our small and medium-sized streams. Unfortunately, we know little about their original physical state, let alone of the flora and fauna that occupied them.

2. Threats to chains-of-ponds

Chains-of-ponds can be destroyed when channel incision cuts through the inter-pond bars from downstream (Eyles, 1977a; Herron, 1993; see Figure 3). Incision of swampy meadows has similarly been related to flow concentration and damage to valley-floor vegetation (Prosser and Slade, 1994). The incision in chains-of-ponds can start when the upstream end of a pond becomes unstable, and develops into a gully head that cuts through the bar to the next pond, thus draining it. Such a process can be contributed to by:

- digging drains through inter-pond bars;
- damaging the vegetation in the flow-line between the ponds, by stock grazing, fire, increased salinity; or
- increased stream flows (or higher peaks) caused by catchment clearing or gullying upstream.

These changes have been associated with increases in stream erosion capacity and sediment transport. The erosion power of a stream determines the morphology of the chain-of-ponds. As stream erosion capacity increases, the most likely morphology progresses from: scour depressions; scour ponds; extended ponds gullying at the head; discontinuous gully; continuous gully containing fixed bar ponds; permanently flowing stream (Eyles, 1977a). A threat of a different kind to chains-of-ponds is a large sediment supply from upstream, as a result of poor catchment management or channel erosion. This can fill the ponds with sediment.

Figure 3. The site of a former 'swampy meadow' in the upper Murrumbidgee catchment, now destroyed by incision.

Most chains-of-ponds reported at first settlement have been destroyed by channel incision or sedimentation. Remaining chain-of-pond systems can be considered to be 'endangered landforms' requiring preservation.

3. Change if no action

A stable chain-of-ponds relies on the equilibrium between many variables including stream flow, vegetation health, and sediment supply and transport. Chains-of-ponds are commonly threatened by channel incision progressing from downstream, or sedimentation from upstream. If there is an active gully head below a chain-of-ponds, or a large amount of mobile sediment in the channel upstream, or the vegetation is damaged in some way, the morphology will be significantly altered.

Once channelisation has occurred, natural reformation of a scour chain-of-ponds morphology would be unlikely, or at best a long-term proposition. An integral feature of scour chains-of-ponds is a non-channelised stream. A scour chain-of-ponds may naturally reform if the channel had widened through meandering enough to provide effectively non-channelised flow and allow vegetation to become established on a flat bed.

4. Potential for rehabilitation

There is limited potential for returning chains-of-ponds to their original state. The incised streams that have replaced the chains-of-ponds have high stream powers, and provide a hostile environment for revegetation (see Gullies, below).

Although we cannot recreate the unique conditions that developed the ponds, we can use the chains-of-ponds as a model for rehabilitating incised streams.

5. Rehabilitation techniques

As a general principle, it is easier to protect chains-of-ponds from damage than it is to recreate them, although rehabilitation experience to date is limited. There follows a list of some tools for both stabilisation and restoration of the chain-of-ponds morphology (Table 4).

Some groups are already using chains-of-ponds as a model for stream rehabilitation. River engineers have had some success in north-east Victoria, and in Gippsland, in encouraging the development of a chain-of-ponds. They stabilised the bed of gullies with rock-chutes, but, to create a pool, set the crest of the chute slightly higher than normal. The upstream end of the pool was then densely vegetated. Phragmites reeds were scooped-up from nearby wetlands (where they are abundant) by an excavator, placed in a truck, and were then dumped into the upstream end, and around the margins of, the pool. The phragmites then began to trap sediment.

Table 4. Some strategies and tools to rehabilitate chains-of-ponds for various objectives.

Rehabilitation objectives	**Strategies**	**Techniques and tools**
To prevent a gully from progressing upstream through a chain-of-ponds.	Stabilise the gully head.	• Rock chute at gully head. • Exclude stock from gully head and inter-pond bars. • Pasture improvement and revegetation in the catchment to reduce run-off.
To protect a chain-of-ponds from a sediment slug.	Manage sediment movement.	• Sediment monitoring and management to prevent ponds infilling with sand.
To recreate a depositional style chain-of-ponds in a channelised stream.	Create stable pools and bars.	• Low earthen and rock weirs, well-vegetated with appropriate species to prevent erosion (eg. plant reeds on low weirs). • Vegetate and fence stream verges. • Install artificial sediment trap or use an existing pond sacrificially. • Controlled sediment extraction from sediment traps, or the channel upstream of the chain-of-ponds.

GULLIES

1. Introduction

Gullies are a subset of 'incised streams', usually referring to streams that are reasonably 'new', that is, there was probably no defined channel before settlement, and the gullies represent deepening and extension of the drainage network (eg. see Figure 4). About 5% of New South Wales is affected by 'severe' gullying (Soil Conservation Service of NSW, 1989). The fullest review of eastern Australian gullying is provided by Prosser and Winchester (1996).

Figure 4. A gully network in the Johnstone River catchment in Far North Queensland.

2. Description

2.1. Original state (physical and ecological)

Gullies have developed in almost every environment across Australia. There was often no defined channel at first settlement, just a swale or swampy area (often called a swampy meadow). In many cases the areas that have gullied can be defined as 'sediment accumulation zones' that gradually build-up with sediment and then naturally strip that sediment out by gullying every few thousand years. The difference with human-induced gullying is that it has occurred within a century right across the country, and often to greater depths than the natural gullying.

There are many triggers for gullying, but they usually included a combination of clearing of vegetation from the catchments, concentration of flow by vehicle and animal tracks, drainage or plough-lines, and periods of intense rainfall. Catchment clearing alone is usually insufficient to trigger gullying.

2.2. Present condition

Gullies rapidly cut a box-shaped channel with vertical walls, with further development continuing at a negative exponential rate (Figures 5 and 6). This means that they will erode at a much slower rate in the future than they have in the past for the same set of rainfall events. The gully proceeds up the drainage network as a set of erosion heads (knickpoints). Once incised, the gully increases the drainage of groundwater into the trench and erosion is increasingly driven by seepage processes.

The large volume of sediment eroded from gullies is often deposited in 'flood-outs' further downstream as the depth of the gully decreases.

2.3. Ecological significance

Many gullies began as chains-of-ponds, or similar ill-defined channels. There are few examples of this stream type left, so rehabilitating examples is desirable.

Gullies often have low ecological diversity because they combine highly variable flow with high velocity flow. They also tend to have unstable bed and banks, providing poor habitat.

One of the major ecological reasons to manage gullies is that they are often the major source of sediment, particularly high turbidity and associated phosphorus, to the rest of the stream network (Caitcheon, 1990; Wallbrink *et al.,* 1996). Controlling erosion in gullies may be justified for this reason alone.

3. Changes if no action

Gullies usually develop at a negative exponential rate. This means that, given the same run-off conditions, gullies will almost always erode at a much lower rate in any successive period (Figures 5 and 6). Thus, research has shown that the numerous gullies that developed in the dry years of the 1940s in south-eastern Australia have, in general, mostly stabilised (Prosser and Winchester, 1996). Remember that raw banks and an ugly appearance do not necessarily imply a rapid erosion rate.

Gullies will eventually stabilise, and the beds will revegetate, but it will take several decades. There are usually three reasons why gullies are slow to heal: (1) because of the high flow velocities that occur in the bed of the gully; (2) because of the seepage erosion driven by the depth of the gully; and (3) because water and soil quality is often poor in the gully floor (eg. saline in many areas), hampering plant growth.

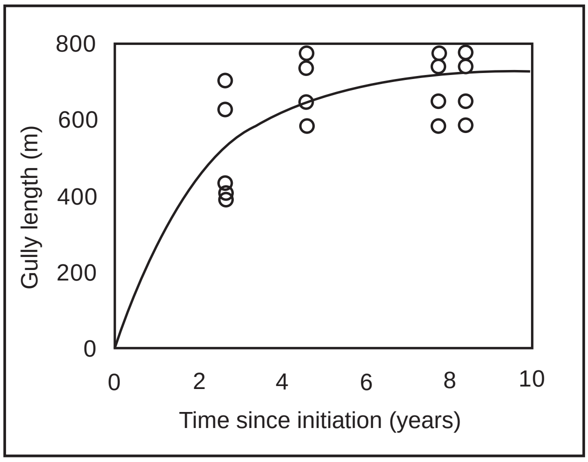

Figure 5. Changes in the length of five gullies over nine years in the Kapunda catchment (from Rutherfurd *et al.*, 1997). Reproduced with permission of the Centre for Computational Hydroscience and Engineering.

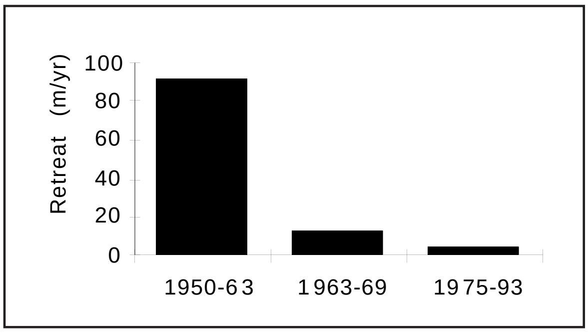

Figure 6. Annual rate of retreat for three periods in a large (12 m deep) incised stream (Yorkies Gully) in eastern Victoria (from Rutherfurd *et al.*, 1997). Reproduced with permission of the Centre for Computational Hydroscience and Engineering.

4. Potential for rehabilitation

The potential for returning gullies to their original condition is determined by how deep they are, and how much money is available. There has been some success in agricultural areas in mechanically filling small gullies, but this is an expensive activity that is usually only justified by the access restored and the agricultural productivity of the land. In general, there are five reasons why the original condition of gullies cannot be artificially restored.

1. There are thousands of kilometres of gullies in Australia. In central Victoria the density of gullying can reach 0.5 km per km^2 (Milton, 1971).

2. The channels are so small that they are dramatically impacted by the condition of the catchment, which is usually poor.

3. There is insufficient sediment to fill the gullies.

4. Adjacent land use may rely on the low watertable produced by the gullies.

5. Gullies may occur in marginal agricultural land where the cost of rehabilitating the gullies far exceeds the value of the land.

Recent cost–benefit analysis of gully control in north-eastern Victoria suggested that it was seldom economically worthwhile to stabilise gullies in order to increase farm productivity (Rush, 1997).

4.1. Appropriate tools for rehabilitation

The management principles for stabilising gullies are:

- aim to accelerate the natural process of recovery;
- always stabilise the bed before the bank (see *Full width structures*, in Intervention in the channel, this Volume);
- encourage invasion of the channel bed by vegetation to accelerate stability; and
- wherever possible divert high flows out of the channel, but encourage low flows to assist revegetation.

There are numerous tools and techniques developed for the rehabilitation of gullies. Controlling gully erosion has been a major activity of Australian soil conservationists for 50 years. Stability is certainly the first prerequisite for rehabilitating gullies, and bed stability is usually the key variable. The three main options for management are to: divert water away from the gully; drop the water gently into the gully floor; or stabilise the gully floor. See your local environmental department for assistance with stabilising gullies.

Because gullies tend to recover themselves over time, they are usually a low priority for active rehabilitation throughout large catchments. The major reasons to treat gullies for rehabilitation are to control sediment and nutrient yield, or to stop erosion heads from moving upstream into valuable areas.

For details of rehabilitating gullies to mimic chains-of-ponds (the original form of many gullies), see the previous section on *Chains-of-ponds*.

VALLEY FLOOR INCISED STREAMS (ALSO, INCISED CHANNELISED STREAMS)

1. Description

1.1. Original state (physical and ecological)

Many small to medium-sized Australian streams have incised deeply into their floodplains since European settlement. As with gullies (above), many of these larger streams were also originally swampy environments that were very sensitive to disturbance. The construction of small drains was a common trigger for incision and widening (Bird, 1982). The incision can be over 15 m deep, making these a major source of sediment and land loss. The most prominent examples of valley floor incised streams have been described in south-eastern Australia, particularly in north-east Victoria, Gippsland (Bird, 1985), and the south coast of New South Wales (Brierley and Murn, in press). There are also many examples in the Mt Lofty Ranges of South Australia (Figure 7) (Bourman, 1975). Valley floor incised streams are larger than gullies, and tend to develop within a well-defined valley-fill of sediment.

The Bega River has been filled with sand from valley floor incised streams in its catchment. These streams have been the focus of the 'River Styles' (Brierley and Fryirs, 1997) method described in *Catchment Review* in Natural channel design, this volume.

Figure 7. A deeply incised stream in the Mount Lofty Ranges in South Australia (note person in top left corner for scale).

1.2. Present condition

The incised streams tend to move through a predictable cycle of erosion and stabilisation. Hupp and Simon (1991) describe a six-stage model of incision and widening followed by aggradation and quasi-equilibrium (Figure 35 in Volume 1 shows this model). Following rapid incision, the channel then widens and begins to develop a new floodplain within a meandering trench. These trenches are also common in urban areas.

2. Changes if no action

If nothing is done, the channel bed will eventually stabilise (eg. Figure 8), but erosion of the high banks will tend to continue for many decades because they are inherently unstable. The rate of stabilisation depends upon the sediment supply to the stream, and how coarse it is. The channel will tend to stabilise more if it has coarser load that can armour the bed. The establishment of vegetation is very effective at stabilising these channels.

Figure 8. Hurdle Creek in north-eastern Victoria. This deeply incised stream now has a stable bed and has almost stabilised its planform.

3. Ecological significance

Although these erosion trenches look spectacular, they afflict only a small proportion of Australian streams. For true ecological rehabilitation of streams, the main problems with these trenches are:

- as barriers to animal migration to higher reaches (when they flow it is at high velocity, with limited base-flow between such events); and
- as a source of fine sediment downstream (they can contaminate long reaches of stream). This fine sediment is hard to manage because it comes from high, raw banks.

4. Appropriate tools for management

In most cases, large incised streams fall into the 'Basket case with hope' category of our prioritisation procedure (see Step 5: *Setting priorities*, in the planning procedure, Volume 1). Thus, if natural stream rehabilitation is your primary concern, then this type of stream would receive low priority. In fact, they would probably have the lowest priority of any stream, because they have considerable potential for recovering on their own (given sufficient sediment and vegetation). This is an important point because this type of stream has traditionally attracted large amounts of money, often justified on vaguely ecological grounds.

Large incised streams would receive higher priority if the fine sediment that they produce was threatening high-value reaches downstream.

If it is necessary to stabilise large incised streams, then the same principles of management apply as for gullies, except that valley floor incised streams are tremendously powerful. The management principles are:

- aim to accelerate the natural process of recovery;
- always stabilise the bed before the bank (see *Full width structures*, in Intervention in the channel, this volume);
- encourage invasion of the channel bed by vegetation to accelerate stability; and
- wherever possible divert high flows out of the channel, but encourage low flows to assist revegetation.

LARGER OVER-WIDENED STREAMS

1. Description

1.1. Original state (physical and ecological)

Some Australian streams have transformed from reputedly stable, narrow, suspended-load dominated, sinuous channels, into broad, unstable, bedload-dominated channels (see Figure 9). Catastrophic channel enlargement (largely through widening) is recorded on coastal streams from Gippsland in the south to the Queensland tropics in the north. The best-documented examples occur in the coastal streams of New South Wales. Stream managers in Queensland often argue that their streams are periodically widened during cyclones, and narrow again between them. Cattle Creek is an example of such change (Brizga *et al.,* 1996a). The enlargement can take place anywhere along the channel, but is most common in confined sections of floodplain, and close to the point where the streams leave the mountain front (Warner, 1992).

More money has probably been spent on this spectacular channel change than any other stream management issue in Australia (with the possible exception of gullying). For example, the New South Wales Department of Water Resources spent $132 million (estimated minimum 1993 dollars) on 90 major and 436 minor river training and channelisation schemes in the Hunter River catchment alone following dramatic enlargement during a series of floods between 1949 and 1955 (Erskine, 1990b; Erskine, 1992a).

Figure 9. The Avon River, Gippsland. An example of a stream that has widened dramatically over the last 150 years.

1.2. Channel destruction

In response to a single unusually large flood, or series of floods, some channels will dramatically enlarge. This enlargement is usually a result of great increases in width, which may be associated with increased meander migration. Other changes include channel straightening from chute cut-offs. The bed may degrade, but it may aggrade as a pulse of sediment from the eroded reach moves down the stream system. The expanded trench then behaves like the valley floor incised streams (described in *Valley floor incised streams*, above). In the decades following the channel changes, the over-widened trench often narrows as vegetation encroaches, the thalweg deepens, benches form, and the channel regains its sinuosity. Reaches downstream can be choked with sand and gravel liberated from the erosion (Erskine, 1993; Erskine, 1996).

There is considerable debate about why these streams erode so dramatically (see, for example, Erskine and Warner, 1998; Kirkup *et al.,* 1998). Although the erosion is triggered by major floods, it is likely that clearing of riparian vegetation plays a role in weakening the banks, leading to the major erosion (Brooks, 1999). The ecological effects of the channel changes may be dramatic. Habitat in the streams can be considerably simplified.

2. Changes if no action

If no action is taken, these streams remain unstable. Repeated cycles of widening and subsequent narrowing by bench deposition have been observed in some streams (Erskine, 1994; Brizga *et al.,* 1996a). It seems that these streams will be unstable for decades to come. They will certainly be sources of sediment. Other disturbances, such as gravel extraction, may also be de-stabilising these streams.

3. Appropriate tools for management

This type of stream has been the focus of stream management work in New South Wales. In terms of the priority system described in *Step 5* of the Stream rehabilitation procedure, Volume 1, these streams would be described as either 'Basket case streams with hope' (because the channels are progressively stabilising) or would be treated as part of protecting better reaches downstream that are threatened by the sediment produced in these eroding reaches. Thus, by that priority system, these streams would attract a low priority for rehabilitation unless they directly threatened other reaches. Most work on these streams must be justified in terms of flood protection or protecting economic assets (Erskine and White, 1996).

If you do decide to rehabilitate this type of stream, expect it to be expensive and difficult. Certainly, the strategy should be to work with the natural recovery of the stream. The Hunter River has stabilised since the massive erosion in the 1950s, and this recovery has almost certainly been accelerated by the channel-training work done by the New South Wales Government, and the absence of flooding comparable in size to the 1950s events.

Building on nearly 50 years of experience, there are now some effective procedures available for managing this type of stream. The 'Rivercare' methodology is targeted specifically at this type of stream on the north coast of New South Wales (Raine and Gardiner, 1995). The management approach described in the Rivercare manual first investigates bed stability. Then the channel width is compared, via an empirical relationship, with catchment area to see if the stream is too wide for its discharge. The aim then is to narrow the channel with a variety of structural tools, but particularly native vegetation. The alignment of the channel is also modified if the planform of the channel is unstable (Raine and Gardiner, 1995).

Many of the techniques described in the *Intervention tools* section, in this volume, come from the experience gleaned from such widened streams in northern New South Wales and in Victoria.

TYPICAL SMALL, ENLARGED RURAL STREAMS

1. Introduction

The temptation is often to concentrate our efforts on the most dramatically damaged streams (see the priorities *Step 5* in the Stream rehabilitation planning procedure). In reality, we should perhaps be concentrating our efforts on the many tens of thousand of kilometres of marginal, slightly damaged rural streams across the continent.

We see this type of stream every day, and probably consider it a low priority, stable stream (eg. Figure 10). These streams are typically quite small, they flow only occasionally, they are often cleared to the banks, and stock have access to them. The channel is eroding at the outer banks, and possibly has deepened by half-a-metre or so. This enlargement is usually due to grazing, combined with the increase in the size of flood peaks coming from the cleared catchment. Large snags may even have been removed because they were causing erosion and possibly some flooding.

Any coarse sediments in the bed are probably contaminated with fine sediment. Not much lives in the stream, apart from carp, and possibly a platypus in the few deep pools remaining. There is little shade and pools tend to be slightly nutrient enriched.

Figure 10. A typical degraded rural stream flowing off the Illawarra escarpment in coastal New South Wales. Note the slight enlargement, poor riparian vegetation, and 'lumpy' slumped banks.

The creek is unlikely to change its condition much if it is left alone. With continued grazing and a cleared catchment there is little prospect for natural recovery in this type of stream.

2. Ecological significance

The degraded rural stream described above is probably the most typical stream type in the settled areas of Australia. These streams can have considerable capacity for recovery. They are small enough that moderate management measures can pay rich rehabilitation dividends. For example, they can be effectively shaded by modest riparian vegetation. Thus, this type of stream could well be a priority for rehabilitation, especially if up or downstream there are sources of plants and animals available for natural colonisation.

3. Appropriate tools for management

What are we to do with such streams? The first response is usually to think of stock exclusion, fencing and riparian vegetation. This is quite right. The main problem is how much can be achieved when probably most of the catchment is in this sort of condition. Certainly, the emphasis must be on working down from any remaining pockets of stream in good condition. It is worth looking at any reaches that are fenced and do have riparian vegetation. Do they enjoy better in-channel structure, more macro-invertebrates, deeper pools? If so, then there is your template for action. If not, then you will have to look for other limiting variables. If there is no obvious source of animal or plant colonists, then you have to be realistic about how long it will take revegetated reaches to recover—probably decades.

SEDIMENT SLUGS

1. Introduction

This section discusses pulses of coarser sediment released into streams. Finer sediments (silts and clays) are discussed under *Turbidity* in the water quality section of Common Stream Problems. Human activities often lead to a dramatic increase in sediment yield to streams. The result is often a pulse of sediment (sand or gravel) moving down the stream network. Sources of sand for the slugs are gully erosion (particularly in granite catchments), catastrophic widening of streams, and hydraulic mining.

Sand slugs from granite catchments can be found in all States. There are descriptions of granite sand slugs in the Southern Tablelands of New South Wales, eg. Tarcutta Creek (Outhet and Faulks, 1994), the upper Lachlan and Murrumbidgee catchments in New South Wales, the coastal south-eastern corner of the continent (eg. the Bega River in south-east New South Wales), in central Victoria (Erskine *et al.,* 1993; Wilson, 1995), the Glenelg River in western Victoria (Rutherfurd and Budahazy, 1996), the Don River in north Queensland (Kapitzke *et al.,* 1996) and the Condamine in southern Queensland. In some streams (such as the Bega River), sand slugs can originate from both catastrophic widening, and erosion of a granite catchment (Figure 11).

Sand slugs from catastrophic widening occur in the lower Genoa (Erskine, 1992b), Cann (Erskine and White, 1996) and Avon rivers (Brizga, 1991) in Gippsland; and the Hunter (C. Thomas, personal communication 1995) and Goulburn rivers in New South Wales (Erskine, 1994). Historical sand deposits in the Macdonald and Colo Rivers have been related to catchment disturbance (Dyson, 1966), but they are more probably related to catastrophic widening (Henry, 1977; Erskine, 1986).

Mining, particularly gold mining last century and up to the 1950s, has introduced huge volumes of sediment into streams across Australia. For example, the Laanecoorie reservoir in central Victoria lost 53% of its capacity in 41 years because of gold sluicing waste (Wilson, 1995). In another example, sluicing for tin between 1875 and 1982 washed over 40 million m^3 of sediment into the Ringarooma River (Knighton, 1987; Knighton, 1989).

Figure 11. A typical sand slug on a tributary of the Bega River, that has a granite catchment in New South Wales.

1.1. Ecological significance

Sediment slugs tend to dramatically simplify channel morphology, replacing complex structure and substrate with flat sheets of sand or gravel. The ecologically obvious result is that pools are filled in, and habitat is lost. Loss of pools is one of the most common observations about the damage done to streams: "When I was a boy you could dive to the bottom of that hole, now you can walk across it up to your ankles!" More insidious effects of the sediment are to fill-in interstitial spaces in coarser bed material (Boulton, 1999), as well as to provide a shifting, unstable habitat that is bad for macroinvertebrates (O'Connor and Lake, 1994).

In general, sediment contamination of streams is one of the main challenges facing stream rehabilitation in Australia.

According to *Setting priorities for stream rehabilitation* in Miscellaneous planning tools (this Volume), reaches affected by sand slugs would be classified as a high priority for rehabilitation only if the sand yield threatens assets downstream. For example, sand on the Glenelg River, western Victoria is threatening the Glenelg estuary which is a declared 'heritage river' under the *Heritage River Act 1984* (Rutherfurd and Budahazy, 1996).

1.2. How do you recognise slugs?

Many streams in arid and semi-arid parts of Australia have flat, sandy beds. These are not usually sand slugs from human impact. On other streams, you might be seeing a sand slug if you observe:

- a meandering stream that does not have any obvious pools, or other bed variation;
- a coarser silty-sand layer on top of the otherwise fine floodplain (this could be Post European Settlement Alluvium—PESA) (Figure 12);
- a sudden change in bed material size (coarser or finer);
- uniform bed material size—little variation; or
- obvious aggradation of bed material relative to objects in the channel (such as bridge piers, pipes).

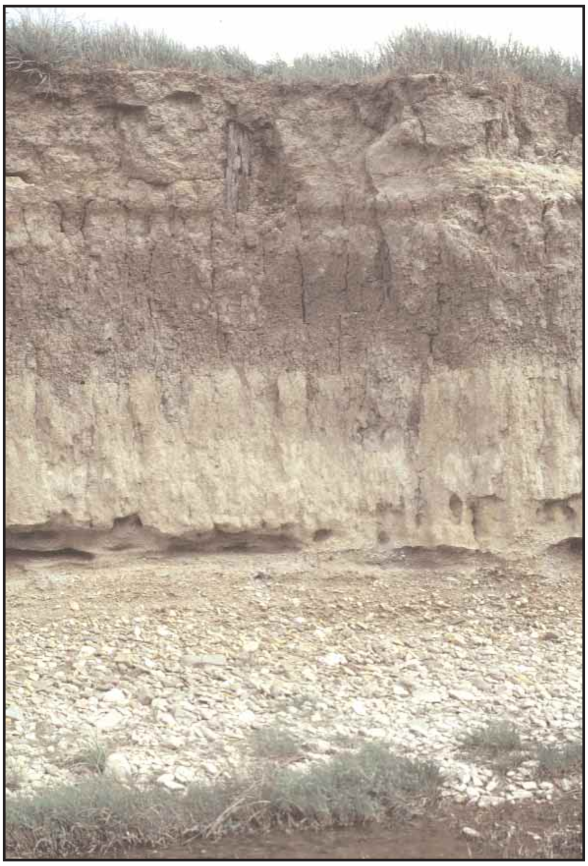

Figure 12. Post European Settlement Alluvium (PESA) on the banks of a gully in Victoria. Note the fence post buried in the upper centre of the photograph.

1.3. What happens if we do nothing?

The delivery of sediment to streams from mining, and from erosion in granite catchments, has declined over the latter half of this century. As a result, these slugs are typically moving slowly downstream as a sediment wave, becoming longer and flatter as they proceed (Gilbert, 1917; Pickup *et al.,* 1983). Thus, the typical channel sequence that you will see over the decades is rapid bed aggradation as the slug arrives, followed by gradual fall in the bed as the wave passes (eg. you will see old bridge piles gradually being exposed). In addition, the bed tends to coarsen as the finer sediment moves through, sometimes leaving an armoured gravel bed. The sediment will also leave some sediment behind in the channel as it moves through. This will be on point bars, as benches, and on the floodplain. If these deposits get colonised by vegetation, then the channel will gradually narrow, and a new sinuous channel will form. Of course, the pattern of adjustment can become more complicated as different tributaries deliver sediment to the stream at different times (Knighton, 1991). Eventually pools will empty of sediment as the original hydraulics of the channel are re-established as the slug moves through.

How long will it take for the sediment to move through? The steeper the channel and finer the sediment, the faster the slug will move through. Some streams have already emptied of sediment after decades. In larger streams, without intervention, it is sure to take centuries (Rutherfurd, 1996).

2. Appropriate tools for management

There are three main options for managing sand slugs:

1. **Intercept sand from upstream.** A weir or other structure can catch sand as it moves downstream. This will tend to clean the sediment out below the structure. Reducing the input of sediment in the first place is the most obvious option. This, however, could take decades to translate into a fall in bed levels downstream.

2. **Artificially remove the sand.** *Sand and gravel extraction as a rehabilitation tool*, in Intervention tools, this Volume, discusses the use of sand and gravel extraction as a management tool. There are many cases where extraction is the only real management option. With commercial extraction, this is sometimes viable, but only if you are able to remove material at the rate that it is transported into the reach, or greater.

3. **Stabilise the sand and constrict the channel.** Sometimes it is possible to gradually stabilise the sediment with vegetation. This will then constrict the channel and may maintain a deeper channel. Structures can also artificially constrict the channel (eg. groynes and retards).

WATER QUALITY PROBLEMS

- Water quality: an introduction
- Fine sediments and turbidity
- Nutrient enrichment
- Dissolved oxygen concentration
- High and low temperatures
- Salinity
- Toxicants

WATER QUALITY: AN INTRODUCTION

There is a wide variety of water quality problems which can affect our streams. However, only those that affect stream ecology are of concern to us in this manual, thus leaving out of consideration parameters important for drinking water, such as faecal coliforms, taste and odour. There are six ecologically important categories of water quality problem:

1. turbidity and fine sediments, that will restrict the area where photosynthesis can occur, clog the gills and guts of animals, and smother the stream bed;

> ***Please note:***
>
> That by mid-2000 a new version of the "Australian Water Quality Guidelines for Fresh and Marine Systems" is to be published by the Australia and New Zealand Environment and Conservation Council. These comprehensive guidelines will probably supersede the following sections.

2. nutrients that, under certain environmental conditions, will lead to nuisance plant growth, and in extreme cases eutrophication;
3. low dissolved oxygen that will cause the suffocation of stream organisms;
4. high and low temperature that will affect dissolved oxygen levels and the metabolism of stream fauna;
5. salinity that can have toxic effects on stream organisms, and also reduces dissolved oxygen concentrations; and
6. toxicants, a large group of toxic materials that includes heavy metals, oils, pesticides and herbicides, and a large variety of naturally occurring and synthetic chemicals used in fuels, manufacturing, and just about anything else one can think of.

1. Common attributes of water quality problems

Every water quality problem shares some common attributes.

1.1. The natural concentrations were variable and are now difficult to determine

Except for the synthetic toxicants, all of these forms of water pollution did exist naturally, although usually not to the extent now seen. Lowland rivers have probably always had higher turbidity and nutrient levels and temperatures than mountain streams. Terminal river systems, such as in the Wimmera River in Victoria's west, are naturally saline. Such lowland streams, with warmer, more saline waters, would always have had lower oxygen levels than cold, turbulent mountain streams. Even heavy metals are found naturally (in very small concentrations) in some streams, because of their presence in the local rock. It is clear that the natural levels of these water quality parameters varied from place to place, depending on geology, soils, climate and topography. Unfortunately, but not surprisingly, no one took too much notice of the natural levels during European settlement, unless the quality was noticeably bad. For example, Sturt commented on the salinity of the Darling River in 1829 because the water was too salty for him or his stock to drink (ANZECC, 1992a).

Why do the natural levels of these water quality parameters matter? The purpose of this manual is to help rehabilitate streams; that is, to return them to their natural state. If a stream was naturally saline, turbid, and had high nutrient loads, then these are not problems in terms of rehabilitation. Indeed, they represent a distinct habitat, often with a correspondingly distinct flora and fauna that should be preserved. Also, it is unlikely that we would have any success in 'improving' such problems beyond their natural condition. **So, the guidelines for water quality should reflect the geographical variation in natural conditions**. Unfortunately, in most cases the natural conditions are not known, and much historical, chemical and biological detective work is required to work out what they might have been. This means that almost all water quality guidelines are either not always appropriate, or given as a range of concentrations that are far too generalised to be very useful.

There are two possible approaches to narrowing this range to make it more specific to your stream. You should consider the potential effect of geology, soils, climate and topography, in combination with searching for historical records of water quality. A complementary approach would be to consider any historical records of plants or animals once found in the stream. The tolerances of these species (where these are known) will be indicative of the natural water quality (see *Biological site assessment* in Natural channel design, this Volume).

1.2. The concentrations of pollutants vary with flow

Stream flow is a major determinant of the concentration of pollutants. High flows will dilute some, while others become more concentrated.

Dilution occurs for pollutants that are delivered to the stream at a steady rate. For example, salts often enter saline streams directly from salty groundwater. The rate at which this occurs is not affected by a single flood. However, because of the larger volume of fresh water, the saline groundwater is diluted, and the salt concentration in the stream will drop. A similar situation would occur where there is a constant discharge of industrial wastewater.

By contrast, some pollutants, such as turbidity and nutrients, will become more concentrated during high flows. There are two reasons for this. Firstly, these pollutants are delivered to the stream chiefly by run-off, which increases during rain. Another example is the mix of toxicants that are washed off urban roads, houses and gardens in the first hour of a storm. Secondly, during high flows there is sufficient stream power to erode and transport sediment in the channel. This combination of factors results in high concentrations of these pollutants, often peaking before the flood itself peaks. A general rule-of-thumb is that 90% of sediment is transported in only 10% of the flow.

The variation in concentration with flow has serious implications for water quality monitoring. Large proportions of some pollutants are carried in peak flood events, which are difficult to monitor—they have unpredictable timing, and require multiple measurements through the flood hydrograph as there is not a predictable relationship between concentration of pollutants and flow.

1.3. The effects of pollution are not always well known

There has been relatively little research on the effects of pollutants on the Australian aquatic biota. Mostly, the guidelines are derived from northern hemisphere data. While this may result in suitable guidelines for Australian conditions, this will not always be the case. Trout, for example, are more tolerant of cold water and more sensitive to high temperatures than many native fish species. Temperature guidelines based on this fish would be inappropriate.

Mostly, water quality guidelines are based on the level of pollution that causes death in an organism. However, long-term exposure to lower levels of a pollutant may cause stress, resulting in lower rates of growth and development, which may flow through to lower reproductive success. Over generations, this can lead to the local extinction of a species.

If there is considerable variation in natural water quality, and in many cases we are uncertain of the effects of the water quality on stream plants and animals, how will you know if water quality is a problem in your stream? In the following chapters, we present **'Thresholds of concern'** for our six water quality problems. These are the levels at which the pollutants in question are likely to become a serious worry.

1.4. Options for biological monitoring

One way of getting around the problems of water quality monitoring is through biological indicators. This involves examining the species of plants or animals present in the stream. Possible water quality problems will be indicated by the sensitivity of species that are absent, and the tolerances of species that are present.

There are several advantages to biological monitoring. To an extent, it will bypass the issue of establishing accurate thresholds of concern, because you are measuring the biological effect directly, rather than relying on laboratory studies of a few species to tell you what important concentrations are. It also allows you to assess the cumulative effect of pollutants in different flows. Moreover, biological monitoring allows you to look for a large variety of possible pollutants in one test. For more information on this, see *Biological site assessment* in Natural channel design, this volume.

TURBIDITY AND FINE SEDIMENT

1. Introduction

Large quantities of fine sediment in streams will affect the stream biota in three ways. When travelling in the water column, the suspended sediment has optical effects, in that it creates muddiness or cloudiness that reflects or absorbs light. This effect is known as turbidity. Fine sediment also has physical effects. During high flows, sediment can abrade and scour plants and animals. At lower flows, material may be deposited, and can reduce habitat in the stream bed by filling the gaps between larger bed material, smothering benthic invertebrates, algae and fish eggs in the process.

1.1. Natural state

There is little doubt that, before European disturbance of catchments and channels, levels of turbidity and unstable fine sediment in many of Australia's streams would have been much lower than present levels, particularly at base flow. Flood events would naturally have been turbid, though again possibly not to the extent of present day floods. Australian rivers are generally thought to have high natural turbidity, because of the naturally sparse vegetation cover and high levels of fine clay in the readily erodible soils (Kirk, 1985). It is assumed that aquatic plants and animals have adapted to these levels. However, the lack of historical data means it is unclear just how turbid rivers would naturally be. Anecdotal evidence suggests that the Brisbane River (Stock and Neller, 1990), and even inland rivers such as the Lachlan and the Murray, were 'clear' until the early part of this century.

For undisturbed rivers at base flows, suspended sediment and turbidity levels are usually quite low, around 5 NTU (Nephelometric Turbidity Units) or 2–5 mg/L (Parliament of Victoria, 1994). During floods, fast-flowing streams are able to carry a lot more sediment, which may be eroded from the stream bed and banks, and also by the floodplain run-off. However, in undisturbed streams the increases in turbidity during floods are relatively small; in the order of 100 NTU in the southern States (Parliament of Victoria, 1994).

1.2. How has it changed

A variety of land management practices has contributed to increased levels of turbidity and sedimentation. In-channel sources of fine material include channel erosion, instream works such as bridge and dam construction, and sand and gravel extraction. Out of channel sources include run-off from tilled land and farm tracks, forestry tracks and stream crossings in upland areas, and run-off from urban areas and construction areas.

Extreme examples of the gross effects of accumulated sediment can be found in some lowland streams in the cane lands of far north Queensland. Bunn *et al.* (1997) estimated that approximately 20,000 tonnes of inorganic sediment had accumulated per kilometre of stream channel in the exotic 'Para' grass in Bamboo Creek, near Innisfail. Oxygen penetration was limited to a few millimetres and few benthic invertebrates were recorded by Bunn *et al.* (1997) in their study of the food web.

2. Biological impacts of turbidity and fine sediment

2.1. Aquatic plants

Aquatic plants include macrophytes and benthic and planktonic algae. Benthic algae refers to the mixture of algae, diatoms, bacteria and fungi which forms the 'biofilm' on submerged surfaces. This layer is the food source for many macroinvertebrates.

Fine sediment: Benthic algae is susceptible to damage in turbid environments by the scouring and abrading effect of the mobile sediment during high flows. Deposition of the suspended sediment is also a problem as it will smother algal growth. Even when very little deposition occurs, sediment can adhere to the biofilm and reduce its potential as a food source. Emergent aquatic plants such as water ribbons (*Triglochin* spp.) and cumbungi (*Typha* spp.) are less vulnerable to damage by high sediment loads, because their photosynthetically active areas are above the water.

Turbidity: Turbidity also affects the growth and health of benthic algae and submerged macrophytes. Again, the emergent macrophytes are less susceptible to damage. The decrease in light and heat transmitted through turbid water, reduces the rate of photosynthesis and thus the production of new algal material. Davies-Colley *et al.* (1992), working in New Zealand, found an increase of 25 NTU in a previously clear stream resulted in a 50% reduction in plant production, and levels as low as 7 NTU (9 mg/L) could have a significant effect (Davies-Colley *et al.,* 1992; in Parliament of Victoria, 1994). In muddier waters, when suspended solids reach 150 mg/L, almost no light penetrates beyond 8 cm depth (US EPA, 1971; in Garvin *et al.,* 1979). The depth of light penetration limits the depth at which algae, the primary producer, can grow. In effect, low flow turbidity will limit the volume of stream habitat that is actually available to the stream biota.

The effect of the nutrient loads commonly associated with suspended sediment loads cannot be ignored. Though high turbidity will reduce light penetration into water, and so reduce plant productivity, in shallow water or in the upper layer of stable water it can have a dramatically opposite effect. Algal productivity which was previously limited by low phosphorus and nitrogen levels can dramatically increase (Grayson *et al.,* 1996). This can lead to nuisance growth of aquatic macrophytes, and also to eutrophication of the stream or water body—an excess of algae smothering all other life, and sometimes poisoning the water. It is thought the 1000 km long blue-green algal bloom on the Darling River in 1991 was largely a result of high nutrient loads.

2.2. Aquatic macroinvertebrates

Fine sediment: Density of macroinvertebrates has been shown to decrease in response to increased fine sediment levels. Invertebrates are affected by the decrease in quality of a major food source, the benthic algae. Deposition of sediment may smother individual invertebrates and their eggs, and can decrease habitat diversity by filling spaces between the stones and reducing dissolved oxygen in the stream bed (Quinn *et al.,* 1992). Sedimentation will also decrease the area of clean surfaces available for those species which require such conditions to attach themselves to the stream bed. High levels of suspended sediment may also damage the gills of all aquatic invertebrates, and the feeding organs of filter feeders such as mussels or blackfly larvae. Metzling *et al.* (1995) reviewed several studies on the effects of sedimentation during dam construction in south-eastern Australia. Over 40 genera of macroinvertebrates were found to decrease in abundance downstream of construction sites. A review of North American research by Newcombe and MacDonald (1991) emphasised the importance of considering the duration as well as the concentration of suspended sediment. They reported lethal effects of suspended sediment at levels as low as 8 mg/L (a short exposure of 2.5 hours resulted in less than 20% mortality, while prolonged exposure of 60 days resulted in up to 50% mortality). In New Zealand, Quinn *et al.* (1992) reported that turbidity increases of 7–154 NTU over several months resulted in decreases in invertebrate density of 9–45%.

Turbidity: Turbidity appears to have little direct effect on macroinvertebrates. The biggest impact is on the growth of benthic algae, which is a major food source for many macroinvertebrates.

2.3. Fish

High turbidity levels can cause stress in fish, reduce feeding efficiency and growth rates, and increase disease (Koehn and O'Connor, 1990). These reactions have been reported at levels as low as 14 mg/L for one North American fish species (coho salmon), though generally reactions are noted when suspended sediment levels reach three figures (Newcombe and MacDonald, 1991). Aside from the direct effects outlined below, fish will also suffer a decrease in food supply because of the effects on algae and invertebrate densities. The European Inland Fisheries Advisory Commission (1965) (in Garvin *et al.,* 1979) suggested that less than 25 mg/L suspended sediment would have no harmful effect on fisheries, between 25 and 80 mg/L would have only a moderate effect, while between 80 to 400 mg/L would be 'unlikely to support good fisheries'.

Fine sediment: Damage to gills has been reported after exposure to over 1,500 mg/L (for rainbow trout, a commercially valuable species in Australia), though fish survived concentrations of 5,000–300,000 mg/L despite damage to their gills (Slanina, 1962). One of the few experiments done on Australian fish found 28, 38 and 60% mortality in common galaxias in response to laboratory exposure to 800, 1,700 and 3,600 mg/L, respectively (J. Koehn, unpublished data in Parliament of Victoria, 1994). Breeding also suffers when deposition occurs. Sediment can smother fish eggs, and may prevent spawning in species which require clean surfaces on which to attach their eggs. Deposition can also reduce habitat used by juveniles and species of small fish. The reduced distribution of Macquarie perch, which deposits its eggs in gravel, is thought to be related to sedimentation in streams (Metzeling *et al.,* 1995). Table 5 lists the native fish in Victoria that are susceptible to egg damage by sedimentation.

Table 5. Native Victorian fish species which lay eggs on or amongst the stream bed and would be liable to smothering due to increased sediment deposition. Source Metzeling *et al.* (1995), adapted from Koehn and Morison (1990).

Species	Conservation status
Geotria australis (pouched lamprey)	Potentially threatened
Galaxias oldidus (mountain galaxias)	Indeterminate
Galaxias brevipinnis (climbing galaxias)	Potentially threatened
Galaxias rostratus (flat-headed galaxias)	Indeterminate
Retropinna semoni (Australian smelt)	Common/widespread
Protrocetes maraena (Australian grayling)	Vulnerable
Tandanus tandanus (freshwater catfish)	Vulnerable
Craterocephalus stercusmuscarum (freshwater hardyhead)	Indeterminate
Nannoperca australis (southern pygmy perch)	Common/widespread
Gobiomorphus coxii (Cox's gudgeon)	Indeterminate
Maccullochella peelii (Murray cod)	Vulnerable
Maccullochella macquariensis (trout cod)	Endangered
Arenigobius bifrenatus (bridled goby)	Common/widespread

Turbidity: The effects of turbidity on fish are not known, but it is likely that significant turbidity would reduce the hunting success of those carnivorous species which rely on sight to catch their food.

2.4. Frogs

Frog eggs, like fish eggs, are prone to smothering by deposition of sediment. Once hatched, tadpoles rely on gills to extract oxygen from the water. Like fish and macroinvertebrates, they are susceptible to damage under extremely turbid conditions, as are the feeding organs of those species which filter feed. Other species graze on algae, and will thus suffer a reduction in food source as lower light levels decrease algae productivity. Adult frogs are less likely to be disadvantaged by high turbidity, as they are largely terrestrial.

2.5. Reptiles

High levels of turbidity are unlikely to have a direct adverse effect on reptiles (Parliament of Victoria, 1994). However, species such as the long-necked tortoise and the red-bellied black snake which rely on aquatic systems as a food source may be affected by the decreases in frog and fish numbers.

2.6. Birds

Turbidity will affect the hunting success of kingfishers, which need to see their prey. Small rises in turbidity are sufficient to shield fish from the gaze of searching kingfishers. The azure kingfisher, which relies solely on aquatic food sources would be particularly disadvantaged.

2.6. Platypus

Platypus hunt with their eyes, ears and nostrils shut, relying on the sensitive skin and electroreceptors in the bill to detect the macroinvertebrates which are their prey (Grant, 1995). As such, their hunting ability should not be directly affected by high turbidity levels. However, they may be affected by the decreases in macroinvertebrate density.

2.7. Water rats

Water rats do not depend solely on aquatic systems for food, though much of their food does come from this environment. As such, it is likely they are able to find alternative food sources, at least during short term turbidity events.

3. Other water quality issues

When considering the reasons for a lack of stream biota (or perhaps an excess of algae), it is important to remember turbidity is only one of many aspects of water quality that could be responsible. High turbidity is often correlated with the presence of other pollutants, such as fertilisers, pesticides and heavy metals. This is partly because these are often transported bound to sediment particles. However, there may be more efficient ways of tackling water quality problems than through turbidity alone. In some cases, turbidity may not be high enough to cause problems in itself, but the chemicals associated with that turbidity can have major impacts on the stream. The main sources of sediment may not be the main sources of nutrients and toxic compounds. All aspects of water quality should be considered when attempting to reinstate the stream biota.

4. How do you recognise turbidity and fine sediment?

4.1. Field characteristics

Fine sediment: Suspended sediment refers to the load of sediment carried in suspension in the water rather than moving on the bed of the stream. Without actually measuring this sediment, it is not easy to judge how much is present. The turbidity of water is an unreliable guide to the amount of suspended sediment present, as different sized particles have different optical effects. Fine sand in suspension will have a less muddy appearance than a much smaller quantity of clay.

After high flows, the coarser portion of suspended sediment will settle on the stream bed, where it will smother invertebrates and algae. From here it can be resuspended in subsequent high flows. It can be difficult to tell if such deposition is occurring on a stream bed, as some fine material is naturally present in most systems. However, if silt or mud is blanketing the stream bed or totally filling spaces beneath gravel and cobbles, it is likely there is a problem.

Turbidity: While suspended, the turbidity effect of fine sediment is easily recognisable as cloudy or muddy water. At low levels, variation in turbidity can be detected by eye, but it is important to be aware that the depth you look through will influence how turbid the water seems to be. Purely visual surveys of turbidity are not accurate.

4.2. Measurement techniques

Fine sediment: Ignoring the more complex issues of suspended sediment distribution through the stream, measurement is a simple matter of taking a water sample of known volume, and filtering, drying and weighing the sediment. The results are expressed as milligrams of sediment per litre of water (mg/L).

Turbidity: Turbidity is a measure of how the suspended sediment affects visibility. Turbidity is measured by the amount of light reflected or absorbed as it passes through the water (usually in NTU—Nephelometric Turbidity Units).

Table 6 gives some idea of how turbidity and suspended sediment levels relate to the water you see around you.

Table 6. Examples of levels of turbidity or suspended sediment concentration (mg/L) seen in water in Australian streams (NTU =Nephelometric Turbidity Units; NK = data not known).

NTU	mg/L	
5	NK	Maximum turbidity for drinking water (just visible in a glass of water) (NHMRC Environmental Health Committee, 1994).
5	2–5	Natural levels for Victorian highland streams at base flow (Parliament of Victoria, 1994).
5.3	10	Yarra River at Launching Place, Victoria (well before it reaches Melbourne) (unpublished EPA data in Parliament of Victoria (1994)).
32	50	Yarra River at the Chandler Highway, in Melbourne, Victoria (unpublished EPA data in Parliament of Victoria (1994)).
1	NK	Mitchell River, Queensland, normal background levels (Frankcombe and Whitfield (1992); in Parliament of Victoria (1994)).
70–80	NK	Mitchell River, Queensland, in times of flood (Frankcombe and Whitfield (1992); in Parliament of Victoria (1994)).
NK	705	Mean during a flood (recurrence 1 in 2) on the Annan River, northern Queensland (Hart and McKelvie, 1986).
NK	12	Mean during low flows on the Annan River, northern Queensland (Hart and McKelvie, 1986).
NK	40	Murray River at low flow (Ian Rutherfurd, personal communication).
NK	300	Murray River at high flow (Ian Rutherfurd, personal communication).
NK	3000	The Queen River, Tasmania (Locher, 1996).

A big issue with measurement of turbidity and suspended sediment is the great variability in concentrations observed at different flows. By far the highest turbidity, and greatest quantity of suspended sediment is transported during peak flows (about 90% of the sediment is transported in less than 10% of the time in most streams). This poses several problems. Firstly, do you attempt to take measurements during high flows, and secondly, which flows will actually cause problems for the stream biota? The impact of fine sediment and turbidity on stream biota depends on the duration as well as the intensity. As far as turbidity is concerned, it may well be the extended low flow levels that are critical; thus, this is probably what should be measured. Conversely, the scouring effects of fine sediments occur at high flows, and the smothering effects are probably greatest just after periods of high flow.

Where turbidity is caused by organic rather than inorganic solids, such as downstream of a sewage farm or a wood-pulping plant, decomposition of the organics can dramatically lower the dissolved oxygen and suffocate the stream biota. Inorganic turbidity composed of metal particulates can have toxic effects beyond those of biologically inactive sediment. The following comments relate to inactive inorganic sediment, though they may also be applicable to organic and toxic sediment.

> The impact of a turbidity event depends on its intensity and the duration (Newcombe and MacDonald, 1991). Thus, long-term low levels of suspended sediment can have effects on the stream biota as profound as much higher levels lasting only a short time.

5. At what stage does turbidity and fine sediment become a problem?

As mentioned above, the great difficulty in measuring turbidity and suspended sediment is the huge variation in concentrations depending on flow. The same can be said for setting reasonable guidelines for turbidity. Even in the best systems, an extreme flood could be accompanied by extreme turbidity. The best way to get around this problem is to look at the frequency distribution of turbidity levels. For example, the Victorian EPA (EPA State Environment Policy in Parliament of Victoria, 1994) requires suspended sediment to be below 80 mg/L for 90% of the time. The Index of Stream Condition (DNRE, 1997a) uses a similar system, examining turbidity in terms of the median value (that is, at this point, 50% of the readings fall above the median, and 50% fall below). This system does require regular monitoring in order to get an appreciation of the range of values. Table 7 rates various turbidity levels for Victorian streams.

Table 7. Guidelines for median turbidity levels (NTU). From the Office of the Chief Commissioner for the Environment cited in DNRE, (1997a). Note that these values are applicable only to streams in the south-east of Australia.

Mountain	Valley	Floodplain	Rating
<5	<10	<15	Ideal
<7.5	<12.5	<17.5	Close to ideal
<10	<15	<20	Moderately different from ideal
<12.5	<22.5	<30	Substantially different from ideal
>12.5	>22.5	>30	Far from ideal

6. Possible treatments of turbidity

It is beyond the scope of this manual to provide information on controlling erosion and suspended sediment. There are detailed guides that assist with the three approaches to managing turbidity: (a) reducing the erosion at its source; (b) trapping the sediment before it reaches the stream; and (c) trapping the sediment in the stream. The most effective of these techniques is the first: reducing the erosion rate. The finer sediment is, the less effective sediment traps become, so dams, detention basins and buffer strips are a second-best option for managing sediment.

Reducing the erosion of sediment relies on identifying where this erosion is occurring. There are many studies that identify sediment sources and sinks (eg. Erskine and Saynor, 1995), but most stream managers cannot afford to do complex isotope tracing or sediment budget studies, or measure large numbers of suspended sediment concentrations. We would suggest that a good start for stream managers (especially in small catchments) is to hunt for turbidity sources themselves.

Turbidity cannot be accurately estimated by eye, because it appears to increase with depth, when in fact the suspended sediment concentration does not change. Therefore, when hunting for turbidity sources, it is important to use a turbidity meter. Take measurements of turbidity throughout your stream network, perhaps running down the trunk stream first. Divide the stream into segments, based on tributary inputs and obvious land-use boundaries. Sediment sources may vary, depending on flow, so complete this survey at both high and low flows. During low flows, the survey can be completed over several days. However, during high flows, the turbidity levels will change with the flow. For this reason, a high flow turbidity survey should follow the flood peak downstream. In such surveys, it is not unusual to find that a single road crossing is the major source of turbidity in a small catchment, as shown in Figure 13.

Figure 13. A plume of sediment entering a stream from a road crossing in the headwaters of the Mary River, Queensland.

If you have identified a discrete sediment source such as a gully, an eroding stream bank, a road culvert, or even a particular type of land use in the catchment, then there is a range of techniques available for you to manage the erosion, such as revegetation, check banks, buffer strips, and so on. A huge amount of information is available on managing such point sources of erosion. We stress here that the main problem is often identifying a source that can be managed, not managing the sediment.

The most difficult problem is managing sediment from diffuse general sources. Riparian vegetation may be a very useful buffer, but this relies on run-off being filtered through grass, leaf litter and soil. Often water will flow through a buffer strip in small channels, and this will dramatically reduce the effectiveness of the buffer strip. Thus, wholesale riparian revegetation is not necessarily a panacea for high turbidity levels. The Riparian Zone Guidelines, published by LWRRDC, provide information on buffer strips (see www.rivers.gov.au).

Key points about turbidity

- Turbidity and fine sediment can damage organisms.
- Australian streams have very variable turbidity levels. Some streams have naturally high turbidity.
- When monitoring, you need to distinguish between high and low-flow turbidity.
- Is your problem high or low-flow turbidity? Each could have a different source.
- A turbidity survey of your catchment could help to track down whether there are obvious sources of high or low-flow turbidity.
- Whilst there are many good techniques for managing point sources of turbidity, managing diffuse sources requires a catchment-wide and long-term approach.
- Turbidity can be difficult to manage, particularly if it is associated with a high percentage of clay (ie. sediments smaller than say 0.004 mm diameter).

NUTRIENT ENRICHMENT

1. Introduction

High levels of the main plant nutrients, nitrogen and phosphorus, can have important impacts on the biota of our streams. Increasing the nutrients available can result in increases in algae and macrophytes in the stream, in extreme cases leading to blooms of toxic planktonic algae, streams choked with macrophytes, or smothering of the stream bed with algae. Extreme quantities of plant material can severely deplete the oxygen in the water, leading to fish kills. Even where plant growth is not obviously excessive, nutrient levels may be high enough to cause changes to invertebrate communities, and may have the potential to cause algal blooms or eutrophication, given the appropriate flow and temperature regime.

1.1. Natural state

Australia has some of the most nutrient-poor soils in the world. It follows from this that natural nutrient levels should also be low. Nevertheless, natural nutrient concentrations are not the same across Australia: they vary depending on variables such as geology, soil type, climate and topography. An alpine stream will have naturally lower nutrient levels than the lower Darling, for example. Present nutrient levels in forest streams of south-western Western Australia are so low they approach the extremely low concentrations found in the open oceans. It is of course impossible to establish with certainty the pre-European levels of nutrients in those streams where land-use changes and wastewater discharge have so altered water quality (ie. most of Australia's rivers). However, some information is available from streams in relatively untouched catchments, and from the relationship between nutrient concentrations and the distribution of nutrient sensitive invertebrate species. It is possible to make a good judgment of at least the nutrient load that will not adversely affect the healthy functioning of aquatic ecosystems, if not the natural level. To the best of our knowledge, such information exists only for Victoria, in a report published by the Victorian EPA (Tiller and Newall, 1995).

1.2. How it has changed

Diffuse and point source impacts such as nutrient-rich run-off and irrigation wastewater from fertilised farmland, erosion of nutrient-carrying sediment, animal wastes, discharges from sewage-treatment plants, urban drains and industrial sources of organic rich wastewater have all contributed to increased nutrient loads in Australia's streams, in extreme cases two orders of magnitude higher than estimated natural loads (ANZECC, 1992a). This increase is partly due to increases in turbidity. Phosphorus readily becomes adsorbed onto clay particles. This means that erosion of soil and stream banks can be a significant source of nutrient. Once in the stream, most of the phosphorus is transported with the clay. Thus, high turbidity usually correlates with high levels of phosphorus (Grayson *et al.,* 1996).

2. Biological impacts of nutrient enrichment

There are four ways in which nutrient enrichment can affect stream ecology. You should remember that these effects will be magnified at downstream sites where sediment and nutrients collect in lakes, reservoirs and estuaries.

1. Relatively small increases in nutrient enrichment can increase plant and algal productivity, which in turn provides increased food for some invertebrate species. This can result in sensitive species (eg. many stoneflies, mayflies and caddis flies) being lost, and pollution-tolerant species (eg. various snails, worms, and chironomids) becoming more common.
2. In combination with appropriate environmental conditions (light, temperature, flow etc.) nutrient enrichment can lead to prolific growth of filamentous green algae and macrophytes. These can reduce water velocities and trap sediments and in extreme cases effectively choke the stream channel resulting in a considerable direct loss of aquatic habitat (see Bunn *et al.,* 1998). Such stands can form barriers to fish passage.

3. Where conditions favour the development of planktonic algae there is the possibility of an algal bloom developing. The most famous example of this is probably the algal bloom that turned over 1,000 km of the Darling River bright green during November 1991. In such situations, algae cell numbers can reach surprisingly high levels (over 10 million cells per mL (ANZECC, 1992a). Algal blooms cause the same eutrophication problems as filamentous algae and macrophytes. To make matters worse, cyanobacteria, or blue-green algae, are often found in large numbers during algal blooms. Also, some species of cyanobacteria produce toxins, including liver toxins, neurotoxins (attack nerves), cytotoxins (attack cells) and endotoxins (mainly contact irritants).

4. When high nutrient levels and suitable environmental conditions allow excessive plant growth, either of macrophytes or algae, this can lead to eutrophication. The decomposition of large quantities of plant material, combined with the respiration needs of the living plants, will deplete the water of oxygen, and alter the pH, particularly in the deeper pools. This results in the death of fish and macrocrustaceans. The same process will occur if large quantities of organic waste (eg. sewage, animal wastes) are dumped into streams.

Figure 14. Filamentous algae in a rural stream, probably associated with high nutrients and water temperatures.

3. How do you recognise nutrient enrichment ?

3.1. Field characteristics

The obvious way to recognise high-nutrient problems is through searching for excess growth of algae and macrophytes. Shallow, faster-flowing streams are prone to infestations of filamentous algae and macrophytes, while deeper, slower flowing rivers are more likely to suffer planktonic (free floating) algal blooms (ANZECC, 1992a). This is largely because light is often limiting in the larger streams, and many planktonic algae can cope with this problem by altering buoyancy to keep near the surface of the water.

3.2. How to recognise algal blooms

While well-developed blooms are unmistakable, early stages, or small blooms can be more difficult to detect.

- A bloom will increase the turbidity, because the algae cells disperse through the water.

- The colour of the water will change. As the concentration of cells increases, so does the amount of chlorophyll, the green pigment in plants. Some blue-green algae form floating colonies of hundreds of cells, which look like green sawdust (Sainty and Jacobs, 1994).

- As the bloom develops, a scum of cells may appear on the water surface.

- Well-developed blooms may smell. Some species of blue-green algae are 'earthy or muddy smelling' (Sainty and Jacobs, 1994). Also, whatever the dominant species of algae, when blooms are decaying, they can produce a rancid, putrid smell.

There are two very important limits to using excess plant growth to mark high nutrient levels.

1. An absence of nuisance plant growth does not necessarily mean there is no nutrient problem.

   Though prolific growths of macrophytes and algae do indicate high nutrient levels, the absence of them does not necessarily mean there is no problem. This is because there are other factors which also regulate plant growth; namely light, temperature, current velocity, substrate suitability and grazing pressure (ANZECC, 1992a). Macrophytes require some fine sediment to root in, and, as with filamentous and other attached algae, need a stable bed. Plants and algae also need light, so deep turbid streams are unlikely to develop infestations. This is despite the way high turbidity often correlates with high nutrient levels. Some planktonic algae can cope with turbid water by altering buoyancy, and floating near the surface. However, the turbulence of flowing water will prevent these algae from remaining near the surface, and so limit growth. For example, nutrient levels in the lower Goulburn River in Victoria are probably always high enough to sustain an algal bloom, but usually the low light penetration through the turbid water, and the turbulence in the moving water prevent a bloom from developing (Tiller and Newall, 1995). Such nutrient-rich streams will suffer blooms during periods of low flow when turbidity and turbulence decrease.

2. Even if nutrient levels are not producing algal blooms at your site, they may be causing a problem downstream.

   Nutrients are transported downstream and will accumulate in the sediments of lakes, reservoirs and estuaries. Moderately high nutrients upstream may eventually cause severe nutrient problems at these downstream sites, so reducing nutrient inputs into streams is always important.

3.3. Measurement techniques

Water samples should be taken from midstream, and about mid-depth. Field test kits that measure nutrient concentration are available, but tests done in an accredited laboratory are more reliable. Talk to the laboratory about what techniques you should use to preserve samples.

- How should you analyse the nutrient concentration in your water sample? Water samples can be analysed using field test kits, such as those used by Waterwatch, or sent to a laboratory for analysis. Though the first option is cheaper, there are two important limits to field test kits. Firstly, they may be unable to detect low concentrations of nutrients. As natural levels of nutrient are very low, these tests will be unable to detect the smaller increases in concentration. Secondly, such tests measure only the dissolved nutrients, which will underestimate the nutrient present. Nitrogen and phosphorus will attach to fine sediment particles, and a significant proportion of the nutrient will travel in this way rather than dissolved in the water. Also, nutrient guidelines given here are based on the total nutrient concentration, rather than the dissolved fraction.

- Is there a existing monitoring program you can use? There are already many groups who monitor water quality, and it may be that enough information already exists to assess the nutrient status of your stream. Ask the EPA or equivalent in your State, as well as any local bodies such as catchment management authorities. When searching for relevant data, a single sampling site can be indicative of the nutrient concentrations for 40 or 50 km upstream, so long as it is distant from point sources of nutrients (and land use does not substantially change) (David Tiller, EPA, Melbourne, personal communication).

- Where should you sample? It is important to think carefully about where you take samples. The sites you choose will depend on whether you wish to assess the impact of a possible point source of nutrients, or measure the background level of nutrient. If you wish to monitor a point source, then obviously you should sample just downstream of that point source. However, if it is the background nutrient levels then it is important to avoid possible point sources.

- How often should you monitor? So long as the sample was taken at a representative base flow (that is, not during a drought, but not just after rain), one sample may be indicative of the background nutrient concentrations for that location. However, it is always safer to have more than one sampling site if you want to be sure that your measurements are representative of the water body.

- When should you measure? Nutrient concentrations vary, depending partly on stream flow. The large majority of the nutrient carried by a stream is moved during flood events, when run-off delivers nutrient from the catchment straight into the stream, and the high flows carry more suspended sediment with its associated nutrient load. It is the total annual nutrient load, dominated by peak flows, that is most important to the ecology of lakes and estuaries downstream. However, intensive sampling during flood events is required to calculate this. It is the concentration of nutrient in the water during base flow that contributes to the growth of nuisance plants in streams, so it is this measure that is used in Victoria's nutrient guidelines (Tiller and Newall, 1995).

4. What nutrient concentration is a problem?

4.1. What are fatal nutrient levels?

There is no need to assign numbers to describe fatal concentrations of phosphorus and nitrogen. When your stream has reached a fatal level, it will become obvious because of the nuisance growth of macrophytes or algae that smother all instream habitat, or the regular algal blooms, that cause eutrophication, leading to regular fish kills. In this situation, nutrient enrichment is the limiting factor. Any attempt to improve the ecology of such a stream should start with strategies to reduce nutrient inputs, and to reduce the likelihood of further eutrophication by managing the other factors that can control algal growth—namely light, temperature, current velocity, substrate suitability and grazing pressure.

4.2. Thresholds of concern

As described in the introduction, natural concentrations of nitrogen and phosphorus would have varied from region to region. For this reason, Australia-wide guidelines are relatively meaningless. The Australian Water Quality Guidelines for Fresh and Marine Waters (ANZECC, 1992a) acknowledge this variability, and suggest the following range of concentrations as indicative of potential nuisance plant growth. They recommend site-specific studies to provide more specific guidelines.

Total phosphorus	0.001–0.1 mg/L
Total nitrogen	0.1–0.75 mg/L

To the best of the authors' knowledge, Victoria is the only State having region-specific nutrient guidelines. Tiller and Newall (1995) divided the State into seven ecoregions, on the basis of topography, run-off, and tract type (see Figure 15). The regions, and their respective guidelines, are summarised below. Most of these regions could probably be extended into at least southern New South Wales and south-eastern South Australia (David Tiller, EPA, Melbourne, personal communication). The report, available from the Victorian EPA, contains more detailed descriptions of the regions, a discussion of how the guideline values were obtained, and the limits to these guidelines. These are preliminary guidelines. For some regions, where adequate information was not available, guidelines were based on the principle of no worsening of present water quality. An updated set of guidelines is due to be released towards the end of 1999.

> ***Important:*** Where possible, the following nutrient guidelines are based on 'threshold levels beyond which marked ecosystem degradation has been observed', rather than 'fatal' concentrations. If your stream is above these threshold concentrations, then reducing nutrient load should be an aim of your rehabilitation. If your stream is below the guidelines, you should aim to at least maintain current concentrations.

4.3. Highlands river region

This region includes most areas in Victoria above 1000 m altitude. Most of the area is minimally disturbed, and is covered by forest or alpine vegetation. Streams are typically small (less than 4 m), shallow and very clear.

Threshold of concern for total phosphorus	0.020 mg/L
Threshold of concern for total nitrogen	0.150 mg/L

4.4. Murray foothills river region

This region is part of the eastern Victorian uplands to the north of the Great Dividing Range. Pre-European vegetation ranged from open forest to woodland, but has mostly been cleared and converted to pasture. Streams typically have pool and riffle sequences and well-shaded banks (where the riparian vegetation remains).

Threshold of concern for total phosphorus	0.030 mg/L
Threshold of concern for total nitrogen	0.200 mg/L

4.5. Southern and isolated foothills river region

This region is the southern equivalent of the Murray foothills, draining the lower relief areas to the south of the Great Dividing Range. It extends from East Gippsland, through central Victoria, to the upper Hopkins catchment. The isolated foothills component consists of the Grampians, the Otway Ranges, the Strezlecki Ranges and

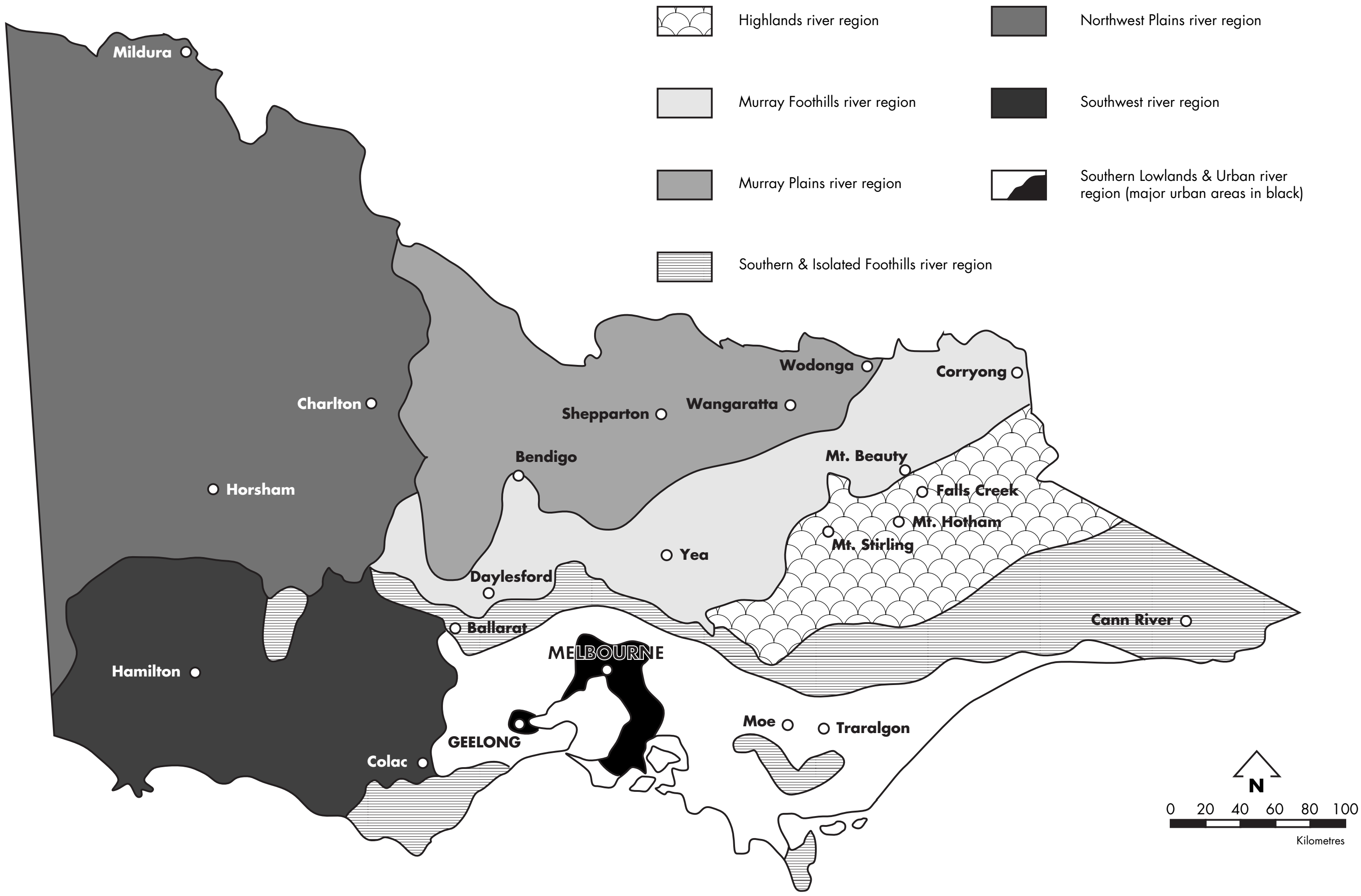

Figure 15. River regions of Victoria, corresponding to the regional guidelines given in the text (from Tiller and Newall, 1995). Reproduced with permission from the Victorian EPA.

Wilsons Promontory. Natural vegetation cover was mostly medium open forest, which today is largely undisturbed or subject to logging in the east of the region. To the west, the land has been converted to pasture and crops. Streams are similar to those in the Murray foothills.

Threshold of concern for total phosphorus	0.030 mg/L
Threshold of concern for total nitrogen	0.200 mg/L

4.6. Murray plains river region

This is a low relief region in the north-eastern and north-central parts of the State, and includes the lower reaches of the Ovens and Goulbourn catchments, and most of the Broken, Campaspe and Loddon catchments. The pre-European vegetation was woodland.Low woodland has mostly been cleared, and the region now supports irrigated and dryland pasture and crops. Rivers are typically deep, clay-bottomed, and turbid.

Threshold of concern for total phosphorus	0.050 mg/L
Threshold of concern for total nitrogen	0.600 mg/L

4.7. Northwest plains river region

This region is typically low elevation sandy plains and dune fields with low run-off. The natural open scrub, shrublands and grasslands have been mostly replaced by dryland cropping or grazing. Streams in this region may be intermittent, and tend to run into terminal lakes. There is a lack of information on the effects of nutrient concentrations in these systems, so these guidelines are based on no deterioration of the current water quality.

Threshold of concern for total phosphorus	0.050 mg/L
Threshold of concern for total nitrogen	0.900 mg/L

4.8. Southwest river region

The southwest region consists of basalt lava plains and coastal plains. The woodlands and tussock grasslands vegetation have mostly been replaced by crops and grassland. A few streams in the area are intermittent. Streams are often slightly turbid, and many have high salinities. Once again, a lack of information on these streams means these guidelines are based on no deterioration of present water quality.

Threshold of concern for total phosphorus	0.035 mg/L
Threshold of concern for total nitrogen	1.000 mg/L

4.9. Southern lowlands and urban river region

This region is delineated by human influences. It includes Melbourne, Geelong and the Latrobe Valley. The non-urban portion of the region is mostly under intensive agriculture. The streams are typically the most disturbed in the State, and are often slow-flowing, turbid, incised and polluted with litter, high nutrient concentrations, heavy metals and petroleum hydrocarbons. Because of the differences in condition of rural and urban streams in the region, the streams have been divided into three classes: rural lowland rivers and tributaries; large lowland urban rivers; and urban tributary streams. Due to the high concentration of nutrients in urban streams, it was recognised that guidelines aiming at no impact on stream ecology would be impossible to meet, at least in the short term. For this reason, compromise, interim guidelines are proposed to offer more achievable goals. Meeting these interim guidelines will not reduce plant production, but will still represent a significant improvement in the water quality of most urban streams.

Rural lowland rivers and tributaries:

Threshold of concern for total phosphorus	0.050 mg/L
Threshold of concern (TOC) for total nitrogen	0.600 mg/L

Large lowland urban rivers:

	Interim	Long term
TOC for total phosphorus	0.080 mg/L	0.050 mg/L
TOC for total nitrogen	0.900 mg/L	0.600 mg/L

Urban tributary streams

	Interim	Long term
TOC for total phosphorus	0.100 mg/L	0.030 mg/L
TOC for total nitrogen	1.000 mg/L	0.200 mg/L

5. Possible solutions/treatments for nutrient enrichment

It is far easier to prevent nutrients from entering our streams than it is to remove nutrients already in the stream. There are three types of nutrient source: point sources; diffuse sources; and instream sources.

1. Point sources are discrete sources of nutrient, such as a stormwater drain, wastewater treatment plant outlets, or farm effluent from dairy sheds or feedlots.

2. Diffuse sources have no clearly defined source, but enter the stream from a large area of the catchment. Examples are farm run-off containing fertiliser or animal wastes, animal wastes entering the stream directly because of stock access, soil erosion, or run-off from forestry areas.

3. Instream sources are usually nutrient that has been stored in sediment in the stream banks or bed. When these are eroded, the nutrient once again enters the water body. This source of nutrient is difficult to treat.

Further Reading

For further information see State of Victoria (1995).

DISSOLVED OXYGEN CONCENTRATION

1. Introduction

All animals and plants require oxygen. It is essential for respiration, the process by which sugar is converted into the energy needed for every part of life. Oxygen from the air is dissolved in water, where it is available to aquatic organisms. Without sufficient dissolved oxygen, aquatic animals would die, just as we would if there was no oxygen in the air we breath.

1.1. Natural state

The concentration of oxygen in water depends on how easily oxygen can dissolve, and the balance between oxygen input and use within the water.

The amount of oxygen that will dissolve depends on the temperature and salinity of the water. Increases in both temperature and salinity will cause a decrease in dissolved oxygen. In fresh water at 10°C, the maximum concentration possible (ie. the water is saturated with oxygen) is just over 11 mg/L. At 25°C, this will fall to around 8 mg/L. This effect is visible when water is heated. Well before boiling, small bubbles will form, as gases which were previously dissolved, leave solution.

Oxygen enters water by diffusing from the air through the water surface. In turbulent streams, where the water is well mixed, the dissolved oxygen concentration is usually fairly close to saturated. However, in deeper, slow-flowing streams, the oxygen concentration may fall below saturation. When deep pools stratify, as can occur with saline pools (see *Salinity*, below), no mixing occurs and the bottom waters may become extremely low in oxygen.

The other source of oxygen is photosynthesis of submerged plants. Oxygen is a waste product of photosynthesis, so in bright sunlight, submerged macrophytes can contribute significantly to dissolved oxygen. However, during darkness, photosynthesis ceases and respiration, which uses oxygen, becomes the dominant process. Where there is a large mass of plants in the water, either algae or macrophytes, this can lead to large differences between day and night levels of dissolved oxygen.

Oxygen is used in the respiration of animals, and by the microorganisms which decompose dead plant and animal material. Low dissolved oxygen concentration can be caused by the presence of too many animals in water that is not well mixed. This biological demand for oxygen will increase with temperature. This effect can be a problem during droughts, when animals are crowded into pools. It is the same process that kills fish if you leave them in a bucket on the stream bank while fishing.

When dissolved oxygen is totally absent, the water becomes anaerobic. Virtually nothing but certain microorganisms will live under these conditions. However, this situation has more serious ramifications. The decomposition of organic material under anaerobic conditions will produce bad smelling gases such as methane and hydrogen sulfide. The latter can be toxic to aquatic insects. Under anaerobic conditions, nutrients that were bound to the sediment (particularly phosphorus) become soluble, and thus available to promote plant growth.

Thus, the concentration of dissolved oxygen depends on the temperature and salinity of the water, how well-mixed the water is, and the balance between photosynthesis and respiration in the water. Mountain streams, with cold, turbulent water and relatively small populations of plants and animals will have high dissolved oxygen, while slow-moving, warm lowland streams will have lower dissolved oxygen. The lowest oxygen concentrations will occur on warm summer nights, when the temperature of the water means concentrations are low anyway and respiration rates are high, low flow reduces turbulence, and the oxygen requirements of plants are greatest.

1.2. How it has changed

Human activities have not changed the biology or physics that regulate dissolved oxygen concentrations. However, we have increased the frequency with which low dissolved oxygen events occur.

- The high nutrient levels now so common in streams (see *Nutrient enrichment*, above) lead to nuisance plant growth under appropriate conditions. The growth of so much plant biomass will lead to low oxygen levels, partly because of the respiration of those plants, and partly because of the decomposition of dead plant material.

- A similar process will occur where large quantities of organic waste are discharged into streams. The decomposition of the organic matter can strip the oxygen from the water.

- Dissolved oxygen will be lower during very low flows, because of the lack of turbulence mixing the water. This occurs particularly in summer (at least in temperate Australia), when the low flow is combined with high water temperatures. Where water is extracted from the river for irrigation and town water use, the extent of this problem increases. Similarly, long stretches of unnaturally shallow water (as may occur over a sand slug) can have low dissolved oxygen.

- Increased salinity will decrease dissolved oxygen concentration. This will affect the large areas of Australia now suffering from increased salinity due to watertable rises. Salinity can also cause stratification of water in deep pools, leading to anoxia in the bottom waters.

- Various toxicants will affect the oxygen concentration in water. For example, sulfate, sulfites, bicarbonate, ammonia, nitrate and iron salts will all deplete the dissolved oxygen as they are oxidised in the stream.

- Clearing the riparian zone reduces shading, leading in some situations to increased water temperatures which in turn will lower oxygen concentrations.

- Discharges of hot cooling-water from power stations and some industrial plants will have very little oxygen, as will releases from the bottom waters of stratified reservoirs.

2. Biological impacts of low dissolved oxygen

The biological impact of an absence of dissolved oxygen is quite simple—suffocation. As mentioned above, oxygen is necessary for respiration, the process by which food is turned into energy. Many types of microorganisms have developed ways of coping with this situation, but the rest of us living things die without oxygen.

This is of course the extreme situation. Smaller-scale variations will cause changes in the stream fauna, as species vary in their ability to cope with low dissolved oxygen. Adaptations to low dissolved oxygen environments include surface breathing (eg. mosquito larvae), a very slow metabolic rate, and therefore low oxygen requirements, having lots of gills, and increasing storage capacity within the body (ie. developing haemoglobin—this is why worms that are adapted to live in fine sediments are often bright red). Even animals used to high oxygen environments can cope with short periods of low oxygen, using strategies such as beating gills more frequently, or, where possible, leaving the area (Wiederholm, 1984).

3. How do you recognise low dissolved oxygen?

3.1. Field characteristics

Cases of anaerobia—a lack of dissolved oxygen—can often be detected by smell. Under such conditions, anoxic decomposition will create rotten egg gas and methane.

Less extreme situations may be detectable by the behaviour of animals. Fish under oxygen stress may float near the water surface gasping.

Low dissolved oxygen can also be inferred from the water temperature. Because the solubility of oxygen decreases with increasing temperature, warm waters are more likely to be oxygen deficient.

3.2. Measurement techniques

Dissolved oxygen is easy to measure using a portable meter or several chemical tests (West, 1988). The most important thing to remember when monitoring dissolved oxygen is the inherent variability. Dissolved oxygen varies with temperature, and will also change through 24 hours because of contributions from plants. During the day, plants produce more oxygen than they need, but during the night, they will contribute to the use of oxygen. So, particularly at plant-rich sites, oxygen will be higher during daylight, and decrease during the night. This will even vary from day to day, depending on the weather—plants photosynthesise more in bright light. Because of all this variation, single measurements of dissolved oxygen are of little use (ANZECC, 1992a). So, when monitoring oxygen levels, you should:

- always remember to measure temperature when you take your sample;
- try to take several measurements over at least a 24-hour period, to give you an idea of the daily variation; and
- remember that dissolved oxygen will be highest sometime during the day, and lowest during the night.

Biochemical oxygen demand is not a measure of oxygen concentration as such; rather it indicates the oxygen needs of biological or chemical processes occurring in the water. It is a measure of the amount of oxygen that would be required to process the chemicals in the water.

4. At what stage does low oxygen concentration become a problem?

The standard dissolved oxygen guidelines are based on the requirements of Victorian fish (ANZECC, 1992a). Dissolved oxygen should not fall below 6 mg/L or 80–90% saturation at any stage during at least one 24-hour period.

5. Possible solutions/treatments for low dissolved oxygen

The treatment of low dissolved oxygen concentration should tackle the specific causes. Where low dissolved oxygen is caused by polluted discharges from a dam, sewage-treatment plant, industry or similar, then the sources of those discharges should be approached with a view to treating the wastewater before it reaches the stream. Where nutrients are leading to eutrophication, then this problem must be tackled. However, as well as treating the source of the problem, which is not always possible, there are several things which can be done when low dissolved oxygen is a very serious problem:

- build instream structures such as riffles which will introduce a stretch of turbulent flow. This will mix more oxygen into the water;
- replant the riparian zone to give more shade to the stream, and so reduce temperatures; and
- in reservoirs, water is artificially aerated with bubblers. It is unlikely the expense of this practice would ever be justified in a stream.

HIGH AND LOW TEMPERATURES

1. Introduction

Changes to the temperature regime of streams include increases (discharges of cooling-water) and decreases (discharges from the bottom of reservoirs). Temperature is a very important component of the environment—it has an influence on the rate of all biological activity. Both increases and decreases in temperature can have important effects on the stream biota, from minor changes, such as altering the timing of insects emerging from the stream, to extreme changes, where the stream may become uninhabitable for many creatures.

1.1. Natural state

Water temperatures vary naturally, depending largely on altitude and the time of year. There can also be a smaller daily variation. However, natural temperature variation is fairly regular and predictable, in terms of both timing and magnitude. Stream fauna are adapted to this regular change.

1.2. How temperature has changed

There are several human activities that affect stream water temperatures. Temperature may be altered by discharges of wastewater. Some industrial plants will have hot effluents to dispose of, and may discharge these into nearby streams. Another source of heat is cooling-water from power stations. Cold water discharges are usually associated with reservoirs that do not have multiple level offtake towers. All releases from such reservoirs are of cold, bottom water. Changes in temperature may also come about through changes to the riparian zone and channel form. Clearing the riparian vegetation reduces shading, and can have an appreciable effect on water temperature, particularly where flow is uniform and shallow, as may be the case in channelised or incised streams. Channels filled by sand slugs can have a flat, shallow bed that will heat up in the sun.

2. Biological impacts of changes in temperature

Temperature changes can affect stream ecology in four ways: changes may exclude some animals from the affected area; temperature increase can affect other water quality parameters; temperature changes can affect timing and development of life cycles; and they can influence algae and plant growth. Through all these mechanisms, species may be lost from a reach either through an inability to cope at all with the changed water temperatures, or through competition with species that can cope better. In some cases, water temperature changes have assisted the spread of exotic species by creating favourable conditions.

2.1. Exclusion

Like other animals, aquatic animals have tolerance limits to both high and low temperatures, outside which they cannot survive because of the effects on metabolism. The tolerance limit will depend on the exposure time, and will vary between species. Murray cod, for example, can cope with temperatures between 2°C and 33°C, while the Lake Eyre hardyhead (also a fish) can tolerate between 10°C and 37°C (Koehn and O'Connor, 1990). When the temperature is outside the tolerance range of a species, that species will be lost from the affected area.

2.2. Effects on other water quality requirements

Raising temperature will reduce concentrations of dissolved oxygen, which, depending on the concentration, can lead to stress, evasive behaviour or death in animals. It is also possible that higher temperatures and lower oxygen concentrations increase the impact of toxic chemicals on stream animals. See *Dissolved oxygen concentration,* above, for more detail.

2.3. Life cycles

Changes in temperature can have serious implications for life cycles of stream organisms. The different life stages of many animals are triggered by changes in stream temperature (as well as daylength, flow characteristics, phase of the moon etc.). When these triggers operate at the wrong times the life history of the organism is affected, perhaps fatally.

For stream insects, for example, changes in the temperature regime (so long as it is within the tolerance of the species in question) may affect growth rate and development, and alter the timing of emergence (the change from an aquatic pupa to a terrestrial adult) and the size of adults. These can be serious effects: warmer water may trick insects into emerging too early, when the weather is till too cold for them to survive. Also, insects that emerge earlier are often smaller than those which had longer to develop as larvae. Smaller adults may also have fewer offspring, leading eventually to a decline in the species at the temperature-affected site. Similarly, cold water can retard development, so adults emerge late, having missed their appropriate season altogether.

Many fish may be similarly reliant on water temperature cues for certain stages in the life cycle. Silver eels, for example, may begin their downstream migration when stream water temperature rises above 12°C (Koehn and O'Connor, 1990). Macquarie perch begin upstream spawning migrations in response to temperature increases (Koehn and O'Connor, 1990).

2.4. Plant and algal growth

Temperature affects plant growth, through its effect on the rate of photosynthesis. Within a range of temperature tolerance, plants become more productive with increasing temperature. Thus, high temperature may be a factor influencing the production of nuisance plant growth leading to algal blooms or excess macrophytes.

3. How do you recognise changes in temperature?

3.1. Field characteristics

Temperature changes are not readily apparent in the field. However, you can look for the causes of temperature change. Expanses of very shallow water and a lack of shade lead to temperature increases in smaller streams. Possible point sources of temperature polluted water include wastewater discharge points, drains or dam outlets. Bear in mind that a dam must be quite large (over several metres deep) before it will stratify and allow the bottom waters to cool.

3.2. Measurement

Temperature can be measured easily using a thermometer. It is important to be aware of factors that will influence temperature locally, so that your results are comparable. Depth, flow rate, and shading or sunlight will all affect temperature.

4. At what stage do changes in temperature become a problem?

Unfortunately, detailed guidelines are not available for appropriate temperature regimes throughout Australia. The ANZECC guidelines (ANZECC, 1992a) suggest that any increase in temperature should be less than 2°C above the natural temperature. There is insufficient information to give guidelines for decreases in temperature.

5. Possible solutions/treatments for changes in temperature

Potential solutions to temperature problems depend on their causes.

If a shallow stream with no riparian shading has led to temperature increases, in-channel works to create pools, and revegetating the riparian zone may be effective tools.

If hot-water discharges are causing the problem, you may be able to come to an arrangement with the body producing the wastewater, where the discharge rate is carefully calculated so that at any given stream flow, the hot water will cause, for example, less than a 2°C increase in temperature.

If releases of cold, bottom water from a dam are causing your problem, then the only solution is likely to be constructing a multilevel offtake tower or destratifying the dam. Unfortunately, this is expensive.

The effects of shade on stream temperature

Rutherford *et al.* (1999) looked at how fast the daily maximum temperature of a stream increases once it emerges from the dense shade of a native forest and into pasture. They found that the initial increase in temperature was quite rapid, especially for small streams. As the water warms up, the temperature rises more slowly. They found that retaining some shade will slow the temperature rise considerably (see Table 8). On small streams, to 2 m wide, 70% shade can be achieved by planting trees 7–10 m apart. If the stream banks provide some shade, trees may be planted further than 10 m apart.

Table 8. The distance required for water temperature to increase from 15 to 20°C after the stream flows from native vegetation (with 95–98% shade) into pasture (from Rutherford *et al.*, 1999).

Stream order	**Distance for temp. to increase to 20°C with 0% shade**	**Distance for temp. to increase to 20°C with 70% shade**
First order	250 m	500 m
Second order	500 m	1,500 m
Third order	1,500 m	5,000 m

SALINITY

1. Introduction

Salinity refers to the concentration of salts dissolved in water. This includes not only sodium chloride (table salt), but also the salts of calcium, phosphorus, potassium, iron and sulfur. The changes made to the Australian environment since European settlement have resulted in increased salinity in many of our streams. Such increases have the potential to make major changes to our stream biota.

1.1. Natural state

High levels of salinity do occur naturally in inland streams, particularly in terminal river systems, which are never flushed out, allowing salt to gradually accumulate in the terminal lakes. Lake Eyre is an example of such a system. Streams through basalt plains are often slightly saline, as various salts are a product of the weathering process of basalt. Many inland streams were naturally saline, especially in deep pools. This means that there are native macrophytes, algae and animals that have adapted to quite high salinity.

1.2. How it has changed

The present salinisation is not due to natural processes, but rather is a response to two major changes in land use since European settlement. Firstly, many of the deep-rooted forests and woodlands have been cleared for cropping and pastures. The second change is irrigation. Both these changes mean an increase in water infiltrating to the naturally saline groundwater, causing the watertable to rise. Eventually, the watertable becomes close enough to the surface for salt to affect the land and streams. Areas that previously were not saline have become so, and areas previously only mildly saline have suffered increased salt concentration.

2. Biological impacts of salinity

For those interested in a detailed discussion of the effects of salinity on stream biota, there are two excellent reviews of the subject by Hart *et al.* (1990; 1991). High levels of salinity make it harder for organisms to regulate their water and salt content. Too much salt outside a plant or animal will 'suck' the water out, causing dehydration and eventually death. Alternatively, some organisms are unable to keep the salt out, and as well as water being drawn out of the animal, salt will be drawn in. Higher concentrations of salt in the cells are toxic, and will eventually cause problems with basic cell functions, leading to the death of the plant or animal.

2.1. Riparian vegetation

Trees will suffer from high salt concentrations in the short term by having difficulty absorbing water with the roots, and in the longer term by salt accumulating in leaves. Such effects can often be seen when salinity reaches 2,000 mg/L. Seed germination can also be inhibited, as can the growth, survival and yield of seedlings (Hart *et al.,* 1991). There is considerable variation in the tolerances of common species of riparian vegetation. Most research in this area has involved eucalypts, casuarinas and melaleucas (paperbarks) (Hart *et al.,* 1991). Results show that there can be great variation between different species of the same genus (eg. different *Eucalyptus* species). There can also be variation within the one species, depending on the long-term salinity of the area in which they are growing. For example, seedlings of *E. camaldulensis* grown from seed collected from Lake Albacutya (a varyingly saline lake in western Victoria) were far more tolerant of salinity than seedlings from the freshwater Goulburn River, near Shepparton (Sands, 1981; in Hart *et al.,* 1991).

2.2. Aquatic plants

High levels of salinity will make it harder for plants to extract water from their surroundings, effectively exposing them to drought. This can kill the plant, or at lower concentrations will result in reduced vigour, which shows up as slower growth rates, reduced leaf or shoot development, development of dead areas and death of growing tips (Metzeling *et al.,* 1995). The salt concentrations at which such symptoms occur will vary between species. Very sensitive species will show such symptoms by 1,000 mg/L, and by 4,000 mg/L most sensitive species will be lost from the community (Hart *et al.,* 1991). Many micro algae are also sensitive, and will be lost at similar concentrations. Increases in salinity will cause a decrease in species diversity as freshwater species are lost and replaced by a few salt-tolerant species.

2.3. Aquatic macroinvertebrates

In Australia's naturally saline streams and lakes there is a variety of salinity tolerant invertebrates. However, some invertebrates in freshwater systems appear to be quite sensitive to increasing salt concentrations. To an extent, sensitivity will vary with the condition of the animal, the time allowed for acclimatisation, the life stage and the water temperature. Sensitive invertebrates include stoneflies, some mayflies, caddis flies and dragonflies, and some water-bugs, as well as some species of snails. Hart *et al.* (1991) concluded that these more sensitive species will show adverse effects at 1,000 mg/L salt. However, there are many species that can survive in saline environments.

2.4. Fish

Adult fish tend to be salt tolerant, with most species coping with salinities of above and around 10,000 mg/L (Hart *et al.,* 1991). However, some species are considerably less tolerant. For example, freshwater blackfish show noticeable effects above 2,000 mg/L (Bacher and Garnham in Metzeling *et al.,* 1995). Fish larvae, however, are considerably more sensitive to salinity than adults. The skin, kidneys, gut and gills may not be fully developed, and all of these organs are needed to regulate the body's salt and water content (Hart *et al.,* 1991). Unfortunately, few studies have been made to evaluate the salt sensitivity of the larval stages of freshwater Australian fish (Hart *et al.,* 1991).

2.5. Frogs

Very little is known about the salinity tolerances of Australian native frogs. However, some information is available from overseas studies. The skin of adult frogs is permeable to water and some ions. Because of this, frogs will quickly die when placed in sea water, partly from a dehydration effect, and partly from absorbing toxic quantities of salt into their bodies (Bentley and Schmidt-Neilsen in Hart *et al.,* 1991). Little is known of the effects of salinity on tadpoles, but it is likely they also are sensitive.

2.6. Reptiles

Crocodiles and turtles are the only freshwater reptiles at any risk of adverse effects from salinity, but very little is known of their response.

2.7. Birds

Most waterfowl have a salt gland near the eye, through which excess salt from the environment can be excreted. It is not known how birds cope with saline water, but possible strategies include seeking a freshwater drinking supply, and extracting fresh water from their food. It is the young animals which may be most susceptible to damage in saline conditions. Australasian shelduck ducklings do not develop salt glands before they are six-days old, and must have access to fresh water during this time (Riggert in Hart *et al.,* 1991). However, evidence indicates that waterfowl experience low breeding success at salt concentrations above 3,000 mg/L. Such birds are likely to suffer from the death of the macrophytes and invertebrates they rely on for shelter and food, before suffering the direct effects of salinity (Hart *et al.,* 1991).

2.8. Platypus and water rats

Nothing is known of the salt tolerances of platypus. Both species of water rat are found in coastal environments, so presumably are tolerant of salinity, although they may still require access to fresh water.

2.9. Saline pools

As well as these direct effects of salinity, in some circumstances salinisation of a stream can lead to the loss of pool habitat. In areas where saline groundwater is discharging into the streambed, the denser, salty water can collect in the pools, eventually causing a stable stratification of the water. The freshwater stream flows over the pool, and the bottom of the pool becomes hypersaline. Because no mixing occurs with surface water, the saline pools have very low dissolved oxygen. This in turn leads to high nutrient concentrations. Saline pools are common in the larger streams of northern and western Victoria (McGuckin *et al.,* 1991). The low dissolved oxygen effectively remove these pools from the available stream habitat. Flood events may flush out such pools, but salinisation and stratification of the bottom waters will re-establish over several months (Metzeling *et al.,* 1995).

3. How do you recognise salinity?

3.1. Field characteristics

Salinity can be recognised in the field in three ways: from the appearance of the water; from the presence of salt-tolerant species of macrophyte and invertebrates; and measurement.

1. Unusually clear water can indicate high salinity levels. Calcium and magnesium salts will cause clay particles to clump together (flocculate) and sink, thus dramatically reducing the turbidity of the stream. This process will not occur in all saline streams, as it depends on the type of salts present. Sometimes, a salty stream will be appear unnaturally black.

2. Saline streams can be recognised by the loss of sensitive species of macrophytes, macroinvertebrates and riparian vegetation, and increase in populations of salt-tolerant species. This will happen gradually with increasing salinity, but should be obvious when salts reach around 4,000 mg/L. Sensitive species of invertebrates are well documented and are identified in Hart *et al.* (1991). They include the mayflies, dragonflies, and some caddis flies. Some sensitive and salt-tolerant macrophyte species are listed in Table 9. This is by no means a comprehensive list, and the macrophyte community will not necessarily change overnight from salt sensitive to salt tolerant. Rather, the salt-sensitive species will show less vigour and be gradually overwhelmed by salt-tolerant species.

   The effects of salinity may also be seen in the riparian vegetation, particularly in areas that are periodically waterlogged. Many species of riparian trees show decreased vigour and dieback from levels of salinity of less than 2,000 mg/L (Hart *et al.,* 1991).

3. Under severely saline conditions, riparian vegetation may be killed by the salt. This occurs particularly in small, ephemeral streams. The result is a stream with a strip of bare ground running either side of the saline channel (see Figure 16). Areas of white salt crystals can sometimes be seen on the surface.

Figure 16. A salt-affected stream in the Kalgan catchment in south-western Western Australia.

Table 9. Some examples of salt-sensitive, salt-tolerant and halophytic (salt-loving) species. From Hart *et al.* (1991).

Salt-sensitive species. Found in water with a salt concentration below 4,000 mg/L	
Myriophyllum propinquum	Water-milfoil
Triglochin procera	Water ribbon
Isoetes muelleri	Quillwort (a fern)
Salt-tolerant species. Found in water with a salt concentration of up to 7,000 mg/L	
Potomogeton pectinatus	Sago pondweed
Lemna minor	Duckweed halophytes (salt-loving)
Found in water with a salt concentration up to and above 10,000 mg/L	
Ruppia spp.	Sea tassel
Lepilaena spp.	Water mat
Lamprothamnium spp.	A plant-like algae

3.2. Measurement techniques

Salinity can be measured in terms of the weight of salts per litre of water (mg/L), or in terms of electrical conductivity, usually measured in microsiemens per centimetre (µS/cm). It is possible to convert one to the other using the formula:

filterable residue (mg/L) =
0.68 × conductivity (µS/cm at 25°C)

The easiest way to measure salinity is using a conductivity meter, which may present the results in µS/cm, or may convert them into mg/L for you. When taking water samples for the measurement of salinity, bear in mind the discussion above on saline pools, and consider taking samples from deep water.

4. At what stage does salinity become a problem?

4.1. What are fatal salinity levels?

Fatal levels of salinity depend on your overall goals, as the tolerances of different groups of organisms vary considerably (Table 10). However, you should remember the interactions between different groups, and that though fish, for example, may be able to cope with quite saline water, the habitat is not much use to them if their food requirements are not met because of the dearth of sensitive macrophytes and invertebrates.

Table 10: Fatal salinity levels for different organisms.

Goals relating to:	Fatal salinity:
Freshwater invertebrate communities	2,000 mg/L (3,000 µS/cm)
Macrophytes and algae	4,000 mg/L (5,900 µS/cm) (Metzeling *et al.,*1995)
Native fish (adult)	10,000 mg/L (15,000 µS/cm) (Metzeling *et al.,* 1995)
Native fish (larvae)	unknown (Hart *et al.,* 1991)

4.2. Thresholds of concern

As with most water quality guidelines, you should be aware of variation in the natural background levels of salinity. Salt concentrations can increase slightly from the headwaters to the lowland reaches. Also, streams tend to be more saline in areas with low rainfall and little run-off. Streams in such regions are often terminal systems that end in a series of lakes of variable salinity. The guidelines below relate to freshwater streams, rather than streams that are naturally saline, though this is not to say that salinisation of naturally mildly saline streams is a good thing.

The Australian Water Quality Guidelines for Fresh and Marine Waters (ANZECC, 1992a) recommend that salinity 'should not be permitted to increase above 1,000 mg/L (about 1,500 µS)'. The Guidelines go on to point out that for other uses, salinity should be much lower (for example, below 500 mg/L for irrigating clover pastures, and many fruit and vegetable crops).

In developing the Index of Stream Condition in Victoria (DNRE, 1997a), salinity ratings established by the Office of the Commissioner for the Environment (1988) were modified using data from six Victorian catchments. These ratings are presented in Table 11.

Table 11. Salinity ratings for streams in Victoria. From (DNRE, 1997a).

Mountain	Valley	Floodplain	Rating
< 34 mg/L (50 µS/cm)	< 68 mg/L (100 µS/cm)	< 68 mg/L (100 µS/cm)	Ideal
< 102 mg/L (150 µS/cm)	< 170 mg/L (250 µS/cm)	< 204 mg/L (300 µS/cm)	Close to ideal
< 204 mg/L (300 µS/cm)	< 272 mg/L (400 µS/cm)	< 340 mg/L (500 µS/cm)	Moderately different to ideal
< 340 mg/L (500 µS/cm)	< 476 mg/L (700 µS/cm)	< 544 mg/L (800 µS/cm)	Substantially different to ideal
> 340 mg/L (500 µS/cm)	> 476 mg/L (700 µS/cm)	>544 mg/L (800 µS/cm)	Far from ideal

5. Possible solutions/treatments for salinity

High salinity is at best a catchment-scale hydrological problem. At worst, it is a regional-scale issue. In short, it is not something that can usually be successfully treated in drainage lines alone.

TOXICANTS

1. Introduction

Not surprisingly, there is a vast array of organic and inorganic chemicals that find their way into streams where they can potentially cause considerable problems for the stream biota. These chemicals are grouped under the general category of toxicants. The Australian Water Quality Guidelines for Marine and Fresh Waters lists 18 inorganic toxicants— mainly heavy metals—and many more organic toxicants, including several pesticides, detergents, and many chemicals used in industry as solvents, chemical intermediates, and so on.

1.1. The natural state and how it has changed

Many of the inorganic toxicants are naturally found in streams in very low quantities, coming mainly from the weathering and erosion of various rocks and minerals. However, there are many anthropogenic sources, including mining waste, sewage and industrial effluent, the combustion of fossil fuels (eg. beryllium and sulfur), street run-off (eg. lead), photographic waste (silver), tanneries, paper mills, chemical plants, gas works, waste incineration, metal production and so on. Many of the organic toxicants are manufactured chemicals, and so are not naturally found in water in any concentration. These chemicals enter the environment through various routes such as industrial and manufacturing emissions and discharges, run-off from agricultural land, municipal effluents, and fuel combustion. In Victoria, one of the most common toxicants in streams is mercury, due to its use in gold mining.

2. Biological impacts of toxicants

The biological impacts of toxicants are too many to list separately, but they range from a reduction in growth rate and development, and pathological changes in gill, liver and kidney tissue (salmonid fish response to chronic exposure to ammonia), to impaired reproduction (response of *Daphnia* to lead) and spinal deformities (response of trout to lead) (ANZECC, 1992b). Some chemicals, such as selenium and some pesticides, are toxic to plants as well as animals. See (ANZECC, 1992a) for a brief description.

3. How do you recognise the presence of toxicants?

3.1. Field characteristics

Because there is such a variety of different toxicants, there is no easy generalisation to be made about how you identify the effects of these chemicals, other than a lack of aquatic organisms. Unless you have a particular reason to suspect the presence of some toxicants (eg. a source such as an urban or industrial drains, of mining effluent), your first step should be to consider if water quality is actually a problem. You should:

1. Search for the macrophytes, macroinvertebrates and fish you would expect to find in a healthy stream.
2. If you don't find any, look around and see if there is suitable habitat and sufficient water for the animals and plants you expect.
3. If there is suitable habitat, check other water quality variables.

4. If none of these can explain the lack of life, talk to a laboratory about testing for possible toxic chemicals in your stream.

3.2. Measurement techniques

Measurement techniques vary for different toxicants. Unfortunately, there are no easy field tests for these chemicals as there are for the other water-quality variables. Collection and analysis of samples for analysis of toxicant concentration is complex. Tests for each chemical will have different requirements for sample collection and preservation. For many of these chemicals, there is a variety of different methods for determining concentration, which may arrive at different results. Seek professional help if you suspect contamination with any of these chemicals.

4. At what stage do toxicants become a problem?

The critical concentration depends on the chemical in question. How toxic a chemical is may vary depending on the pH and hardness of the water, and whether it is a 'bioaccumulant' (some chemicals will be absorbed by animals, and not excreted, so they eventually accumulate in the animal in much higher concentrations that the surrounding water). For many chemicals, a suitable threshold of concern is not known. See the ANZECC concentration guidelines for further information.

5. Possible solutions/treatments for toxicants

Again this will depend on the chemical: seek professional advice.

OTHER BIOLOGICAL PROBLEMS

- Other biological problems: an introduction
- Barriers to fish migration
- Large woody debris
- Stock management
- Rehabilitation for platypuses
- Rehabilitation for frogs

OTHER BIOLOGICAL PROBLEMS: AN INTRODUCTION

In this section we discuss some of the problems, other than water quality, that relate specifically to stream plants and animals. We include some issues of habitat availability (fish barriers and large woody debris), the effects that domestic stock can have on streams, and the specific requirements of some common flagship animals—platypus and frogs.

BARRIERS TO FISH MIGRATION

By John Harris and Tim O'Brien†*

1. Introduction

Fish, like other wild animals, exploit different parts of their habitats to ensure the continued survival and success of their species. Fish commonly spawn in one part of their habitat, use a different part as a nursery area, and then disperse into a third area for adult growth. Golden perch, for instance, spawn during floods in lowland river reaches; the young develop in floodplain or river margin nurseries; then eventually travel upstream as juveniles. Murray cod have recently been shown to make upstream spawning migrations, using anabranches and flood-runners, then returning to their original home territory. Each of these habitat areas, plus free passage between them, is required for the fish population to be sustained. Furthermore, within adult growth habitats, each fish moves around to feed within an area known as the home range. This movement is needed for effective use of food resources; preventing it is equivalent to shutting horses in a small paddock—the food supply runs out.

The scale of these different movements varies greatly: golden perch and silver perch can travel the length of the Murray–Darling River system. Australian bass or eels may migrate hundreds or thousands of kilometres to marine environments to breed. Some small fishes such as gudgeons and hardyheads, on the other hand, may undergo life-cycle movements that extend only a few kilometres, and thus are not so readily recognised as 'migratory'. Other fish species fall between these two extremes.

Most of Australia's approximately 200 freshwater fish species are considered to be migratory, and all of them have some need to move between habitat areas within streams (Harris, 1984; Mallen-Cooper and Harris, 1990; Harris and Mallen-Cooper, 1994; McDowall, 1996).

> There can be natural barriers to fish migration (eg. waterfalls, sand slugs or zones of poor water quality) that could already exclude native fish from upstream reaches. If such barriers exist, then it would be a waste of resources to provide fish passage across artificial barriers upstream of the natural barrier.

2. Effects of blocking migrations

What if migrations are blocked? Extensive declines in fish populations in both coastal and inland drainage regions have been linked to the obstruction of fish passage, among other factors (Wager and Jackson, 1993; Harris and Mallen-Cooper, 1994; McDowall, 1996). For both inland and coastal species, obstructed fish passage has led to many instances of declining populations or extinctions of species from affected catchments.

Migration barriers interfere with the two main ecological processes that sustain populations: recruitment and growth. Population recruitment includes spawning, the nursery phase, and juvenile dispersal into adult growth habitats. Growth relates primarily to home-range feeding activity, and may occur in pulses associated with the seasons and with river-level rises. Another ecological process is the dispersal of fish from drought-refuge areas

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(such as remnant deep pools) into newly regenerated habitats (for example, billabongs or previously dried-out river channels) after rainfall and renewed stream flow.

Complete obstruction of migrations leads to local extinction of some species (Harris and Mallen-Cooper, 1994). This seems attributable mainly to blockage of the recruitment migration of young fish, so that the upstream population gradually ages and dies out. For example, populations of at least four migratory coastal species disappeared from above a small weir at Dight's Falls in the lower Yarra River before a fishway was installed. There are many similar cases. Less-restrictive barriers such as low-level weirs, however, usually allow some fish movement in periods of high stream flow. Nevertheless, the obstructive effects of individual weirs in a system are cumulative, and weirs are more insidious in their effects than high dams. Movements are diminished rather than prevented, and fish populations decline rather than disappear. Home-range movements are interrupted. Upstream migrating fish accumulate below the weirs while waiting for suitable conditions for passage, where their crowded populations suffer radically accelerated mortality rates because of increased predation by the birds and fishermen often seen congregating below weirs, because the food supply is quickly used up, or because of disease in the crowded conditions. Sampling of fish at the Torrumbarry Weir on the Murray River showed that 98% of native fish (mostly golden and silver perch) were located below the weir wall at times of rising flow and temperatures. When a fishway was built, thousands of native fish moved over the weir, at rates of up to 700 per day (Anon, 1990). Without building fishways or removing weirs, fish passage can occur only infrequently, when weirs are inundated or 'drowned-out' by high stream flows.

3. The extent of the problem

Barriers to fish passage are major limitations to stream rehabilitation in any modified catchment (ie. most catchments in Australia). Although the most obvious barriers are large structures such as weirs, dams and barrages, road culverts, fords, and even open shallow stretches of water can block fish passage. A recently completed survey by the Victorian Department of Natural Resources and Environment gives an indication of the magnitude of the problem. It found over 2,500 potential obstructions to fish, including dams, weirs, culverts and fords (O'Brien, 1997). In the streams of New South Wales, there are 3,000–4,000 artificial barriers impeding fish passage. A survey of 293 such structures in south-eastern Australia by Harris (1980) found that less than 10% of them had any provision for fish passage. Other studies have questioned the effectiveness of existing fishways (Russell, 1991).

Much of the literature describing work to overcome obstacles to fish migration has come from the study of salmonid species, which migrate upstream for spawning when fully grown. Many Australian fish behave in the opposite way, migrating downstream to spawn in estuaries, juvenile fish making the journey upstream to freshwater reaches. As well as the obvious size and strength difference between juvenile and mature fish, Australian native fish are not strong swimmers or jumpers (compared with salmonids), hence barriers pose much more of a threat to Australian native fish species than to those of the northern hemisphere.

4. Identifying barriers to fish passage

An important step in any rehabilitation design is to identify barriers to fish passage. The things to look for are extended stretches of shallow flow, perching or high drops, and high velocity. Australian streams display huge variability in stream flow, and many of our major waterways are ephemeral systems. Even under natural conditions there will be times when fish passage is not possible. As a general stream rehabilitation design rule, fish passage should be possible for 95% of flows. So when identifying barriers, the minimum design flow is that which is exceeded 95% of the time *the stream is flowing* (ie. do not count the period when there is no flow). For many ephemeral streams this means providing adequate conditions for fish passage for only a few weeks per year.

4.1. High velocity

Generally, Australian fish have difficulty traversing long stretches of uniform fast-flowing water. The preferred solution is to provide roughness features such as boulders which break up the current and provide low-velocity zones for fish to rest and feed. High velocity areas are often a feature of modified, smooth sections of streams like culverts or fords. As a guide, there should be periods when the flow velocity does not exceed 1 m/s and regular (approximately every 1–2 m) low-velocity rest areas like those provided by large rocks.

4.2. Shallow flow

Depending on their size, fish cannot pass through sections of very shallow flow. Stream rehabilitation projects should generally aim to have a 'natural' species composition, thereby necessitating passage of all native fish. This translates to a depth of at least 15 cm in smaller coastal and headwater streams (O'Brien, 1997) (and deeper for inland streams where some larger fish species are likely to occur) for 95% of the time the stream is flowing.

4.3. Perching (around culverts)

A perched stream is one in which there is a drop or waterfall that acts as a barrier to fish passage (refer to *Full-width structures*, in Intervention tools, this volume, for details on providing fish passage in such structures).

Culverts are common causes of stream perching. Remember that for many smaller Australian fish species, a drop of only 15 cm can be an insurmountable barrier. Perching can be caused by downstream bed lowering, or poor design of the culvert exit.

To solve the much larger perching problems created by weirs requires the installation of fishways. The design of concrete fishways is not covered in this manual, as these structures can cost hundreds of thousands of dollars, and are therefore beyond the means of stream rehabilitation groups. (Contact the relevant water or conservation department in your State for technical assistance if you want to build one.)

4.4. Day migrant species

Culverts can pose another barrier to those fish which migrate only during daylight. Some of these species will not enter darkened tunnels. The only solution in this case is to replace the culverts with fords.

4.5. Wide, shallow stretches of water

Wide, shallow stretches of water can be barriers to fish because of depth or velocity as mentioned previously, or through predation. Wide, shallow stretches of stream make fish easy prey for birds. A series of rocks or logs placed in the channel will provide cover, depth and low velocity to allow easier fish passage.

5. Techniques for creating fish passage

There are several ways of overcoming barriers to fish passage. The simplest is the rock ramp, a simple pile of rock below the offending barrier that creates a gentle enough water slope to provide fish passage. See *Overcoming barriers to fish passage*, in Intervention tools, this Volume.

LARGE WOODY DEBRIS

1. Introduction

The following notes on the management of large woody debris (LWD, or snags) in streams are, in part, summarised from the National Riparian Zone Guidelines produced by LWRRDC (see the full document, with full referencing, at www.rivers.gov.au).

It is now appreciated that LWD plays a crucial role in the rehabilitation of Australian streams in humid regions. It is clear that in many streams, especially the lowland sand–clay streams that make up much of the length of our perennial streams, snags are the single most important habitat component. Set against this is the fact that a great deal of effort has been directed at removing snags from our streams over the last 150 years.

Key points about large woody debris

- In streams with a mobile bed and deep water, LWD is arguably the single most important habitat feature for fish, algae and macroinvertebrates.
- Large volumes of LWD can increase flood stage, but the effect of a single log is trivial.
- LWD can cause minor bank erosion.
- In almost every case, the ecological value of LWD far outweighs the minor flooding and erosion problems caused by the blockages.
- **Removing further LWD from streams should be prohibited, except in special circumstances.**
- Artificially returning LWD to streams will be a critical part of many stream rehabilitation projects until riparian vegetation is able to supply sufficient material.

2. Biological and physical effects of LWD

2.1. LWD and stream habitat

2.1.1. Woody debris as habitat for fish

Large woody debris provides important habitat for direct use by a number of aquatic and terrestrial organisms. Such uses include shelter from fast flows, shade, feeding sites, spawning sites, nursery areas for larvae and juvenile fish, territory markers and refuge from predators.

Snags are most effective as habitat if they have a complex structure providing a number of different-sized spaces, including hollows and spaces between branches. Branches extending into the water column and above the water surface provide habitat at the different water levels required by different fish species. Single large trees that fall into a river can often provide the full range of complex spaces required.

Snags positioned at different locations within the stream channel benefit different species. For instance, trout cod (*Maccullochella maquariensis*) utilise snags that are located in high-current zones towards the middle of the channel and downstream of a bend. Murray cod (*Maccullochella peelii peelii*), on the other hand, live around the bases of snags in slower-flowing currents closer to river bends.

2.1.2. Snags as habitat for other organisms

In general, the types of snags that provide habitat for fish also provide habitat for other aquatic and terrestrial organisms. Submerged wood with a complex surface structure of grooves, splits and hollows provides space for colonisation by a range of invertebrates, microbes and algae. Some invertebrates feed directly on the wood, while others graze the biofilm (that is, the combined microbe and algal community).

The species composition within the biofilm community depends on the position of the wood substrate within the water column. The shallower the water in which the wood occurs, the higher the density of algal species. There are fewer algae deeper in the water column where less light penetrates.

Species composition of both biofilm and invertebrates also depends on the character of the surface on which it forms (the substrate). Snags of willows and other introduced tree species appear to have a less diverse invertebrate community than native/indigenous tree species (see *Willow infested streams*, in Intervention tools, this volume). Similarly, community composition varies according to the type of substrate (for example, wood is better than a concrete pipe).

Birds, reptiles and mammals also use woody debris for resting, foraging and lookout sites. Birds commonly use the exposed branches of snags as perch sites, while turtles often climb out onto the surface of snags. Snags spanning the channel may also be used by mammals and reptiles as stream crossing points. Many aquatic invertebrates have a terrestrial adult stage and require snags extending above the water surface to provide sites for their emergence from the stream.

2.1.3. Snags as sites for carbon and nutrient processing

Another important—but often overlooked—function of snags is their role in carbon and nutrient processing. Snags provide important substrate for the development of biofilm. The bacterial and fungal components of biofilm contribute to the decomposition of the woody substrate and hence to the supply of dissolved and particulate organic material (carbon) to the water column. Organic matter is a major source of food for invertebrates and fish. The algal component of biofilm may also produce a significant amount of food, through photosynthesis. Many invertebrates and some fish, eat the algae that grows on wood surfaces.

> In sandy, turbid rivers where woody substrate may be the only hard substrate available for colonisation, or in rivers that have been isolated from floodplain organic food inputs by river regulation and clearing, most of the food for aquatic animals is found on snags.

The biofilm also readily transforms available nitrogen and phosphorus by converting them to less-available compounds. This has the potential to restrict nutrient supply to nuisance algal and macrophytic growth.

In upland streams, large accumulations of woody debris (debris dams) often span the entire channel. These retain large amounts of particulate organic material. This material decomposes into smaller pieces and is then transported downstream. As stream size increases, large debris dams become less common and the ability of woody debris to retain these small particles may decrease. Nevertheless, retention of organic material and stabilisation of sandy substrate by snags may still be significant in lowland rivers. Flow over snags also helps to re-oxygenate the water and prevent stagnation which can cause fish deaths, odours and other water quality problems.

2.1.4 . The role of snags in habitat formation

As well as providing habitat for a range of aquatic and terrestrial species, snags also contribute to the development of other habitat types by their impact on channel structure. The main types of habitat formed by snags depend on snag orientation and stream power. Scour pools formed by snags spanning the channel are particularly important for wildlife, especially in streams with low or no summer flow. When flow ceases these pools provide the only habitat available for aquatic species, from which animals can recolonise the rest of the river when water level rises.

3. The physical effects of large woody debris on streams

As well as providing habitat for stream organisms, woody debris can have a significant effect on the stream itself, in terms of erosion, and increased flood stage. Generally, for a single piece of debris, these effects are so small that they pose no significant threat to the stream as a whole but, as described above, they may contribute to stream habitat. For more information on the physical effects of snags, see *Management of large woody debris* in Intervention tools, this volume.

4. Managing large woody debris

There are two options available to increase the amount of woody debris in your stream.

1. Revegetating the riparian zone will encourage the natural recruitment of debris to the stream. Unfortunately, this will take a long time, because the vegetation has to mature to a stage where natural aging leads to large branches or entire trees falling into the stream. For example, silver wattle, a common small riparian tree in south-eastern Australia, can fall into the stream after only 30 years, while some eucalypts probably do not begin to contribute large pieces of debris to the stream until they are at least a hundred years old.

2. The second option is to manually add wood to the stream. This is discussed in *Management of large woody debris,* in Intervention tools, this volume.

STOCK MANAGEMENT

1. Introduction

The most dramatic impact European settlement has had on our river systems is through our land-use practices, especially clearing and grazing. Very few stream rehabilitation strategies would be complete without addressing stock management in the riparian zone.

Grazing in the riparian zone and using streams and rivers as stock watering points (Figure 17) has several impacts on the streams. Trampling of the channel and banks will increase turbidity, while animal faeces will add to the nutrient load. Trampling and grazing will also damage the riparian vegetation. In the natural state, rivers and streams are lined with diverse riparian vegetation, which helps stabilise the banks, reduces scour, filters sediment and nutrient from run-off and adds to the habitat and food chain in the river as well as being a valuable part of the environment in its own right. Grazing will damage the understorey of grasses and shrubs, as well as the rushes and sedges at the waters edge. It can also prevent tree seedlings from becoming established. For these reasons, it would be ideal to exclude stock from the riparian zone and the stream channel. More information can be found in Bell and Priestley (1999).

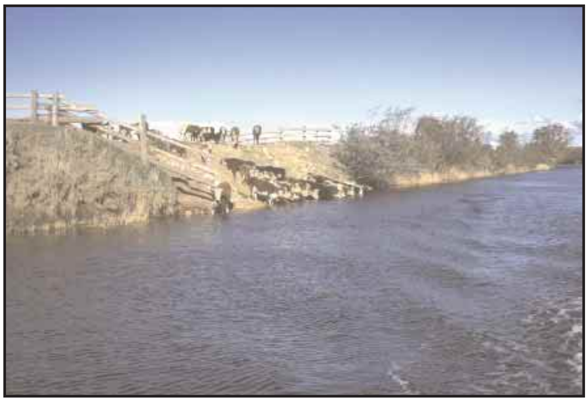

Figure 17. Stock can do a lot of damage to a stream bank. This photo shows a stock access point on the Mitchell River, in eastern Victoria.

2. The effect of stock on stream rehabilitation

Where stock have access to stream channels and banks, this will make the job of stream rehabilitation much more difficult. A healthy riparian zone is a vital part of many rehabilitation programs, because of the role it plays in bank stability, as well as its importance as part of stream ecology. If no action is taken to manage stock access to stream channels and banks, it is likely the stream will continue to be unstable and unsightly, with reduced ecological value.

Stock management in the riparian zone has often been neglected as it was seen to disadvantage the landholder, but there are many returns for the farmer who fences off a stream and replants or allows natural regeneration of the riparian zone.

Here is a list of positive returns for graziers in fencing their stream (after Nicholas and Mack, 1996):

- reduced bank erosion and gullying;
- improved water quality;
- improved biological pest control;
- fewer cross-creek fences;
- improved wildlife habitat;
- windbreaks for stock;
- improved appearance of farm and increased farm value;
- better land stewardship; and
- reduced stock losses (due to stock getting stuck in the creek).

Fencing off the riparian corridor does not mean 'giving up' land. One of the main concerns for graziers who are being urged to fence off their stream is that they do not want to lose part of their land. Farmers can usually retain the use of the 'river paddock' for selective gazing. The basis for keeping stock away from the riparian corridor for most of the time is to permit the natural regrowth of native vegetation. Once the plants are well established, the corridor can still be crash grazed during non-vulnerable growing stages (when desirable plants are well established, and not flowering) (Nicholas and Mack, 1996).

3. Managing stock access

Managing stock access to streams requires that some form of fence be erected around the riparian zone and, where necessary, that alternative stock watering points constructed. For information on this, see *Managing stock access to streams,* in Intervention tools, this Volume.

REHABILITATION FOR PLATYPUSES

*By Kathryn Jerie and Tanya Rankin**

Information used to prepare this section was sourced from Tom Grant's 1995 book *The Platypus: a Unique Mammal* and *Platypus Profiles* (a series of information notes produced by the Australian Platypus Conservancy). Expert advice was also given by Mr Geoff Williams of the Australian Platypus Conservancy, Melbourne.

1. Introduction

Platypus (*Ornithorhynchus anatinus*) are so distinctive that they need little introduction. They are an extremely charismatic animal that can excite great enthusiasm for conservation in local communities. Maintaining platypus populations or encouraging the re-establishment of platypuses in impacted streams can be an excellent goal for a community rehabilitation project, as it can muster wide community support for generalised improvements to the stream and riparian zone. This can have positive impacts on many other important aquatic values, such as improved water quality, increased fish and macroinvertebrate biodiversity, and the revegetation of riparian zones. Community rehabilitation projects focusing on platypuses can also succeed in improving the visual appeal of a waterway and its value for recreational users.

2. Biology of the platypus

2.1. Description and habit

The platypus is one of only two egg-laying mammals (the other is the echidna). Platypuses are well adapted for their aquatic lifestyle, and have a dense covering of dark brown waterproof fur; only their webbed feet and distinctive, duck-shaped bill are hairless. Male platypuses average 1.7 kg in weight and 50 cm in length, while females are quite a bit smaller, weighing around 0.9 kg and are about 43 cm long. They excavate burrows in earth and clay river banks, burrowing at a rate of up to half a metre an hour. They may spend as much as 17 hours a day asleep in their burrows.

When diving for food, platypuses close their eyes, ears and nostrils, and use their electro-sensitive bill to pick up tiny electrical impulses from muscle contractions in their prey which live in and among sediments and rocks on stream bottoms. Their prey consists of a wide range of macroinvertebrates, including worms, insects, molluscs and crustaceans. Platypuses feed voraciously: it has been estimated that they can eat up half their own bodyweight in food each night. They come out of their burrows mainly at night to forage in still pools in rivers, but can occasionally be seen during the day, especially in the morning.

2.2. Distribution

Platypuses are unique to eastern Australian watercourses and are found naturally in and around many different types of water body, from coastal rivers to reservoirs, billabongs and highland streams in eastern Australia and Tasmania. Platypuses are reasonably common and widespread and so are not currently in any danger of extinction. Numbers, however, have declined, particularly in urban streams and in waterways in intensively farmed regions. This is thought to be due to a number of anthropogenic factors, the main ones being habitat degradation, litter inputs to streams, and poor water quality.

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2.3. Life cycle

The platypus mating season is from about July to October, with most mating occurring in September. The two to three eggs produced are laid about one month after mating, and hatch about 10 days after that. The young are fed milk by the mother for about three and a half months, after which the juveniles leave the nesting burrow and begin to feed independently, first entering the water between January and March. In late summer and early autumn they leave their mother's range to find territories for themselves. During this time, they may occasionally be found a considerable distance from the nearest waterway as they move overland in search of new territories. At this stage, young animals may be at great risk of being killed by dogs or foxes.

Platypuses are long-lived animals. In captivity, some have survived for over 20 years. In the Shoalhaven River, New South Wales, Dr Tom Grant has re-trapped a female over 13 years after she was first captured, so platypuses can potentially remain in the same area for a very long time. Unfortunately, very little is known about rates of population growth, how platypus go about finding new habitat, or how many individuals are required for a sustainable population.

3. Do you already have platypuses?

3.1. Surveying for platypuses

If you want to know if you have platypuses in your stream, you can get your community group to conduct a survey. Surveys are usually visual, consisting of coordinated observations of the stream at the times when platypuses are most likely to be active. Other survey methods involve capturing the animals in special nets. Netting is often considered to be more conclusive than a visual survey, but netting surveys can be conducted only by experts who are trained and licensed by the relevant authorities. Only visual surveys are conducted by community groups.

Visual surveys are quite simple and can be very effective. They involve sitting quietly on the stream banks, with minimal movement, and watching the stream for signs of platypus activity. Observers should be stationed at regular intervals, every 25 m or so, along likely-looking pools from about an hour before dusk until it is too dark to see, or from dawn for an hour or two. Binoculars can sometimes be useful for these surveys. Platypuses can be identified by their characteristic double splash duck-dive, and when resting on the surface while they chew their food. The only other animal that might be confused with the platypus is the native water rat. Water rats can be readily distinguished from platypuses as they usually have a white tip to their tail, and ordinarily swim rapidly along the surface between landmarks, such as rocks or logs jutting out of the water. Platypuses dive frequently and, unlike the water rat, are rarely seen resting on landmarks, spending most of their time in the water. The swimming action of water rats is also quite different from platypus swimming, to the eye of an experienced observer. It doesn't take too long to become familiar with the distinctive swimming and diving of platypuses. Don't be disheartened if no-one spots a platypus the first time out—try again a few weeks later. Other native aquatic animals that may be seen during these surveys are the eastern water dragon, long-necked tortoises, and various water birds. Record observations carefully (date, location, time, and number of animals seen). This information can then be used for monitoring platypus populations over time, which is particularly important if stream improvement works are made. State and local wildlife services are also often interested in the results of these surveys, and usually appreciate the data being passed on.

If your community group is really keen, radio-tracking studies can also be conducted to identify burrow locations and activity patterns of platypuses. These, however, require considerable expertise, and involve the use of specialised and very expensive equipment. Contact your State wildlife service for further information.

4. Habitat requirements

4.1. Habitat for platypuses

Bank stability is very important to platypuses, because of the need to have stable and secure burrows for resting and breeding. Platypuses excavate burrows in the stream bank, up to several metres long, where they may spend many hours asleep each day. The burrows usually have domed-shaped entrances which can be difficult to spot, under or near the water surface or in undercut banks, usually where there is dense overhanging riparian vegetation. Burrows are often associated with tree roots along the waters edge. The extensive roots of native trees like river red gums and casuarinas provide structure and stability for the burrows, preventing them from collapsing, especially during floods. Revegetating the riparian zone with native endemic trees, shrubs and sedges can help provide suitable burrowing habitat for local populations or may encourage platypuses to return to the area and will help stabilise eroding banks. Remember, when seeking to stabilise banks, you should try to avoid hard engineering techniques that can reduce invertebrate habitat as well as remove suitable platypus burrowing sites. The most platypus-friendly bank stabilisers are native endemic trees with extensive root systems, with an understorey of smaller shrubs and sedges.

4.2. Platypuses and willows

In the past willows have been used to stabilise stream banks but these days, for environmental reasons, willow planting is discouraged. Platypuses often excavate their burrows amongst willow roots, but the benefits the trees provide are outweighed by the damage they cause through choking stream channels, slowing or otherwise altering stream flows, and increasing sedimentation of pools. Macroinvertebrate communities are also affected by over-growth of willows. The Australian Platypus Conservancy has been conducting a study on the effect of willow eradication on platypuses in Diamond Creek and the Yarra River, Melbourne. In the study, willows were killed but their stumps and roots were left in place to maintain bank stability and prevent collapse of platypus burrows. Though the study is still incomplete, animals monitored by radiotracking behaved in a normal manner during willow removal, and later continued to use the burrows associated with the dead willow roots. More than two years on, platypus densities in the cleared reach were the same or possibly higher than before the willow eradication program began. It seems from this study, that willow eradication is not likely to drive platypuses from the reach if the stumps and roots are left in place and disturbance to stream banks is minimised. Eventually, removal of willows will allow streams to return to their natural flow regimes, reduce sedimentation of pools, and allow stream macroinvertebrate communities to increase and diversify. Willow eradication may act to encourage platypus populations, but remember that bank stabilisation and revegetation with native plants are of utmost importance to maintain and improve platypus habitat.

4.3. Platypuses and flow regulation

A good riffle-pool-riffle sequence is also important in streams, as it provides a range of flow regimes which encourage diverse and abundant macroinvertebrate populations, which the platypus need to eat. Channelised stream reaches may need extra attention to re-create these diverse flows. Regulation of rivers may also pose problems. Although platypuses are often found in and below artificial impoundments they are not usually found in waters deeper than several metres—it is thought that this is because their macroinvertebrate food supply is restricted at these depths. Flow regulation can also threaten long-term survival of platypus populations in other ways. Firstly, where water use extends the extreme low-flow periods, this may prolong drought stress and reduce the food supply of the platypuses. Secondly, impoundments may reduce the frequency of scouring flows, resulting in increased sedimentation and reduction of pool habitat downstream of the dam. Long-term studies on the Shoalhaven River in New South Wales have suggested that platypuses are sensitive to sedimentation of pools when environmental flows are inadequate to scour and flush sediments downstream. In addition, a wire mesh cover (mesh less than 8 cm^2) should be fitted over all intake pipes to prevent water pumps killing or injuring animals.

4.4 . Macroinvertebrates and hunting

When hunting, platypuses turn over rocks and stir up sediments in the stream bottom with their strong webbed forefeet, and quickly snap up any macroinvertebrates they sense. Therefore, habitat that encourages macroinvertebrates is always beneficial to platypuses. For example, re-creating riffle habitats, replacing woody debris, and increasing hydraulic diversity can improve conditions for macroinvertebrate communities, which in turn are the food supply of platypuses.

4.5. Area of suitable habitat required by platypuses

Unfortunately, the total area of suitable habitat required to support a permanent platypus population is not well known. It depends on combinations of characteristics such as the width and depth of the stream, flow rates, macroinvertebrate production rates, the availability of suitable burrow sites, and even the risk of predation by dogs and foxes. Platypuses can have large overlapping home ranges: females use about one to two kilometres of stream, while males may patrol up and down six to seven kilometre long stretches of stream. In fact, some male platypuses have been shown to move several kilometres in a single night. It is therefore suggested that up to ten kilometres of quality habitat is needed in a wide stream, longer for narrower streams, to maintain healthy platypus populations. If this seems daunting, remember that any improvement will be beneficial to platypuses, no matter how small it may seem, particularly if improvements are maintained and added to over time.

5. Water quality requirements

5.1. Water quality issues

Platypuses are not directly affected by many water quality issues such as turbidity, dissolved oxygen, and nutrient loads. Platypuses are more likely to suffer indirectly as a result of decreases in water quality if these, in turn, reduce the quantity and diversity of macroinvertebrates. Because of this, any management to improve the diversity and abundance of macroinvertebrate populations has the potential to encourage platypuses. Very high levels of turbidity, low dissolved oxygen, high nutrient and pollution levels, and low pH can all have detrimental impacts on macroinvertebrate communities. These problems can often be difficult to tackle, as many stream inputs have diffuse sources. Some improvements that can be made include increasing the size of riffles, which will help to oxygenate the water, and restoring and maintaining riparian buffer strips that will filter some of the sediment and nutrients from run-off. Reducing nutrient loads will also serve to reduce the risk of algal blooms—some algal blooms are potentially toxic, but the effect of these on platypuses has not yet been investigated.

Though platypuses are less directly affected by poor water quality than macroinvertebrates or fish, in Tasmania recent research has implicated the influence of poor water quality (especially elevated levels of faecal contamination) on the incidence of a fungal infection in a few localised populations of platypuses. This disease has not yet been found in mainland platypus populations, but its occurrence suggests that good water quality may be more directly important to platypus than previously thought.

5.2. Litter and refuse problems

Platypuses are affected by litter and refuse in streams. There have been many reports of badly injured or dead animals found tangled in discarded fishing line, beer packaging, and similar coarse plastic litter. This is an important problem in urban areas—recent platypus surveys in urban Melbourne have found up to 10% of animals were fouled by some or other extraneous material. Many of the animals had severe injuries as a result; some were so badly injured they had to be euthanased. Platypuses are also drowned in illegal eel nets and in yabbie traps if they are left unattended and improperly set. Clean-up days and the use of litter traps can greatly reduce litter problems for platypuses.

6. Rehabilitation tips

- It is not known how likely it is that platypuses will find a newly rehabilitated site a considerable distance from current populations. For this reason, if you wish to increase platypus populations in your area, it is probably best to start restoration work up or downstream from a known population. Be sure your improvement work does not disturb platypuses while it is in progress.

- A well-vegetated riparian zone is important to platypuses, as it provides cover from predators, and contributes to stabilisation of banks for suitable burrowing sites. Native vegetation is preferred for stream macroinvertebrates as they are better able to process native leaf litter compared with introduced trees and weeds. Diverse and abundant macroinvertebrate communities are important to platypuses as their food supply.

- Platypuses travel considerable lengths of stream during their nightly foraging and territorial patrolling. To maintain platypuses, you may need well over six kilometres of suitable habitat, depending on stream depth, width and other factors previously discussed.

- Rubbish in the stream is possibly the most important aspect of water quality to affect platypuses directly. It is important to keep the stream free of potentially fatal rubbish, such as fishing line, beer packaging, wire and other rubbish. Also ensure there is community education about the dangers of badly set yabbie traps and illegal eel nets.

- Indirectly, water quality can affect platypuses. It is vital to have a good macroinvertebrate population as food supply for the platypuses. If poor water quality prohibits this, problems must be addressed before you can expect to support platypuses in your stream.

- Intake pipes for water pumps may suck in and kill platypuses. To prevent this, wire mesh covers (mesh less than 8 cm^2) should be fitted over all intake pipes.

- When doing instream works in areas known to support platypuses, try to avoid working between the breeding and rearing season (August to March) when damage to the burrow could be fatal to young animals. At the very least, attempt to identify areas of suitable burrow habitat and important foraging areas, and avoid excessive disturbance to these sites.

- Try to keep disturbances of the stream minimal in known platypus areas. If extensive works are planned, consider staging the works so that no more than a 500 metre stretch of stream bank is disturbed in any one year.

- Shallow riffles that are too long can expose platypuses to predators; alternating sequences of pools and riffles are preferred in riverine habitats.

7. Further reading

For those who are interested in reading more about this remarkable animal, we recommend Tom Grant's excellent book *The Platypus: a Unique Mammal* (1995, UNSW Press Ltd, Sydney).

REHABILITATION FOR FROGS

By Fleur Bound

1. Introduction

Amphibian ambassadors such as Kermit and Tidalik have raised the community awareness of frogs to a point where they adorn almost as many T-shirts as whales and dolphins. Popularity of this magnitude can be very useful when you are trying to focus a community upon the task of stream rehabilitation.

Frogs are commonly found near slow-moving, or stagnant water bodies, from the backwaters of rivers to lakes, ponds, waterholes and billabongs.

2. Do you already have frogs?

You can check to see if you already have frogs by listening for calls, spotlighting at night or searching typical hiding places during the day. Most frogs are active during the warmer spring and summer months in the evening or after rain.

You can identify frogs from their calls. Use a hand-held tape recorder to record calls and compare these with commercially recorded calls. The calls can also be used to locate frogs, so they can be identified visually. When locating frogs by their calls, a technique of triangulation requiring two people is invaluable. The two people stand a few metres apart and each aim their torch in the direction they think the sound in coming from. The frog will be located where the two beams cross.

It is also possible to locate inactive frogs by day. Most species shelter in damp places close to water; ie. under logs, rocks or old fence posts (remember to replace the shelter), in drains and water tanks; even on occasion in rain gauges and public toilets.

Identifying frogs is best done by experts, but if you just want to capture, identify and release them, it is important to handle frogs carefully. Their skin is delicate, and dries out easily, so you should always have wet hands when you touch them. Grab your identification book and attempt to identify the frog. A good text to start with is:

Barker, J., Grigg, G.C., Tyler, M.J. (1995) *A Field Guide to Australian Frogs*. Surrey Beatty & Sons Pty, Ltd.

According to Barker *et al.* (1995), it is still possible to discover new species, especially in remote areas.

3. Habitat requirements

Because they are amphibious, frogs have two sets of habitat requirements: one aquatic, and one terrestrial.

While frogs require some rainfall to survive, they are not totally dependent upon permanent freshwater bodies (Tyler, 1994). In fact, most Australian frogs breed in intermittent bodies of water, but time their life cycles so that their tadpoles (which cannot live without water) have developed legs and can leave the water holes before they dry up.

Arid areas have highly variable rainfall, making them the least hospitable environment for frogs. However, some frogs can still be found in the arid areas of Australia. These frogs survive by burrowing in the soil to a depth where it is cooler than the surface and where moisture is retained. Desert burrowers, as they are referred to, require soils they can dig in (Tyler, 1994).

Most frogs prefer slow-moving water bodies, and are commonly found in backwaters and billabongs. They are most dependent upon aquatic habitat while breeding and as tadpoles, as these stages of the life cycle are spent submerged. Very few species of frog can tolerate saline water, so if you are in an estuarine region, or your river is naturally salty, you should not expect to find too many frogs.

The terrestrial habitat requirements of frogs include plenty of dense riparian or marginal vegetation. This helps frogs avoid predators, and also reduces the desiccating effects of the sun on the frogs delicate skin. Frogs also utilise woody debris and large rocks as shelter from desiccation and predation. A diverse terrestrial habitat will also make a larger range of invertebrates (such as insects) available for frogs to eat.

Habitat requirements of frogs:

- a consistent source of moisture;
- water for breeding;
- places to shelter from predators and drying out; and
- fresh, rather than saline, water.

4. Food and hunting

Frogs generally locate food by sight. They capture prey on their long sticky tongues. When they sense movement, the tongue is flicked far forward so that the top surface lands upon the prey, which is then drawn into the stomach. This entire process occupies a fraction of a second. Almost all frogs have small teeth, but these play a minor role to the tongue, and are only used for gripping larger prey until the tongue can gain control of it.

Most frogs feed out of water, as an adhesive tongue is of little use under the water. Those species which do feed in water usually lunge at their prey with jaws open and use their front legs to stuff the prey into their mouth.

Numerous factors influence the range of prey consumed, significantly the habitat and season, but a frog's diet also depends on its size. Larger species of frogs tend to consume large prey (such as grasshoppers and even other frogs), while small species tend to consume smaller prey (such as ants and other insects). Tadpoles usually eat algae and detritus.

5. Flow regulation

Flow regulation can affect frog populations by eliminating suitable habitat and by altering flow regimes and water temperatures downstream that may be critical for the survival and growth of eggs and larvae (Watson *et al.* 1991).

Many species of frog rely heavily upon the temporary water bodies provided by the inundated floodplain. These habitats occur less frequently with river regulation, and in some cases have disappeared altogether.

6. Life cycles

Following courtship, males and females couple, and the male fertilises spawn as it is laid. Where and when this spawn is laid can help to identify the frogs involved. The spawn develop into tadpoles which eventually metamorphose into frogs. The amount of time it takes for a tadpole to mature to a frog can vary from as little as a couple of weeks, to as much as a year.

7. Water quality

Frogs are very sensitive to environmental change, and declining populations in your area may therefore indicate water quality degradation. Monitoring frog populations in some situations has the added potential of indicating the presence of contaminants in water systems thereby alerting people to possible human health and livestock hazards (Rauhala, 1997).

The aquatic environment can be polluted with a variety of chemical substances, the most common being heavy metals, insecticides, herbicides and fungicides. The effects of these upon frogs is covered in detail in Tyler (1994).

Common malformations in frogs that can result from these chemicals include extra limbs that can be either functional or dysfunctional, the absence of one or both eyes, a failure of the lower jaw to grow at the same rate as the upper jaw and one limb that grows to half the normal size.

Many of these contaminants can be controlled by changing the way the original chemicals are used. Reducing the amount of chemicals you use, applying them directly, and avoiding spraying them directly onto riparian vegetation, can all reduce their impact on frogs.

8. Rehabilitation tips

In summary, the following considerations are important when rehabilitating for frogs:

- Restrict stock access to the stream to allow vegetation to grow and to minimise compaction of soil on the stream bank. This will also allow the development of a thick riparian zone which will provide habitat for frogs, and their prey.

- When placing rehabilitation structures, place logs and other structures in positions that will provide shelter for frogs during the day from predation and the sun.

- Areas of slow flow are essential for frogs to breed. These can be instream, but they are more commonly on floodplains, or in temporary water bodies.

- A wire mesh cover should be fitted over all intake pipes to prevent frogs and other wildlife from being sucked in.

- Good water quality within the stream, and in adjacent temporary water bodies is essential for tadpoles to mature enough to become frogs.

- Minimise herbicide, insecticide or fungicide spraying near stream banks, and in any areas that may provide habitat for frogs. Their highly permeable skins make them very susceptible to chemicals in the water and on riparian foliage.

PART 2: PLANNING TOOLS

NATURAL CHANNEL DESIGN

- Catchment review: developing a catchment perspective and describing your stream
- Designing a more natural stream
- Empirical approaches to designing a naturally stable channel
- Channel evolution approach to rehabilitation design
- Predicting the scour produced when you put things into streams
- How changing the channel can affect flooding

CATCHMENT REVIEW: DEVELOPING A CATCHMENT PERSPECTIVE AND DESCRIBING YOUR STREAM

In Step 3 of the Stream rehabilitation procedure (*How has your stream changed since European settlement?*) (Volume 1) you were asked to describe and characterise your stream. This section of the manual provides more detailed information on the tasks that were described in Steps 3 and 4. Step 3 had four tasks:

- Task 1: Divide the stream into management units (eg. segments and reaches)
- Task 2: Construct a template of the rehabilitated channel
- Task 3: Describe the present stream condition
- Task 4: Map the condition

In this section we provide more guidance on completing Tasks 1–3 of Step 3 as well as some information on assessing the interactions between reaches. Finally we provide some extra information on identifying the main problems in a reach for Step 4.

1. An introduction to catchment review

While the focus of most stream rehabilitation projects is limited to a particular reach of a stream or river, it must be remembered that this reach does not exist in isolation from its upstream catchment. The catchment land use, and the processes of run-off and groundwater flow, help to determine the character of the river. Whatever happens in the rehabilitation reach will have an effect on the reaches downstream. Also, conditions downstream will determine the potential for migration of fish into the rehabilitation reach. Lowland rivers cannot be considered in isolation from their floodplains, which perform various functions such as storage of flood waters, provision of food supplies for organisms that live in the stream, and provision of habitat for species that need access to floodplains to complete their life cycle.

One of the most important tasks in river management is to gain an understanding of the rehabilitation reach from the catchment perspective. This is done by undertaking a catchment-scale investigation. There are many forms a catchment review can take, such as a drive through the accessible parts of the catchment, walking and observing the entire length of stream, examining topographic maps, or detailed monitoring and recording of stream variables on a geographical information system (GIS).

The first task is to divide the stream into manageable units that will form the basis of planning. This is not a trivial task.

2. Dividing the stream into manageable units (Task 1 of Step 3)

It is impossible to manage entire catchments without dividing them into manageable units. Defining these units is essentially a classification exercise. By classifying the stream into reaches, or groups of reaches, we are really saying that each reach of the stream is more similar to itself than it is to the next reach up or downstream. This means that reaches can be used as planning units, allowing management effort to be more effectively distributed.

This section discusses one approach to doing this classification. Step 5 of the procedure emphasises that priorities should be set at progressively smaller scales, from catchments down to reaches, and then to problems within reaches. We propose the following hierarchy of management units for rehabilitation planning: catchments; sub-catchments; segments; groups of reaches; and reaches.

2.1. Catchments and sub-catchments

Catchments are, of course, the fundamental management unit for stream work. For detailed rehabilitation planning we suspect that it would be unrealistic to develop detailed plans for catchments that are more than about 400 km^2. Above this size the number of reaches and problems becomes prohibitive. In other words, we are suggesting that when deciding between catchments to work on, you would compare large catchments first. You would then choose between sub-catchments on the order of hundreds of square kilometres, and only then would you begin to break the sub-catchments into reaches and smaller units. See Step 5 of the Stream rehabilitation planning procedure (Volume 1) and *Setting priorities for stream rehabilitation* in Miscellaneous planning tools (this volume) for advice on how to work out which catchment, subcatchment or reach is the top priority for rehabilitation.

2.2. Segments

Once you have decided upon a sub-catchment that is a rehabilitation priority, then you break it into successively smaller management units. The first of these is segments.

Segments reflect major structural changes that influence the general character of a large proportion of a stream network. For example, it would be typical for a stream to have an upstream headwaters segment, characterised by a confined floodplain, and an unconfined segment with a broad a floodplain. Other landform types such as plateaus, gorges, foothills or alluvial fans may also be useful to define segments. These segments are then subdivided into reaches.

Segments tend to be defined in relation to geological criteria whose influence will affect many other variables, and tend to be too large for humans to alter. Valley slope can be a good indicator of segment boundaries. Plotting the valley slope from a topographic map with at least 10 m intervals may show obvious changes that coincide with geological boundaries (Figure 1). Drainage density, floodplain width, vegetation and stream morphology can all coincide with this boundary. These variables then influence the rehabilitation potential of the stream.

> Reaches are delineated by changes in physical and biological characteristics or processes, such as erosion or deposition rates, stream order, riparian zone species, or land use. Topographic, geological and land-use maps, aerial photos, field inspections and discussions with locals are useful in defining suitable management reaches.

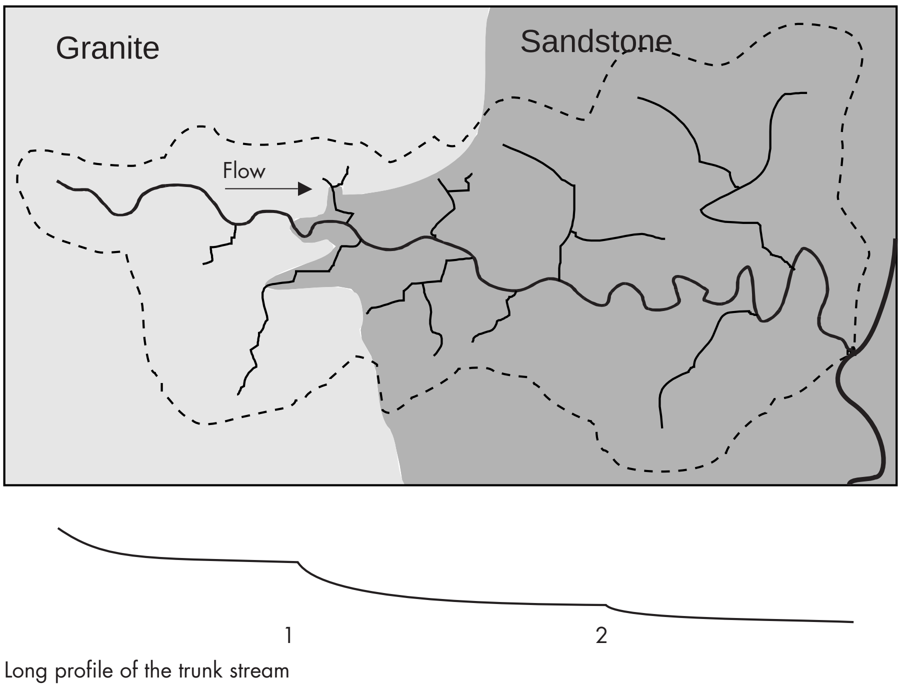


Figure 1. An example of using the long profile to define stream segments. The two changes in slope mean that this stream would be broken into three segments. Note that the first break in slope coincides with a change in geology.

2.3. Defining reaches

A reach is the basic stream management unit. It represents a length of stream with reasonably uniform characteristics, and might vary in length between a kilometre and tens of kilometres. In practice, the reach can be defined on the basis of many criteria (Table 1) including physiography, bed material, discharge, riparian vegetation and aquatic organisms (species present) (eg. Figure 2). Reaches can also be defined in relation to point impacts such as dams or sewage-treatment outlets, if these are important to your management objectives.

The transition from one reach to the next may not be clear, so defining the start and finish of reaches is a subjective process (except where major abrupt changes take place like a dam or change of stream order). There is no hard and fast rule about how long a reach should be. The main principle is to make sure they are of a manageable size. For example, a 40 km reach running through many properties may be difficult to manage.

Most larger catchments in Australia have gone through some form of catchment review. The responsible administrative authorities are usually familiar with the catchment. They should be consulted to help with this process of dividing the catchment into management reaches. The normal procedure for selecting reaches is to initially define them from maps and aerial photographs, then check them for uniformity in the field.

Dividing your streams into manageable units requires a classification. Within a catchment, streams can be classified into segments, which can be subdivided into reaches. Smaller streams can be grouped.

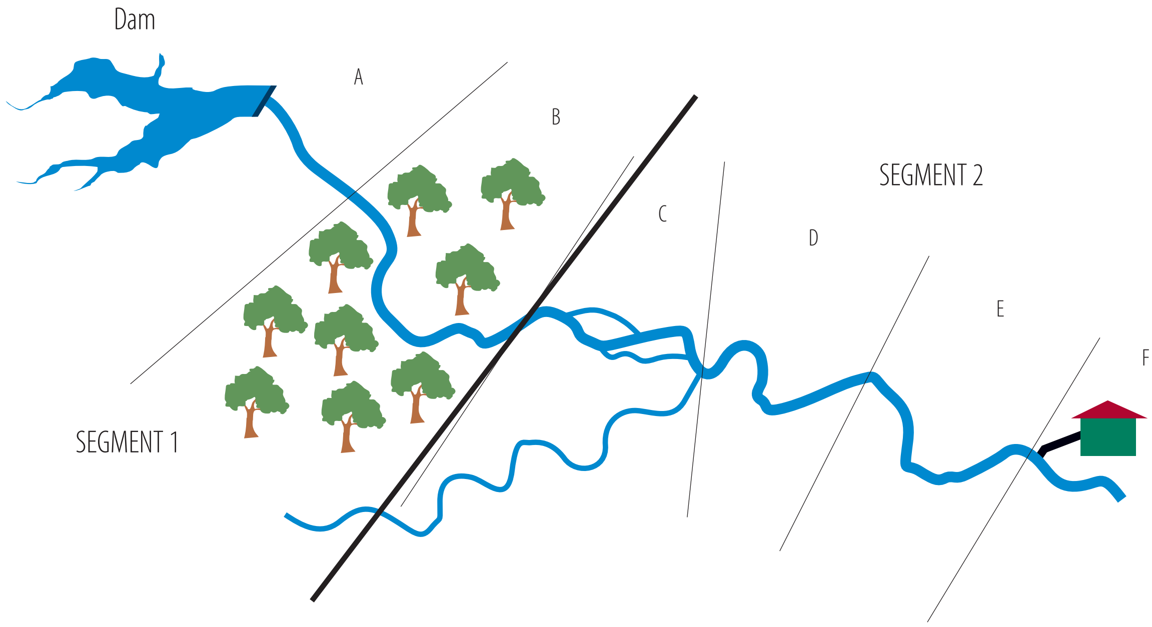
The River Styles approach (Brierley and Fryirs, 1997; Brierley, 1999) provides a methodology for classifying streams based on physical criteria.

2.4. Stream groups

Reaches are the traditional unit of management for streams, and they are easy to define in larger streams. However, most of the length of the stream network is comprised of smaller streams rather than the bigger ones that are the traditional target for management. A stream network is usually a bifurcating (ie. tree-like) network. Streams of different sizes are described as 'orders', with two of the smallest streams with no tributaries (1st order streams) joining to produce a 2nd order stream, two 2nd order streams joining to produce a 3rd order stream, and so on. Most larger Australian catchments would contain up to a 5th or 8th order stream. A rule of thumb is that there are 3 to 5 times as many streams of one order as the next higher order (Strahler, 1964). The implication of this is that for every 4th order stream that you define a reach for, there might be 16 2nd order and 66 1st order streams. If we call each of these small streams a 'reach', there would

Table 1. Criteria for defining reaches.

Area	Examples of criteria
Floodplain	Slope. Confinement (floodplain width). Anabranches/avulsions.
Channel	Boundary materials (bedrock, boulder, gravel, sand, silt, clay). Sinuosity of planform. Size (as a general rule, a new reach is defined when the discharge changes by about 10%). Shape (wide and shallow, or narrow and deep). Tributary junctions.
Land use	Urban, farming (grazing or cropping), or forest.
Vegetation	Grass, willows, or native vegetation.
Biology	Presence of important species (eg. endangered species, or distinctive species such as platypus).
Hydrological discontinuities	Dams, weirs, major points of water abstraction or input.
Administration	National Park, State Park, or different local governments.



SEGMENT	REACH	BASIS FOR DEFINITION
1	The headwaters segment, characterised by a steep slope, a single channel and small floodplain	
	A	Immediately below the dam, grazing on riparian zone
	B	State forest with good riparian vegetation
2	The floodplain segment, with a gentle slope, wide floodplain and multiple channels in one reach	
	C	Floodplain widens out, anabranches develop
	D	Tributary junction, 10% increase in size
	E	Very similar to D, split to maintain a manageable length
	F	Sewage outfall, rumours of high nutrient status

Figure 2. An example of how you go about dividing a stream into segments and reaches.

be an unmanageable number of reaches, and we probably could not inspect them all anyway.

So, how do we classify all of these streams for rehabilitation? The answer is to define reaches as far up the stream network as you can before the number of reaches gets unwieldy (perhaps 20 reaches would be an upper limit). Upstream of this point you group the smaller streams based on their similarity. For example, you might note that all of the 3rd order streams on the granite portion of the catchment are very similar in form and condition. So these might become Group G2 streams (the name is up to you). Cleared streams in this group might become Group G2c streams, and so on. When it comes to the prioritisation step (*Step 5* of the Procedure) you can compare the condition of the stream groups with the condition of the stream reaches. In other words, the group of streams becomes a card in the *Reach priority shuffle* (see *Setting Priorities* in the Miscellaneous tools section of this volume). Note that when the group of streams is allocated a priority in the *priority shuffle*, you will then have to go through the priority procedure again for all of the streams included in the group. This helps you to decide which streams to work on first.

3. Developing a template of the stream condition (Task 2 of Step 3)

Task 2 of Step 3 of the Stream rehabilitation procedure is to construct a template of what the target stream should ideally be like. This template is based on a combination of information.

- A historical reconstruction of its condition before the major disturbance.
- A nearby reference reach that is undisturbed. (In general, the more your reach differs from the reference reach in terms of cross-section, size and shape, planform, substrate, vegetation and water quality, then the worse its condition.)
- Established criteria. (These exist for water quality, and in some areas the expected assemblages of macroinvertebrates or fish are known.)
- General models of a desirable stream condition (eg. perhaps in order to have high species diversity, the stream in the area of interest should have a pool–riffle sequence, and continuous stands of native vegetation along the banks).
- Known empirical relationships (eg. measures of channel width against catchment area may suggest that the target reach is unusually wide).

You should develop the template by grouping all of the above information. You then compare the template with the existing condition, and look for assets, degraded assets and problems that threaten those assets. Assets are components of the present condition that closely resemble the template (that is, they are close to ideal). Degraded assets are features that no longer closely resemble the template. Problems are features or processes that threaten to degrade assets, or have already damaged degraded assets. Once you have identified these components of the stream, you can decide which features of the stream need to be protected, and which need rehabilitation. Complete rehabilitation is often not possible, because many of the differences between the template and the present condition may be irreparable.

Another way of thinking about the template is in terms of developing an idea of **the ecological potential** of a stream. Ecological potential is the expected condition of the stream if it was unaffected by undesirable disturbances. These disturbances are usually taken to be the large-scale impacts that occurred after European settlement, some of which may have ceased and some of which may still be operating. Even when a disturbing activity has ceased (such as mining) its legacy (sand slugs) may remain as a major stream disturbance. Streams also suffer major natural disturbances, such as might result from major floods, droughts, landslides or avulsions. One important difference between human and natural disturbances is that human disturbances were often undertaken with the intention of altering the stream to a desirable condition that could be maintained, whereas after a natural disturbance the stream might recover to its previous state, or perhaps shift to another condition. These days, natural disturbances are superimposed on human disturbances, and this may change their impact. For example, catastrophic floods may cause more serious changes in channel morphology if the riparian vegetation has been removed or replaced by less-dense or less-robust species.

For further information on developing the **template** see the section *How to design a more natural channel*. This section begins with ways to find historical information, as well as methods for using nearby 'reference' reaches. Note that, in practice, you will probably develop your template at the same time as you describe the present condition of the stream.

Remember, the key is to look for assets, degraded assets, and threats to those assets. The aim is not to simply catalogue human damage to the stream.

4. Describing the condition of the reaches (Task 3 of Step 3)

At this stage you have divided the stream into sub-catchments, segments, reaches, and reach-groups. You have developed a template of what the stream could be like (Task 2). Now it is time to describe the present condition of your stream.

It is important to remember that 'condition' is a highly subjective concept. Stream condition can be assessed only relative to some arbitrary benchmarks. Establishment of benchmarks involves application of value judgments, such as that native species are superior to exotic species, high diversity is better than low diversity, an unregulated flow regime is better than a regulated flow regime, stable channels are more desirable than unstable channels—all these are human constructs! Again, remember that we are interested here in the natural assets of the stream, not simply in a catalogue of perceived damage. **Something is only a *problem* if it threatens or damages a natural asset, or stops a natural asset from recovering**.

This section describes some existing methods that you could use to assess the condition of your stream.

4.1. What variables to use

As described in *Step 3: How has your stream changed since European settlement*? of the Stream rehabilitation process,

Describing reach condition

The purpose of the following three sections is to describe the condition of a stream reach, and the impact of that reach on reaches up and downstream. This can best be thought of in relation to Figure 3 below. The condition of the stream should be described in terms of the bed and banks (in-channel), and the riparian zone, including point impacts. Then you must consider what is entering the reach from upstream and downstream. Finally, you consider what is leaving your reach and affecting reaches up and downstream. By doing this you are really carrying out a whole of catchment assessment of the stream condition.

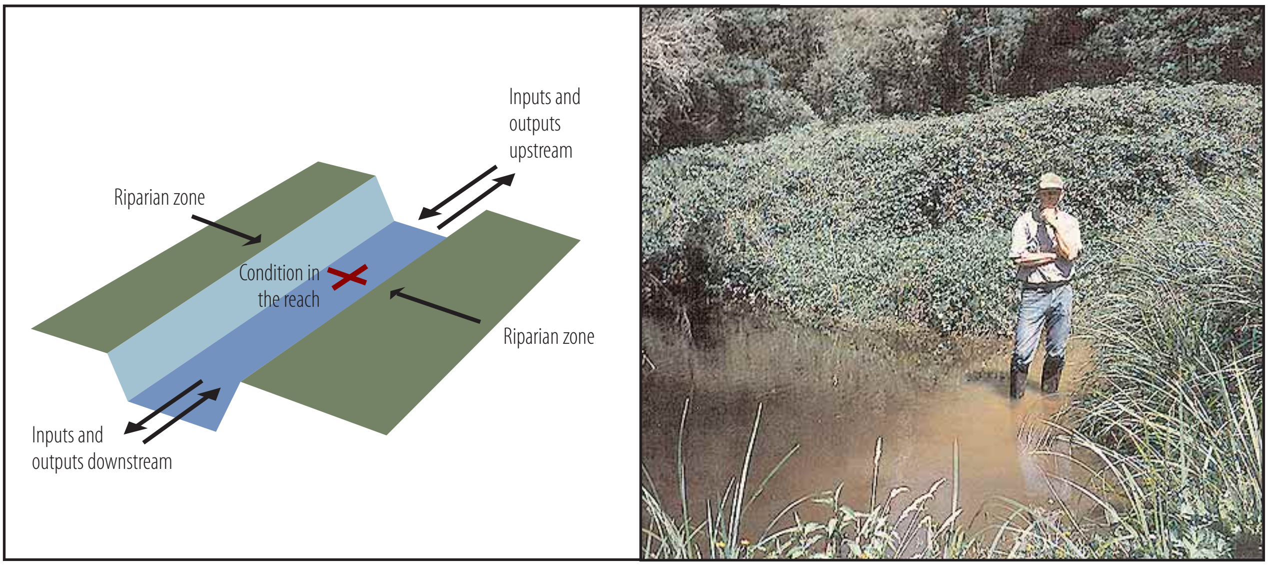


Figure 3. The impacts of the catchment and up- and downstream condition on a reach. The photo on the right shows turbid water from a tributary entering a stream with better water quality (Tarago River, Gippsland).

Volume 1, ideal stream rehabilitation projects will routinely describe the condition of the following:

1. The **diversity and populations of animals and plants**, as well as whole stream communities (eg. platypus, fish, macroinvertebrates, macrophytes).

2. **Riparian vegetation** (diversity, structure (eg. forest or grassland), weed invasion, natural).

3. **Flow regime** (flow duration and magnitude, any regulation or water diversion).

4. **Longitudinal connection along the river** (artificial barriers to movement of water, sediment and organisms along the stream, eg. dams, diversions, weirs, willow encroachment).

5. **Lateral connections across the floodplain** Connection of the stream with the floodplain, including billabongs and anabranching channels. (Things that change lateral connectivity include levees, channel enlargement, channelisation, changes to flow regime, blocked flood channels, connection with billabongs.)

6. **Water quality** (turbidity, nutrients, oxygen, salinity, temperature, toxicants).

7. **Structural complexity and stability** in the channel (size of the channel, sediments, large woody debris).

4.2. How to describe the variables

A description of the condition of a reach can be both static and dynamic. That is, it can include both the present state (eg. willows along banks) and the rate of change (eg. willows are invading the tributaries).

There is a hierarchy of detail that can be used to describe the condition of a stream reach. The basic levels of the hierarchy are shown in Table 2. The level of detail that you use depends on your resources and upon how important it is to be accurate.

4.3. Stream condition surveys

Over the last decade, several methods have been developed to characterise the condition of streams. These methods were reviewed in the Index of Stream Condition Reference Manual (Appendix 2) (DNRE, 1997a), so only a selection of these methods will be briefly described here.

Please note that the 'River Styles' approach developed by Gary Brierley and colleagues at Macquarie University is presented separately in the section *Channel evolution approach to rehabilitation design*.

Table 2. Possible approaches to describing the condition of the stream.

Measure	Examples
Visual description of presence or absence at one point in time.	"Native vegetation was absent from the reach, with willows being the only species present." "The water looked turbid."
Measured description of presence or absence at one point in time.	"Willows were present at density of one tree per 20 m^2." "Turbidity was 43 NTU on 26/12/96."
Visual comparison with a template reach or original state.	"The upstream, uncleared reach had a dense stand of *Eucalyptus camaldulensis*, whereas the target reach had only willows."
Measured comparison with template reach.	"The template reach had twice as many fish as the target reach when it was sampled."
Visual description of change through time.	"According to the landholder the headcut had migrated 200 m since 1974."
Measured description of change through time.	"Three electro-fishing sweeps, one year apart, showed a statistically significant decline in the number of blackfish present."

Limitations of the approaches

It is very important to emphasise that none of the stream condition methods, applied in isolation, will provide enough information to enable stream rehabilitation to immediately commence with a high level of confidence. In some cases they provide a lot of specific data, but may lack guidance on how to make the information relevant to the problem of river rehabilitation. Some methods are specific to a particular aspect of stream condition, such as geomorphology or biology. In most cases these methods do not provide an indication of possible recovery rates, nor do they indicate how adjacent reaches may interact. No single method presently available provides all of the information required to rehabilitate a stream. Neither, it is fair to say, were the existing methods ever designed to do so.

Also, all of the methods described here are rapidly evolving. The latest versions (that we may not have seen) will incorporate new features that will expand their application.

4.3.1. The 'Rivercare' approach

The north coast section of the New South Wales Department of Land and Water Conservation has developed the 'Rivercare' methodology that is based on the premise that the foundation for stream rehabilitation is a stable, vegetated stream. The report by Raine and Gardiner (1995) summarises the Rivercare approach, with special emphasis on north coastal streams. Stream reaches are classified by a traffic light system, where reach vegetation and reach stability (comprising width and alignment) are ranked as being in red (bad), yellow (average) or green (good) condition. Landholders decide on the course of action in the reach (usually a few kilometres of stream) by overlaying clear sheets onto an aerial photograph base. Each layer covers property boundaries, environmental values, geomorphology, permits, management options, and a final management plan.

The traffic light approach can be applied across a whole catchment to help prioritise reach treatment.

4.3.2. The 'State of the Rivers' method

In Queensland (and increasingly in New South Wales and Western Australia), a popular method for characterising stream condition has been the 'State of the Rivers' methodology (Anderson, 1993) which builds on the original Victorian 'State of the Rivers' reporting method (Mitchell, 1990). The method assesses the "state of a river in terms of the physical and environmental condition of the rivers and streams throughout the catchment at the time of the survey, relative to the presumed pristine original condition" (Anderson, 1993). The State of the Rivers method has been developed for characterising a whole stream network, so it can be readily adapted to the prioritisation approach used in this manual.

Assessment of the Rivercare method

The Rivercare system provides a comprehensive community planning tool for managing stream erosion and deposition in short reaches. The emphasis is on producing a stable stream by creating a stable width and stable alignment (both being defined by empirical equations), by clearing inappropriate vegetation from stream channels, using some engineering structures, and planting riparian revegetation. The empirical relations used in the north coast streams may not be applicable elsewhere and the methods apply to the specific character of those streams. The method does not directly consider issues of water quality, flow regulation, or natural recovery. The treatment of riparian vegetation is very impressive.

When to use the Rivercare approach:

- if a rapid (but coarse) assessment of reach condition is required;
- applies best to the larger over-widened streams described in Geomorphic problems (this Volume);
- if your major problem is stream alignment, stability and the absence of riparian vegetation, and you want to efficiently mobilise community planning and action;
- if you want to emulate an outstanding riparian rehabilitation program; or
- if your stream is in coastal northern New South Wales the method will be even more useful.

Note that:

- The method is descriptive, and does not identify the rate of change in condition.
- The pristine condition is defined using a local, undisturbed site as a reference.
- The method is applied to a selection of "homogenous stream sections" across the entire catchment with each sample section usually being about 50 m long.
- Data are recorded on field sheets and entered into a spreadsheet program that provides tools to analyse the data, which can be displayed in a geographical information system (GIS).
- The published version of the method does not consider issues of water quality or regulation, or interaction between reaches. These capabilities may be added.

An example application of the State of the Rivers method: the Maroochy River in Queensland (Anderson, 1993)

A total of 185 reaches was surveyed within the Maroochy River catchment, which has an area of 620 km^2. Each reach took 45–60 minutes to survey; a two-person team surveyed the catchment in about 4 1/2 weeks.

Each site was assessed for channel and aquatic habitat, bank condition, bed and bar condition, and riparian and aquatic vegetation. Each variable was scored, using five categories, in relation to how closely it resembled the original condition, with the highest category (100%) being pristine, and the lowest (0%) being highly degraded.

Assessment of the State of the Rivers method

The State of the Rivers method provides a structured method for recording information about sites. It also provides a large quantity of valuable information about the condition of a stream system. In its easy-to-use GIS format, the data could provide a strong basis for planning and prioritising rehabilitation. Some limitations are that the usefulness of the method relies heavily on how accurately the operator can determine the 'pristine' condition of the stream (but this problem is difficult to avoid). The method does not attempt to explain why a reach is in a particular condition. In part this is because it emphasises individual sites rather than the interaction between sites. Neither does it assess the trajectory of condition over time.

When to use the State of the Rivers method:

- Use the method if you want a detailed, reproducible, static description of the condition of a stream system (a snapshot).
- It is particularly useful for comparing reaches across the whole catchment (such as when prioritising reaches for rehabilitation).

4.3.3. The Index of Stream Condition (ISC) (DNRE, 1997a,b&c)

The ISC:

- is designed to provide a broad, long-term summary of all of the major environmental attributes that affect river health;
- may be used for monitoring, but is not useful for scientific hypothesis testing (ie. a change may be measured through time, but the cause of the change can only be speculated);
- is designed to measure long-term changes (ie. reported every 5 years) over tens of kilometres of stream reach; and
- "may be used to flag potential problems, but may only broadly indicate their cause".

Table 3. Summary of indicators and measures in the Index of Stream Conditions (ISC).

Sub-index	Indicator	Measure
Hydrology	Hydrologic deviation (measure of flow regulation).	Sum differences between actual and natural monthly flows, then divide by annual flow
	Percentage of catchment urbanised.	Measure area
	Presence of hydroelectric stations.	Yes/no
Physical form	Bank stability.	Visual classification
	Bed condition.	Visual classification
	Presence and influence of artificial barriers.	Presence of barriers + frequency of their drowning
	Origin and density of coarse woody debris.	Visual classification
Streamside zone	Width of streamside zone.	Width in metres for small streams, as channel widths for large
	Longitudinal continuity of vegetation.	Discontinuities in bank vegetation
	Structural intactness.	Continuous–patchy–sparse
	Proportion of cover which is indigenous.	Visual assessment
	Presence of regeneration of indigenous species.	Visual assessment
	Condition of billabongs.	Percentage classes
Water Quality[1]	Total phosphorus.	Total P mg/m^3 (<10–>100)
	Turbidity.	NTU (<5–>30)
	Electrical conductivity.	Ec (µS/cm) (<50–>800)
	pH.	pH range (less is better)
Aquatic life	SIGNAL macroinvertebrate index[2]	Sum of sensitivity grades of macroinvertebrates to family level

[1]Values vary for reaches in mountains, valleys, floodplains (all increasing downstream).

[2]This measure (discussed later) is to be replaced by the AusRivAS macroinvertebrate approach.

The index is compiled by measuring variables (Table 3) and allocating a rating to the measure when compared with the expected 'natural' state (Table 4). Data for the ISC are collected from four transects of a reach at least one kilometre long. The final index of stream condition is presented as a sum of the sub-index values, each of which is put through an equation to produce a maximum value of 10. Thus the index shows the relative value of each sub-index, plus the total value. This allows the user to identify the aspect of the stream that is in the worst condition.

Table 4. The point scale for indicator measurements in the ISC.

Category (naturalness)	Category relative to ideal state	Rating
Essentially natural	Ideal	4
Some modification from natural	Close to ideal	3
Moderate modification from natural	Moderately different from ideal	2
Major modification	Substantially different from ideal	1
Extreme modification	Far from ideal	0

4.4. Biological site assessment of stream health

*By John Gooderham**

The condition of a stream can be assessed in terms of the organisms that live in the stream. This section describes some methods available for 'biological assessment'.

The organisms in a stream reflect the health of the stream. Using them as a measure of stream health is called 'biological assessment'. Biological assessment of reaches and sites has two distinct benefits. Firstly, it gives a direct indication of the ecological health of your site, and secondly, it allows an indirect assessment of the water quality at your site. Most water quality variables require long-term monitoring and large numbers of samples to overcome their inherent variability, whereas biological samples are more consistent, and are a direct result of the recent water quality history at your site.

Biological assessment is notoriously complicated as it involves attaching values to the occurrence of species of fish, plants, or macroinvertebrates. Some of these

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Assessment of Index of Stream Condition

The Index of Stream Condition (ISC) is similar to the State of the Rivers method in that it includes some subjective rankings of condition based on comparing the current conditions with pristine conditions. However, the ISC is not limited to subjective information. It also includes some measured physical characteristics of the stream.

The feature of ISC is that stream health is based on a core group of variables that are relatively easy to measure. The index also includes water quality and bio-indicators (ie. macroinvertebrates), specifying key variables to measure and the acceptable levels or ranges.

The ISC provides a powerful and comprehensive tool for rapidly assessing stream condition in a repeatable way. It is particularly powerful when comparing whole catchments.

As with the other methods, it does not consider the cause of stream condition, or the direction of change. Water quality assessment is often restricted to low-flow measures, which may not detect all problems, but are realistic to measure.

The classification is developed for Victoria and some elements may not be directly relevant elsewhere.

When to use the ISC:

- If you want a well-structured, rapid assessment of the condition of stream reaches that is comparable between reaches and between streams.
- The ISC was not designed to be used as the basis for a detailed rehabilitation program, but it is a very useful precursor to such a program.
- If you want to include some basic hydrological, water quality, and macroinvertebrate indices in your assessment (no other general approaches include these variables).
- The index may not pick-up all natural assets in a stream system, but it provides a strong basis for comparing the condition of whole catchments. This aspect makes the ISC very attractive for the early stages of prioritisation described in Step 5 of this manual, where you have to select between whole catchments for rehabilitation.

communities (particularly plants and macroinvertebrates) are exceptionally diverse, and can consist of hundreds of species. Biological assessment has the unenviable task of converting these hundreds of species into simple data that can be used to assess ecological health and water quality.

The following methods are set out in order of increasing complexity, effort and cost. In all of these methods, the extra effort and cost corresponds with an increase in the amount that can be learnt about the ecology of your site. **All of the following methods require biological samples to be taken using standard methods. This allows comparisons between sites, samples, and guidelines to be performed more easily**. Identifying fish, macrophytes, and macroinvertebrates can be quite difficult, so it is best to get expert help with your identifications at first. The following books may also help:

Macrophytes: Sainty, G.R. and S.W.L. Jacobs, 1994. *Waterplants in Australia* (3rd Edition). Sainty and Associates, Darlinghurst.

Fish: McDowell, R.M. (ed.), 1996. *Freshwater Fishes of South-eastern Australia*. Reed, Sydney.

Macroinvertebrates: Williams, W.D.,1980. *Australian Freshwater Life: the Invertebrates of Australian Inland Waters*. Macmillan, Melbourne.

Standard macroinvertebrate sampling techniques: Tiller, D. and L. Metzeling, 1998. *Rapid Bioassessment of Victorian Streams: the Approach and Methods of the Environment Protection Authority*. Environment Protection Authority, Melbourne.

4.4.1. Direct observation

With a minimum of fuss, you can get a rough idea of the health of a stream by simply observing the more visible components of the ecological community (such as macrophytes and macroalgae). Table 5 introduces some interpretations that can be made from simple observations of macrophytes and macroalgae. Similar information can be extracted from simple observations of macroinvertebrate communities. Lifting a few stones in your stream, or running a net through some macrophytes, can give you a quick idea of whether there is a rich diversity of macroinvertebrate life at your site. A site with poor health will have a smaller range of macroinvertebrates and, as a general rule, the worse sites will have more legless macroinvertebrates (eg. worms and fly larvae).

Table 5. Possible observations of macrophytes and the implications for stream health. From (Sonneman and Breen, 1997).

Observation	Interpretation
Occurrence of submerged aquatic macrophytes.	Native submerged species tend to be sensitive to nutrient enrichment and hydraulic and hydrologic changes. Many introduced plants tend to be more tolerant.
Occurrence of submerged macrophytes in riffles.	Indicative of sediment or moderate nutrient pollution.
Presence of submerged macrophytes anywhere in the bed.	Indicative of a reasonably stable bed substrate (their roots will not survive major bed movement).
Occurrence of annual colonising species in the channel bed.	Indicative of moderate to substantial sediment pollution.
Occurrence of species indicative of a particular water chemistry.	Indicative of regional water quality, eg. pH, alkalinity, salinity.
Presence of obvious epiphytic algae, ie. colonial or filamentous algae growing on the surface of other plants.	Spring—indicative of imbalance between grazers and epiphytes suggesting moderate nutrient enrichment. Late summer—indicative of early stages of nutrient enrichment.
Presence of obvious filamentous macroalgae.	In edges and low flow zones—indicative of moderate nutrient enrichment. In main channel—indicative of severe nutrient enrichment.
Absence of aquatic macrophytes.	Indicative of erosion/instability, turbidity, introduced riparian canopy, or carp impact.
Absence of benthic algae (eg. *Cladophera* spp.) in nutrient enriched systems.	Potentially indicative of heavy metal pollution.

Assessment of direct observation

- This method is easy, quick and intuitive.
- Direct observations are always helpful, but should probably be carried out with other more detailed forms of assessment.
- Care should also be taken in the interpretive steps, as different local ecologies may react differently to standard models outlined in the literature. For example, the absence of aquatic macrophytes in Table 5 could be perfectly normal in a high gradient, low nutrient upland stream (rather than indicating erosion or instability).

4.4.2. Species/family richness measures

One of the commonest and simplest methods for assessing ecological health in streams is to simply count the number of species (or families if identification is difficult) present in your stream. Larger numbers of species or families usually indicates better ecological health. These numbers are meaningless, however, if you don't have something to compare them with, such as a set of guidelines (from your local environmental department), or data from a similar site that is known to be in good condition. Fish and plants are usually identified to species level, whereas macroinvertebrates tend to be more difficult to identify, and are sometimes only identified to family level. Family level identifications are commonly used in the monitoring programs of the environment protection authorities in several States. Tables 6 and 7 give a worked example.

EPT richness measures

Several key groups of macroinvertebrates are consistently associated with sites of good ecological health. EPT stands for Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddis flies). All of these orders of insects are associated with good stream health. EPT richness scores work exactly the same way normal richness measures do, but they count only the numbers of families or species from the EPT groups that occur at a site. As with the previous measures, healthier sites get higher scores. Tables 6 and 7 give a worked example.

4.4.3. Limitations of richness measures

The methods of assessment above assume that diversity is the single most important ecological characteristic, and that a stream with five species of fish in it is better than one with a single species. This form of assessment can sometimes prove inaccurate. If the five fish in one stream are rainbow trout, redfin perch, and three species of carp, while the solitary fish species in another stream is native blackfish, then using diversity as a measure of ecological health is deceptive. Some geographic regions are also naturally less diverse (for example, low nutrient sand bed streams in the Otways (Victoria)). Increasing the diversity in one of these streams could possibly be a negative thing, as it would suggest that the original nutrient levels had been increased, and the new ecological system would be less ecologically healthy even though it was more diverse. This sort of mistake can be avoided in macroinvertebrate studies by using a combination of richness measures and the SIGNAL index (discussed below).

4.4.4. SIGNAL Index

The SIGNAL index (Stream Invertebrate Grade Number – Average Level) (Chessman, 1995; Chessman *et al.*, 1997) sidesteps diversity, and assesses a site based on the types of macroinvertebrates found there. In the SIGNAL system, animals are given scores based upon whether they commonly occur at healthy or unhealthy sites. Animals that prefer healthy sites (such as stoneflies) have scores closer to ten, animals like worms which can tolerate severe pollution score closer to zero. SIGNAL indices are calculated for individual sites by adding the scores for all the families of animal found at a site, and dividing by the number of families.

SIGNAL indices vary between 0 and 10, higher scores are awarded to sites with better ecological health. Tables 6 and 7 give a worked example. SIGNAL index systems are available for New South Wales (Chessman *et al.*, 1997) and Victoria (Tiller and Metzeling, 1998), but the New South Wales system includes a methodology for tailoring the scores to your part of Australia. Indices like these are constantly being improved by environmental agencies, so it is probably worth contacting your local EPA or equivalent to see if they have been altered for the streams and sites you want to work on.

SIGNAL indices can also be weighted by the numbers of each type of animal occurring. A common reaction of macroinvertebrates to mild organic pollution is an increase in the numbers of tolerant animals such as fly larvae and worms. These have lower SIGNAL scores which will decrease the weighted SIGNAL index calculated at a site. This reaction can happen before the EPT animals start to die, so the weighted SIGNAL index is more sensitive to mild pollution. Counting all of the individual animals in a sample can increase the effort involved. Tables 6 and 7 give a worked example.

Assessment of richness measures

- This method is fairly quick, intuitive, but still requires expert supervision.
- Biological samples have to be taken using standard methods (Tiller and Metzeling, 1998).
- These methods require a minimum of family level identification.
- These methods are good for comparing a number of sites/streams, or for comparing with State environmental guidelines.

Assessment of SIGNAL scores

- This method is fairly quick. These scores can be generated from the same samples as the previous richness measures, provided a relevant set of SIGNAL scores is available for your area.
- Biological samples have to be taken using standard methods (Tiller and Metzeling, 1998).
- Requires a minimum of family level identification (same effort required as for richness measures).
- SIGNAL scores were developed originally to assess impacts from organic pollutants (such as treated sewage effluent), and are therefore best used to assess water quality.

Table 6. The two samples below were taken from riffles in the same stream, the second sample was taken immediately downstream of a sewage treatment plant. Note that this sample is unnaturally poor, you would expect many more animals in a real sample, and therefore much higher richness scores.

Macroinvertebrate	No. in sample 1	No. in sample 2	SIGNAL score
Stonefly family 1 (Austroperlidae)	2	–	10
Stonefly family 2 (Gripopterygidae)	5	–	7
Mayfly family 1 (Leptophlebiidae)	7	–	10
Mayfly family 2 (Baetidae)	4	10	5
Mayfly family 3 (Coloburiscidae)	12	–	10
Beetle larvae family 1 (Psephenidae)	4	3	5
Beetle adult family 2 (Dytiscidae)	–	2	5
Caddis fly family 1 (Leptoceridae)	6	–	7
Amphipod family 1 (Ceinidae)	20	1	5
Fly larvae family 1 (Simuliidae)	5	100	5
Fly larvae family 2 (Chironomidae)	3	5	1
Worm (Tubificidae)	–	20	1

Table 7. An assessment of the samples from Table 6 using the different biological site assessment techniques.

Assessment	How it works	Score at site 1	Score at site 2
Family richness	Count the number of families present in a sample.	10	7
EPT richness	Count the number of Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddis flies) in a sample.	6	1
SIGNAL	Add family SIGNAL scores, and divide by the family richness.	6.50 (clean water)	3.86 (polluted)
Weighted SIGNAL	As for SIGNAL, but multiply family SIGNAL scores by the number of individuals of each family present, then divide by the total number of individuals.	6.69	4.29
AusRivAS O/E Families	Number of observed families, divided by the expected number (ie. that predicted by the model).	0.95	0.6
AusRivAS O/E SIGNAL	Observed SIGNAL score, divided by SIGNAL score predicted by the model (Expected).	0.9	0.6

4.4.5. AusRivAS

AusRivAS is based on a set of statistical methods which simply highlight ecological differences between groups of sites. It then predicts the macroinvertebrates that should occur at your site. It does this by comparing a range of physical measurements from your site (such as annual temperature range and elevation), with a large database of 'reference' sites. It then compares the macroinvertebrates you found at your site with a prediction based on what was found at similar sites. This comparison is phrased as an 'observed' value (your number of families, or SIGNAL score) divided by an 'expected' value (the number of families, or signal score predicted by the model). Sites that are healthy have scores around 1, whereas degraded sites usually score less than about 0.8. The AusRivAS network is now quite extensive, so there is a fairly good chance that your site will fit into one of the regions they have already constructed models for. Tables 6 and 7 give a worked example.

Assessment of AusRivAS

This method is complicated and requires professional assistance. More information available at the web site **http://ausrivas.canberra.edu.au/ausrivas/**

- Biological samples have to be taken using standard methods (Tiller and Metzeling, 1998).
- If the analysis is done by an anvironmental agency, the results can be distilled into an easily interpreted report.
- AusRivAS requires a suite of environmental and water quality data to be taken at the same time as the biological samples, and for this reason requires a serious commitment. Different regions require different types of data, so it is important to check that you are looking for the right data before you start.

5. Determining the interactions between reaches

Now that you have described the condition of your stream reach, it is time to see how the reaches interact with each other.

Streams are usually continuous longitudinal systems, so the arbitrarily defined reaches are not isolated—they interact. Identifying these interactions between reaches is one of the key tasks in effective stream and catchment management. The sorts of issues you need to consider in terms of the interconnectedness of the stream are:

- **Sediment**

What are the sediment sources and depositional zones and how are they affecting downstream reaches? For example, a reach of willows may be trapping sediment from upstream reaches, in which case you would have to consider the downstream ramifications of removing the willows and releasing the sediment. The Brierley 'River Styles' method provides an approach to predicting change in the stream system (see Channel evolution approaches to channel design).

- **Water quality**

Changes in water quality can influence the condition of downstream reaches.

- **Bed degradation**

Bed degradation usually moves upstream, so consider how downstream headcuts would effect the reach if allowed to continue upstream.

- **Recolonisation sources**

Rehabilitation of streams requires the presence of adequate populations for recolonisation, such as seeds from upstream forests for revegetation, or fish populations from upstream or downstream reaches.

At this point you should have a look at *Common stream problems* (this volume). You may recognise your stream problem type there, and this may help in the following assessments.

6. Determining the key problems in the reach

This section provides more information for Step 4 *What are the stream's main assets and problems*? and Step 5 *Setting priorities: which reaches and problems should you work on first*? in the Stream rehabilitation procedure (Volume 1).

An important task in stream rehabilitation is to correctly identify which problem needs to be fixed in order to improve the streams natural assets. There is no point developing elaborate rehabilitation plans to treat the wrong problem, or to fix a symptom and not the cause. Some hypothetical examples of incorrect identification of causes are:

- Stream managers remove trees from the stream banks in the belief that they cause bank slumping. In reality the trees are falling in because the bed is deepening, and the banks are becoming unstable.

- Managers build in-stream structures to restore habitat, when it turns out that the declining fish population were caused by predation by trout.

- Anglers blame flow regulation from a dam for the poor fish numbers, only to discover that they have been fishing in pools that have become saline.

Problem definition is a matter of perspective and depends on the values attached to the river. A problem is usually expressed as a symptom, such as "fish numbers have declined" or "the river is eroding". These descriptions of a problem do not, in themselves, explain the problem. An explanation is needed for the river manager to be empowered to effectively address the problem. Some problems are not as simply explained as they may initially seem. The difficulty of isolating changes due to a host of human disturbances superimposed over natural variability and changes, means that it is advisable to seek specialised scientific assistance to investigate the cause of river problems.

Environmental problems in streams are usually defined in terms of their impact on a specific organism (eg. fish, platypus, macroinvertebrates), or in terms of generic deficiencies in stream health: poor riparian vegetation, poor water quality, erosion and deposition.

It is not the purpose of this manual to tell you how to diagnose all possible problems in your streams (although Common stream problems (this volume) provides some detailed information on the more common problems) and, more importantly, we cannot tell you why a particular problem exists (eg. why a particular fish has disappeared, or why this bank is eroding). This is very often a specialised, site-specific task. But what we can do is describe some approaches that you can use to diagnose the cause, and the range of possible problems that you could face.

If your interest is in organisms in a stream, then population declines can relate to habitat, breeding, water quality, food supply, hydrology and predation. The changes can be related to the magnitude, duration and frequency of impacts. For example:

- Turbidity levels can usually rise dramatically for short periods with little impact on organisms, but long periods of slightly higher turbidity could harm some species.

- The demise of one organism could be a secondary effect of the disappearance of another (eg. macroinvertebrates disappear because they are smothered by sediment, leading to a loss of a fish species that relied on them for food).

Table 8 shows some factors that could be influencing the organisms in your stream. In reality there are probably many of these factors influencing the abundance and diversity of organisms in the reach. However, it may be that one or two of these factors is of overriding importance—a 'fatal' or limiting problem. Until these are corrected, there is little point tackling the rest of your problems.

6.1. Biological limits approach

The concept of biological limits is also discussed in *An introduction to stream ecosystems*, in Stream rehabilitation concepts, in Volume 1.

The 'biological limits approach' sets out to identify the critical factors that control the population of particular target organisms. This approach can be called the 'limits' approach, because it is targeting the main limiting factor for a particular faunal group. The rehabilitation program is then aimed at providing these factors in the most appropriate way; for example, by altering flow regime, improving water quality, or by building in-stream habitat structures (Swales, 1989; Beschta *et al.*, 1994). This approach requires that the habitat requirements for the target fauna be known. Unfortunately, it is seldom the case that these are known in detail.

Table 8. Some examples of problems that directly influence stream organisms by impacting on their major requirements, and some stream processes or human impacts that could cause those problems.

Major requirement	Problem	Possible process or human impact that could cause the problem
Habitat	Reduced cover, ie. limited large woody debris (LWD), undercutting, overhanging vegetation or larger rocks.	Channelisation—removal of LWD, and vegetation.
	Limited velocity variability.	Homogenisation of streams by erosion, channelisation, sediment slugs.
	Low depth variability.	Pools filled with sediment (homogenisation), removal of LWD and other obstructions.
	Uniform substrate: fine material.	Unstable beds, eroded clay beds, sand slugs, fine sediment filling spaces between gravels.
	Uniform substrate: coarse material.	Increase in regulated discharge below a dam leads to more regular movement of bed-material, stock trampling, sand and gravel extraction.
	Reduced shade.	Vegetation removal, reduced cover; decreased depth with bed aggradation.
Breeding	Reduced flooding limits floodplain access for breeding.	Dams reduce flooding.
	Low egg survival.	Sedimentation on rocks, increased velocities.
	Limited nursery areas for young fish.	Channelisation reduces habitat diversity, hydraulic diversity.
Water quality	Turbidity levels too high.	Increased catchment and channel erosion.
	Dissolved oxygen levels too low.	Levels decreased by decomposition of increased organic matter, increased temperature in still water.
	Temperature too low or high.	Reduced temperature from low-level dam releases, elevated temperature with reduced shade or from wide, shallow streams.
	Nutrient levels too high.	Elevated by agricultural run-off, sewage treatment, or channel erosion.
	High or low pH, high levels of heavy metals and pesticides.	Point source enrichment issues such as mining, industrial processes, agriculture.
Food and nutrient supply	Low food input from vegetation.	Inadequate riparian vegetation to provide food (leaf litter, flowers, fruit, insects).
	Lack of large woody debris.	Desnagging of streams removes an essential food source in lowland streams.
	Low food distribution downstream.	Dams trap organic material moving downstream.
	Low food input from floodplains.	Reduced flooding decreases organic debris and carbon from floodplains.
	Not enough food due to competition.	Exotic fish and other creatures can out-compete native species for food.
Hydrology	Shorter flood duration.	Regulation of stream for drinking water and irrigation.
	Stream communities changed from riverine to lake.	Dams and weirs change the character of the stream.
	Altered seasonality of flows.	Altered seasonality from dam storage and releases affects breeding.
	Lower flood frequency.	Reduced flooding affects breeding and food sources.
	Increased rate of change.	Rapid rises and falls of stage leave organisms stranded.
Fish passage	Barriers to fish passage.	Low weirs, culverts, fords, shallow wide expanses of water, high-velocity water.
Predation balance	Predation.	Exotic species can eat native species.

If you are interested in identifying habitat deficiencies for specific organisms, then descriptions of habitat requirements exist for some species. By comparing your reach with the description in Table 9, or in the detailed descriptions of native fish habitat in Koehn and O'Connor (1990), you can attempt to tailor your reach to the requirements. Such habitat matching has reached a very detailed stage for salmonids in the northern hemisphere, where they can specify exactly the particle-size distribution required for spawning, or the radius of curvature of bends preferred by trout.

6.1.1. How do you know what the limiting variable is?

One crude, but useful, way to identify some limiting variables is to look for places that have the characteristics that you want to achieve, and see if they have the environmental values that you are looking for. For example, is in-stream habitat the limiting physical variable for macroinvertebrate population diversity in your reach? Try inspecting any portion of the stream that already provides elements of the physical habitat that you are interested in restoring. Do these habitats have satisfactory populations of the organisms that you are interested in fostering? If not, then do not expect to be too successful with your own habitat enhancement. It would be wise to look for other limiting variables.

Other examples of the same approach would be:

- The effects of flow regulation often decline downstream in a stream system. Do you find a corresponding downstream improvement in the target organism? If not, it may suggest that there are more complex problems that may not be related to flow regulation.

- For riparian vegetation, ask yourself "why is there riparian vegetation here and not there?" Why hasn't it regenerated? Could it be because there is no seed source, because the erosion rate on the bend is too great and the regenerating vegetation is being washed away, or because stock grazing is preventing revegetation?

6.1.2 . Concluding comments on identifying limiting variables

It is important to emphasise that, even with the methods described here, you may not be able to identify the limiting environmental variable in your reach, or explain why a trend exists. For example, despite detailed sampling and monitoring, scientists are still unable to explain why the Broken River in northern Victoria has a much richer fish fauna than its neighbouring stream, the Campaspe River. Is this a trend (ie. a decline in once higher diversity in the Campaspe), or could it be something to do with the larger dam on the Campaspe River?

Table 9. Criteria for assessment of fish habitat values for the Numerella River (information is based on the requirements of two native species, trout cod and Maquarie perch and of the introduced species, brown trout). From The Numeralla: River of Change, by Barry Starr (1995).

Feature	Undesirable	Desirable
Gradient	Regular and even so that water depth remains constant.	Regular grade changes, sequence of pools and riffles.
Cross-section	Regular and even.	Variable, a mixture of deep holes (>1.5 m), shallow areas, wide and shallow riffles, narrow and deep riffles.
Bed material	Uniform composition—whether rock, shingle, pebble, mud or sand.	Mixture of large boulders and cobbles, smaller shingle, pebbles, sand and mud.
Aquatic flora	Few or no aquatic plants. Abundance of only 1 or 2 species or aquatic plants. Abundance of filamentous algae.	Range of species (reeds, pond weeds, milfoils etc.) distributed throughout the stream. Little if any filamentous algae.
Riparian vegetation	Little or no riparian vegetation. Abundance of non-native trees or shrubs (eg. willows).	More or less continuous and wide fringe of a range of native species (trees, shrubs, herbs, grasses). Provides shade, input of food and organic matter, enhances bank stability.
Instream cover	Few if any logs, large boulders, steep banks etc. which provide refuge from the flow and predators.	Logs, large boulders, steep banks etc. are common to abundant throughout the stream.
Water quality	Low levels of dissolved oxygen (ie. <5 mg/L). Low pH levels (ie. <6.5).	Moderate to high levels of dissolved oxygen (6–10 mg/L). Neutral to slightly alkaline pH levels (ie. 6.5–9.0).
Temperature	High water temperature (ie. >23°C).	Low to moderate water temperature.

A hypothetical example of the importance of targeting the limiting problem

The lower Problematic River is in fair to poor condition. It is fairly typical of the streams in the region. The banks are mostly lined with willows, but there are pockets of intact native riparian vegetation. There is some local bank erosion, but generally the river morphology is relatively undisturbed (gravel bed, pool–riffle sequence). There is good potential to rehabilitate the stream by improving riparian vegetation, and controlling stock access to the stream. There are also two large dams on the river. If the stream manager's goal is to return the stream to something like its pre-European settlement state, with a full complement of native fish, what should be done?

Fortunately we know a lot about the Problematic River, because extensive baseline studies of the fish fauna were done before the upper dam was built. At the time the fish biologists urged the dam designers to build a multi-level water off-take because the water released from the dam would be too cold for native fish to survive. The multi-level off-take was not built. Later surveys showed that the healthy populations of native fish were no longer present in the river, and had been replaced by brown trout. The reason, as predicted, was the low temperature of water released from the dam.

Stream managers on the Problematic River can draw two conclusions. First, fish numbers were healthy before the dam was built, suggesting that in-stream habitat was not fatally degraded for fish, although it could probably be improved. The in-stream habitat has not changed much since the dam was built. Second, the limiting variable for fish (at least) along this stream is water temperature, and this is the problem that must be targeted first.

Thus, if the return of native fish and other creatures to the Problematic River is the manager's primary goal, then they should put their resources into increasing the temperature of water released from the dam, so that it is closer to the natural temperature range. The natural range is known in this case, but otherwise it could have been estimated from the range of temperatures in a template reach.

The stream manager would then ask three more questions:

- What temperature ranges would be *acceptable* if I could not achieve the original temperature range? (Having this compromise position is essential for negotiations.) In this case, temperatures within the known range of tolerance of the native fish would be acceptable.

- If acceptable temperatures are achieved, can the fish return? First check if any fish at all survive in the river. Are there enough for a breeding population? The Problematic River runs into another large dam downstream. This could prevent migration of fish into the Problematic River. Fish may have to be artificially restocked.

- If the fish were artificially restocked would their populations be sustainable? Since they existed before the upper reservoir was built, the population probably would be sustainable.

Assessment of the limits approach

*By Michael Stewardson**

It is difficult to know which variable is the most important in limiting the success of an organism. This habitat-based approach has been widely applied in the United States, but in some cases it has been shown to be unsuccessful. For example, a review of over 1,200 stream restoration projects in Oregon revealed that early stream restoration efforts concentrated largely on creating pools for summer fish habitat. Recent research has shown that for many Oregon streams, pool habitat is not necessarily the factor limiting fish productivity, and the focus for restoration of streams in Oregon is now the provision of cover as refuge for young fish during high winter flows (Andrus, 1991). Similarly, in south-eastern Australia, the provision of in-stream cover is emerging as a critical factor in determining fish populations (Koehn, 1987).

The habitat enhancement approach requires that habitat requirements for the species at different life-stages have been established (Hey, 1992), and that factors currently limiting productivity are correctly identified (Hicks and Reeves, 1994). It is also possible that efforts to enhance the habitat of a limited faunal group may ignore, or have a detrimental effect on, other members of the aquatic community (National Research Council, 1992). Even when expertly done, modifications intended to maximise habitat may result in symptomatic treatment of perceived defects from the perspective of one or a few fish species. Current stream restoration practices are rarely based on sufficient knowledge of the physical-habitat requirements of the biota (Borchadt, 1993).

A key characteristic of productive streams is habitat diversity (Gorman and Karr, 1978; Wesche, 1985). Hicks and Reeves (1994) argue that the impact of restoration efforts must be considered in the context of the fish community and not just a single species or age-class. For this reason, many projects are now attempting to create a variety of habitat conditions that will potentially benefit all fish species and ages. The object of these restoration projects is frequently termed 'habitat diversity', although this term is rarely defined.

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DESIGNING A MORE NATURAL STREAM

*With contributions from Dr Chris Gippel **

This part of the manual links to Step 9 of the Stream rehabilitation procedure (Volume 1) *How will you design your project to achieve your objectives ?* It also describes approaches for developing a template of the desirable condition of your stream (Task 2, Step 3, *How has your stream changed since European settlement ?*

If you have gone through the procedure you may have decided that you want to directly intervene in a stream to make it more 'natural'.

This section of the manual describes a procedure that you can follow to design a more natural stream and provides information on:

- the limitations of recreating 'natural' streams;
- applications and limitations of the available channel- design procedures; and
- what to measure when developing a template of another stream.

WARNING!

Is it time for you to be exploring this section yet? It is very tempting to explore the possibility of rebuilding your damaged stream. This is a very common activity around the world, and there are good design guides available for doing it. However, the prioritisation procedure (Step 5) emphasises that the first task of stream rehabilitation is to protect the natural assets that remain in streams. We should only be considering **improving** stream reaches when we have protected the assets that already exist. So we should only really be contemplating rebuilding a more 'natural' stream if we are confident that we have already protected the remaining natural assets.

1. Setting realistic objectives

This section deals with streams that have undergone some substantial modification to their basic form, or morphology, so that they are regarded as degraded (or ecologically inferior) compared to with their pre-disturbance condition. Before undertaking any kind of stream works that aim to 'naturalise' a stream, it is important to set some realistic and meaningful objectives. The term 'natural' is so subjective, that, on its own, it is inadequate as an objective. A possible starting point is to determine the ecological potential of the stream—what it would be like if there was no significant human disturbance? It can be assumed that the stream was in this condition before European settlement. It is important to note that it was the stream 'processes' that were undisturbed at that time. By processes, we mean the things that drive the system and give it its character, such as the catchment hydrology, the sediment transport system, the ecological interactions, and the in-stream habitat hydraulics. Attempting to restore the detailed physical characteristics of the stream (such as channel width, meander shape or pool–riffle sequence) as it existed perhaps 150 years ago could fail to produce the expected ecological recovery if the driving processes have substantially altered since that time. In this case it is necessary to adjust expectations by scaling the potential

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stream condition according to the degree of disruption to the processes. Obtaining a catchment perspective of the problem should reveal any substantial disruptions in the processes operating in the catchment.

Even if all the processes operating in the catchment are returned to their pre-disturbance level of functioning, it is unlikely that the resulting stream will ever be the same as that which previously existed. This is because stream systems are highly dynamic and continually adjusting to variations in the processes that shape them. The traditional idea of a well-behaved stream was one that was physically stable. We now know that while such a stream suits human needs to protect things like infrastructure and property boundaries, in ecological terms very stable streams are not only rare, but they tend to have lower biological diversity than streams that move around. Movement, or change, occurs at all time and space scales, and includes things like transport of bed material, undercutting of banks, migration of meanders, creation of cut-offs, input of large woody debris, and migration of bedforms. Streams do undergo catastrophic change naturally (such as a major flood). Episodes of catastrophic instability simply reset the ecology, which then goes through a recovery phase until the next major disturbance. Along the way, the stream is continually subjected to minor disturbances. The organisms that live in streams have evolved mechanisms to cope with these disturbances. Highly degraded streams may be persistently unstable, or fixed in a certain state. Such streams tend to have low diversity because there is no opportunity for recovery.

It appears logical that partial or even full restoration of stream and catchment processes should lead to a stream that has more ecological diversity and abundance. If this were the case, there should be no need to construct meanders of a certain dimension, or build pools and riffles. This is essentially true, but there are two very strong reasons for undertaking aggressive intervention in this process. The first reason is that often the natural processes that formed the pre-European stream cannot be reinstated. For example, the supply of sediment that builds channel features may be cut off by a dam, or the flow regime may be altered by diversion. The second reason is that the natural rates of physical and biological response to changes in the driving processes may be too slow for the expectations of the people who take an interest in the river. In this case, it might be desirable to 'assist' the recovery of the stream, to speed its return to a condition that can support a diverse ecology.

Even if the restoration of stream and catchment processes was an effective way of rehabilitating the stream, the reality is that it is often not possible. In some cases it may be possible to partially restore some natural processes, such as through provision of an environmental flow regime in a regulated river, or to reinstate some processes, such as through removal of stream barriers. Thus, we usually have to scale back our expectations of how the stream will look compared with its pre-disturbance condition. In the channel rehabilitation design process, this translates to scaling, or applying correction factors, to the known relationships between channel form and process that operate in relatively pristine systems (or reference systems). The other broad approach to natural channel design is based on the assumption that a physically stable channel is desired. Engineers have developed equations that can be used to design a stable channel given certain conditions of bed material transport and hydrology. These equations usually have a high degree of uncertainty associated with them, even under ideal conditions when detailed data on the input variables are available.

Key points

- It is better to reinstate the natural processes than some known previous physical condition. When catchment and stream processes are corrected, the appropriate channel form will usually follow.
- 'Assisted recovery' is used to speed the rate of recovery where the catchment and stream processes cannot be fully reinstated, or where the expected recovery rate is slower than what is desired by stream managers.
- Instability of channel features is an important characteristic of a healthy stream.
- Pre-disturbance condition, reference streams (templates), or empirical relationships derived from undisturbed streams provide a guide to rehabilitation design, but these models have to be scaled according to the existing level of disturbance to catchment and stream processes.
- Channels that have relatively stable form can be designed using engineering equations. This approach will be limited by availability of input data, and uncertainty in the model predictions.

2. Selecting a procedure to design the stream template

After the difficulty in setting the objectives for rehabilitation are overcome it may be decided that resources should be spent in creating a channel with specific characteristics. To so this, you need to develop a template on which to base rehabilitation of your stream. The template may be based on some pre-existing condition of the stream, or a nearby stream in a healthy condition, or a stream that has a predictable level of stability.

There can be confusion between terms here, so here are some definitions. The **template** is the general 'model' of the stream that you are developing. It can be based on information from many sources, including nearby reaches. The **'target'** reach is the reach that is to be rehabilitated. **Reference** reaches are reaches that are considered to still be in good condition, and that can be compared with the target reach. In the rehabilitation procedure described in Volume 1, the reference reach would usually be described as a 'natural asset', and would be given a high priority for protection. The target reach would be ranked lower, perhaps as an impeded recovery reach.

It is now time to select a channel design procedure. There is a hierarchy of design methods (Table 10), from restoring the stream to its pre-disturbance condition, to simply understanding its current stage in the process of evolution, or change, towards a more dynamically stable system, and perhaps assisting its recovery if appropriate. The hierarchy is based on the degree to which a rapid return to a known desirable condition is demanded. Thus, it is not necessarily a ranking of best to worst methods.

Some possible problems with the five methods are highlighted below:

> All of these methods represent an attempt to develop a template of what the stream should or could be like. This template becomes the rehabilitation target.

Table 10. Five approaches to natural stream morphological design.

Method	Speed of result	Certainty of short-term result	Long-term dynamic stability
Historical reconstruction (recreate the pre-disturbance stream).	rapid	certain	May be uncertain if catchment and stream processes are different.
Reference reach approach (copy a high-quality stream, and scale for changed catchment condition).	rapid	certain	Uncertain under these created conditions.
Empirical catchment model approach (use hydraulic geometry equations to predict channel dimensions).	rapid	certain	Highly uncertain under these created conditions.
Stable channel approach or erosion potential approach (use engineering equations to predict stable channel conditions).	rapid	certain	Uncertain under these created conditions.
Channel evolution approach using classification.	slow, but can be accelerated	unlikely	Certain, but condition will change through time.

- **Historical reconstruction**: reconstruct the original condition of the stream from historical information (eg. use the pre-disturbance stream form as a template for rehabilitation).

> Problems: Catchment and floodplain conditions may have changed so much that the original form is no longer appropriate.

- **Reference reach approach**: copy the characteristics of a remnant of a good quality stream (eg. use a good-quality upstream, downstream or nearby stream reach as a template for rehabilitation).

> Problems: There may be no reach available, or the only reach is too far away to be strictly comparable.

Where to find more information on the five approaches to designing your stream template

- Historical reconstruction is discussed below in *Using historical reconstruction to develop a template*.
- The reference reach approach is discussed below in *Using a reference reach to develop a template*.
- The empirical catchment model approach is discussed in the next section Empirical approaches to designing a naturally stable channel.
- The stable channel or erosion potential approaches are not discussed further in this manual.
- The channel evolution approach is discussed in the following section Channel evolution approach to rehabilitation design.

- **Empirical catchment model approach**: apply generic, empirical relationships, based on hydraulic geometry, or regime relationships to predict the 'equilibrium' form of the stream (eg. use width/discharge relationships, planform/width relationships to predict an equilibrium channel form that you can use as a basis for stable channel design).

> Problems: Empirical relationships are notoriously unreliable when applied to different rivers, and must assume that streams used in data sets were in equilibrium. Uncertainty about application to Australian streams.

- **Stable channel or erosion potential approaches**: include the hydraulic–geomorphic approach and tractive stress or maximum allowable velocity approaches which allows a stable bed slope to be predicted such that there is no net degradation of the reach.

> Problems: Bedload equations used in the hydraulic–geomorphic approach are notoriously inaccurate, so even though this appears to be a 'scientific' numerical solution to predicting a stable bed, we need to be aware of its limitations.
>
> The tractive stress approach assumes cross-section average values, but we know that flow velocities are concentrated in certain parts of the channel, so the tractive stress is not evenly distributed across the channel cross- section. We do not discuss this approach further.

- **Channel evolution approach using classification**: use conceptual models of the morphological stages through which a stream evolves after major disturbance. By classifying the stage of evolution its relative stability can be assessed, and its recovery path predicted. The evolutionary process can be speeded by assisted recovery techniques that might involve revegetation or in-stream structures.

> Problems: Channel recovery may take too long to satisfy the expectations of stream managers and the general community. There is a level of uncertainty in the form that the channel will take through time.

In reality, elements of the first three approaches are used for almost all stream rehabilitation projects, and the erosion potential approach is undertaken only where bed stability is a problem. The geomorphic evolution model is useful if there is no pressure to achieve instant results. One thing is clear—there is no single method or approach that is universally applied to the problem of channel rehabilitation design. This is evidence of the difficulty of the problem, and signals the need for professional help in any project that involves channel design. A professional might apply several methods to the problem. Agreement between results of different methods suggests a reasonably high degree of certainty that the objectives will be achieved.

Apart from the desired speed of results, and predictability of the results over the short-term longer and the long-terms, the type of rehabilitation project will determine the most appropriate approach to designing the template. The type of project relates to whether the primary focus is on channel stability, aesthetic factors, riparian vegetation, or in-stream habitat. For the urban creek discussed above, every aspect of the channel had been undergone major changes, so all aspects of the stream would have to be considered when developing the template. However, consider a stream with acceptable erosion rates (equilibrium stream form) that is infested with exotic vegetation. Here the goal of stream rehabilitation is to restore the riparian vegetation. In this case, we may only need to know only the riparian vegetation characteristics of a healthy stream using the template or historical reconstruction approach. Table 11 provides a guide to help you decide what approach to use.

Applying the different approaches to a hypothetical case study

Consider a typical urban stream. The low- flow channel is contained in a straight, lined channel, within a floodway designed to carry the 100 year flood. The channel lining (bluestone cobbles) has lost its integrity and the stream is starting to develop a meandering planform. The stream managers want to produce a more natural equilibrium channel rather than force the low-flow channel back into the artificial gutter. Consider the rehabilitation in terms of the alternative approaches:

Historical reconstruction: Aerial photographs from the 1940s provide information on the creek's original planform, width, pool spacing and size of vegetation. Anecdotal descriptions from locals tell us what the stream was like. In fact, it was a chain-of-ponds morphology, which is nothing like its current form.

Template approach: There are no really good remnants of this type of stream left in the vicinity of the project (ie. no good template reaches for stream form), but we can get some clues as to the vegetation and disturbed but stable morphology from reaches of a nearby creek in the adjacent catchment. There are a few isolated chain-of-ponds streams in the State but their geometry has not been measured.

Empirical catchment model approach: Good discharge records allow us to estimate what the stable morphology should look like, compared with other channels of this type.

Stable channel or erosion potential approaches: Bed stability is not a concern on the creek, so the hydraulic–geomorphic approach was not used.

Evolutionary stage classification approach: The creek is highly modified from a chain-of-ponds to an incised channel. It is unlikely that the current catchment conditions will allow a natural evolution back to a chain-of-ponds morphology. This approach is not applicable here.

The final plan for the creek is to develop a rehabilitation strategy to produce a channel in dynamic equilibrium (but confined within stream corridor boundaries) that is based on the guidance provided by the above methods, and considering budget constraints.

Table 11. Matching the approach to developing a template to the stream problem.

Project type	Approaches Historical reconstruction	Template	Empirical catchment model	Stable channel or erosion potential	Evolutionary channel model
Bed stability	X			X	X
Bank stability	X	X	X	X	X
Aesthetic	X	X			
Revegetation	X	X			
Instream habitat enhancement	X	X			

3. Using historical reconstruction to develop a template

What was the target stream originally like? This information can be very useful for constructing a template of the desired condition for the stream. Even if it will never be possible to reproduce the original condition, it is still a useful goal.

As a guide you should be able to get a good picture of the following information from historical information:

- old river courses;
- any channel training or other engineering works (may indicate potential instability);
- pre-disturbance stream dimensions;
- pre-disturbance planform (sinuosity);
- presence of pre-disturbance habitat features like pools and riffles and woody debris;
- general vegetation information—size and type of dominant vegetation; and
- bedload transport in the system.

Useful sources of historical stream data are:

- explorers' diaries;
- early surveyors' charts and notebooks;
- aerial photographs;
- topographic maps;
- land surveys;
- old photographs;
- bridge construction surveys (road and rail);
- land tenure titles (parish maps);
- water authority records;
- stream gauging surveys;
- previous cross-section and long-profile surveys;
- flood studies; and
- interviews with locals.

Most of this information is usually archived in State departments and catchment and river management authority files. Old records may not be well maintained, and information is often incomplete or inconclusive. As a starting point, relevant sources of historical data for New

South Wales are presented in Table 12. Similar information is available in most States. It is a matter of doing the detective work to see what you can find out about your stream.

At best, historical records are likely to provide a picture of the type and location of the stream. Accurate dimensions suitable for design are unlikely to be available, hence a reference site from up or downstream and from a nearby catchment should then be adopted as a reference reach by which to model detailed channel design.

Table 12. Sources of historical information for New South Wales streams. Source: Brierley *et al.* (1996), based on Herron (1993).

Location	Information held	Comments
Lands Department.	Portion plans.	Contains vegetation information and comments on available surface water. Occasionally have nothing at all except the types of trees used as portion markers.
	Bridge surveys.	Invaluable for assessing changes in channel structure, ie. widths and depths.
	Surveyors field books.	
	Parish maps.	Show portion numbers, boundaries and first property owner.
	Recent air photographs.	Can inspect these.
	Older air photographs.	Earliest date from 1940s. Problems include delays and poor indexing.
	Topographic maps.	
Mitchell Library, Sydney.	Old maps, correspondences, books, journals, small picture files, laser disk storage of photographs, some newspapers.	There is a lot of information kept here, but there is a certain amount of pot luck in finding what you are looking for. Be patient.
State Library of NSW, Sydney.	Books, journals, newspapers.	This is the best place for looking up newspapers.
Archives Office of NSW, The Rocks, Sydney, or Kingswood.	Maps field notebooks, journals.	
Land Titles Office, Sydney.	Portion plans.	The plans are all on microfilm.
Bureau of Meteorology, Sydney.	Rainfall data—monthly means, also daily data from most stations, temperatures, frosts, winds etc.	Length of records for daily data generally less.
Department of Land and Water Conservation.	Air photographs. Historical records of stream work.	
AUSLIG	Air photographs.	
Australian National Library of Australia, Canberra.	Books, journals, maps, early air photographs, oral histories, newspapers.	
Historical societies.	Newspaper clippings, letters, journals, photographs.	Often hold unexpected information, but very hit and miss.
Local museums and libraries.	All sorts of oddities.	

Some examples of historical reconstructions that can be used to guide rehabilitation

Starr, B. (1999). The use of historical data in community river management planning. Second Australian Stream Management Conference, Adelaide, South Australia, Cooperative Research Centre for Catchment Hydrology, pp. 589–594.

Using the Murrumbidgee as a case study, Starr emphasises that careful reconstruction of past condition and changes produces a realistic expectation of what can be achieved in rehabilitation.

Davis, J. and B. Finlayson (1999). The role of historical research in stream rehabilitation: a case study from Central Victoria. Second Australian Stream Management Conference, Adelaide, South Australia, Cooperative Research Centre for Catchment Hydrology, pp. 199–204.

Davis and Finlayson reconstruct the pre-disturbance condition of the streams, and this becomes the basis for future rehabilitation. They emphasise that the same rigour must be brought to historical reconstruction as to any scientific work. In particular, you should not believe everything that you hear without corroboration.

Limitations to the historical reconstruction approach

- Quantitative information (eg. water quality measurements) may be not be available.
- There may be insufficient information available to form a basis for defining previous stream channel form.
- Available information may be conflicting (ie. historical records or anecdotal information may be inaccurate).
- Current catchment land use, sediment transport, or hydrological conditions may mean that it is not possible to not re-create pre-disturbance conditions.

4. Using a reference reach to develop a template

Another good source of information for the template that you are building-up can be nearby reaches of stream that remain in better condition. The 'reference reach' approach is useful for rehabilitation because it is achievable. Rather than having to understand everything about what a stream **should** look like, all you need to do is copy the characteristics of the reference reach. This approach can be used for the design of major features such as channel geometry, or smaller features, like dominant riparian species, or the types of in-stream cover. The basis of this approach is that an undisturbed system is the most ecologically sound basis on which to model rehabilitation works. Detailed information about habitat requirements of specific species is not required. Rather, the morphological characteristics of an intact system that appears to have a high ecological integrity are duplicated in the rehabilitation reach.

There are, of course, three limitations on the use of references reaches as templates.

1. If the reference and target reaches should be similar (see below), why aren't they? That is, what has caused the target reach to be different from its original good condition? Is it something to do with changes in catchment land use, discharge, erosion, channelisation or some other stream process? Without addressing the cause of stream degradation problems, the same forces may result in failure of the rehabilitation efforts (Kondolf, 1996). For example, a stream that was channelised and concrete-lined in response to major erosion events following urbanisation might be rehabilitated by removal of the hard lining and reinstating the previous channel morphology. However, these works will almost certainly fail due to channel erosion, because the urban influenced discharge is no longer in equilibrium with the previous channel form. As rivers are dynamic in their nature, rehabilitation measures that are based on a static appraisal of the river condition can produce uncertain results.

2. The characteristics of the reference reach need to be scaled to 'fit' the target reach. That is, the reference reach will probably be in a different part of the catchment, with a different catchment area, discharge and sediment load, compared with the target reach. You need to make sure that you scale the size of the reference to the size of the target reach. This sizing is normally done on the basis of bankfull discharge. This scaling is discussed below, and discussed well in Newbury and Gaboury (1993).

3. This approach is based on the assumption that the chosen reference reach is stable, is in dynamic equilibrium, and does support the stream organisms that you wish to encourage in the target reach. If this is not the case, then the template you develop for the target reach is unlikely to be successful.

> There is no need to fully understand the many processes operating in the reference reach that seem to produce such ideal ecological conditions— the objective is simply to copy the channel form, vegetation, and habitat characteristics in the hope that the desired ecological processes will become established.

4.1. Selection of the reference reach

For this template design approach to work, the reference reach must be a suitable goal for the target reach. That is, the two reaches should have been similar, until one of them was disturbed. If the two reaches were never similar, because of fundamental differences in the character of the catchment and stream, then it is unlikely that we could succeed in making them similar now.

When searching for a suitable reference reach, first look for sites up and downstream of the target reach. If unsuccessful, look in an adjacent catchment with similar geology. If unsuccessful, look for the closest catchment that appears to have similar geological and size characteristics.

In some cases the best template reach can be intact remnants of the target reach itself. Remnants of modified channels are often left alongside the target reach in the form of cut-off meander bends or longer reaches of old stream. At the very least, these can provide information about the width and planform of the original channel. In most Australian streams the dimensions of these relict channels will not alter much after they have been abandoned. However, you should check old maps to make sure that the stream you are looking at is not a relic of a former hydrological or sediment transport regime (palaeo-channel). For example, many of the old meanders flanking the Murray River and other streams of the Riverine Plains are several times larger than the present channel, reflecting larger flows that occurred at least 20,000 years ago (Bowler, 1978).

Issues to compare between reference and target reaches and their catchments are listed in Table 13.

Table 13. Issues to consider when selecting a reference reach.

Issue	Why?	How close do you have to be?
Catchment size and shape.	Catchments of different size and shape have different responses to rainfall events. For example, a short, wide catchment will have a 'peaky' run-off response to a storm compared with a long, narrow catchment.	The catchment above the reference reach should be as close as possible in size and shape to the catchment above the target reach.
Floodplain character (confinement).	The behaviour of a stream is strongly influenced by the width of the floodplain. Streams in narrow floodplains tend to be straighter than those on wide floodplains because the valley walls restrict meander formation.	Look for reaches with similar floodplain widths.
Catchment land use.	Catchment land use may affect stream characteristics. For example, compared with forested catchments, catchments with more than about 5% of the area urbanised should be expected to have wider channels for the same catchment area.	Try to follow the general catchment characteristics of the target reach when selecting a reference reach. For example, forested headwaters, stock access to lower stream, continuous riparian vegetation etc.
Stream bed slope.	For the same discharge, higher gradient streams will have a greater velocity (other factors being equal), which means a greater capacity to erode bed and bank materials.	Select a reference reach with slope that is similar to that of the target reach. Slope is such an important hydraulic variable, that channel slopes should be as close as possible. However, the variable nature of stream slope means that differences of $\pm 20\%$ could be due to measurement error.
Flow regime.	Streams that have peaky flood events may have different morphological characteristics than those with floods having long rising and falling stages.	Catchments that appear similar may have different low- flow characteristics and flood frequency curves. Base flows have little effect on channel morphology, but statistically significant differences in the flood frequency curves will give rise to different channel morphology for the same catchment area. In this case it is better to select a reference reach with similar magnitudes and durations of channel- forming flows (say 1–2 year average recurrence interval floods on the partial series) as in the target reach, rather than relying on catchment area similarity.
Geology.	Geology of streams is a major factor in determining stream-form. For example, catchments with basaltic geology give rise to streams with cohesive bed and banks, while granite catchments give rise to coarse sand-bed streams.	Reference and target reaches should have similar geology.
Sediment transport.	All other parameters being equal, a sediment-starved stream will look and behave differently to one with a large sediment load.	Identify sediment sources and sinks in reference and target catchments and consider the mechanisms by which sediment is transported through the systems. The existence of significant sediment sources (eg. sediment slugs or eroding sub-catchments) or sinks (eg. impoundments) may mean that the reaches are not comparable.

4.2. Describing the reference reach

The idea of using a reference reach as a template is not to make the target reach a meticulous precise replica of the reference reach, down to the position of every tree and the length of every pool. Rather, it is to recreate to the character of the reference site—the type of vegetation present, and the normal size of pools.

The following are some variables that you might measure when comparing a target and reference reach:

1. catchment conditions;
2. planform character;
3. cross-section information;
4. materials—substrate and banks;
5. slope;
6. vegetation; and
7. biota.

Flow conditions are discussed later.

> You must sample so that your measurements reflect the *range* of values found in the reach as well as the *average*. Often the range is more important than the average when it comes to ecological factors.

The best way to decide what to measure is to think about what you want to do with the data. For example:

- The vegetation may be the only feature of the reference site that is relevant to the target site, so just describe that.
- If you only want to use the reference reach to provide some general ideas to display to a stakeholder consultation committee, then perhaps photographs are the only information that you need.
- If you are going to use the reference both to design the target reach, as well as to provide some data against which you can evaluate later performance, then expect to do make detailed measurements.

Example of the reference reach approach: North Pine River, Manitoba (Newbury and Gaboury, 1993)

Pine River (Manitoba, Canada) supports rainbow and brook trout populations. However, sections of North Pine Creek are steep and shallow due to armouring of the bed with large rocks and cobbles. In order to increase the trout habitat, one of these steep sections was selected for stream rehabilitation. A reference or template reach that had been identified as having plenty of trout was used as a reference reach. The characteristics of the pools, riffles and meanders in the reference reach were then used as design guidelines for constructing experimental meanders in a straight reach of North Pine Creek.

4.2.1 . Catchment conditions

Catchment conditions are the external factors influencing the template and target reach. The most obvious descriptions of these are **catchment area**, **bankfull discharge** (if possible), **bedrock** outcrops, and features that confine the channel, such as **terraces**, **or floodplain restrictions**. The best way to describe the catchment conditions is to produce a map of the template and target catchment with all of the above details marked.

4.2.2. Planform

Planform can be described in detail in terms of wavelength, arc radius, amplitude and radius of curvature. Such data can be useful in re-meandering projects, and in defining buffer zones. These variables can be measured in the way shown in Figure 4. Usually it is sufficient to compare the general meander patterns on maps of the target and template reaches.

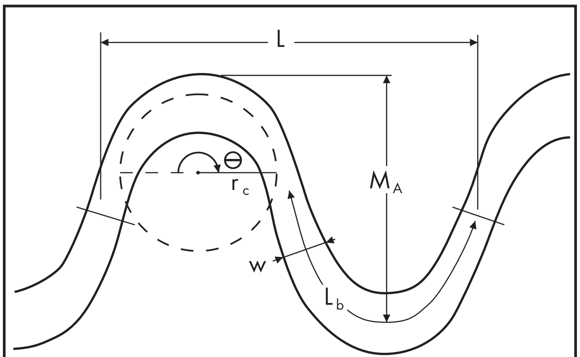

Figure 4. Variables used to describe planform of a stream (from Shields, 1996). Reproduced with permission from John Wiley & Sons.

Other information that can be included on the maps includes:

- in-channel benches;
- point-bars;
- major erosion areas;
- pools;
- riffles;
- artificial levees; and
- vegetation.

4.2.3. Cross-section

The number of cross-sections required to characterise the channel depends on the degree of variation in the channel form. The most rigorous way to collect the data is to survey cross-sections at fixed distances along the channel. This avoids the temptation to pick out features that could bias the result. The sampling distance must be chosen to reflect the size of the channel, and a good rule of thumb is that you should survey a cross-section every three channel widths, followed by two widths, then three widths etc. This sampling approach will pick up any systematic variations, say in a pool–riffle sequence.

The main features that must be recorded in a survey are:

- degree of channel confinement (width of the floodplain or other confining feature);
- top-of-bank points on both banks;
- bank slopes;
- width of the active bed; and
- bankfull depth.

Unless you are going to be using these features for detailed evaluation, they all can be surveyed with a tape and inclinometer. One of the best ways to survey cross-sections in small streams is to simply hang a tape or surveying staff across the channel, check that it is horizontal using a spirit level, then measure the distance from the tape or staff to the bed at set distances. Dumpy levels and theodolites can allow quick collection of accurate data in a short period of time, but may be difficult to carry in the field. In larger streams that cannot be easily crossed easily, a range finder can be used to estimate width.

4.2.4. Slope

Measuring the slope is important for hydraulic design. This needs to be done with a level or theodolite, as inclinometers and other hand-held devices are not accurate enough over tens to hundreds of metres.

Where do you measure slope in a highly variable stream? Since most channel design uses the bankfull flow and dimensions, the following are the slope lines that can be measured, in order of preference.

- Water surface slopes at a range of flow levels (difficult to measure during flood events).
- Bankfull water surface profile (if you happen to be in the field when the river is flowing close to bankfull then survey the water level over a reach of at least 100 metres).
- Slope at top of bank on each side over a reach of at least 100 metres. If possible this should be measured over a full meander wavelength (ie. three riffles or two bends).
- Bed slope can be even better than bank slope, but only if it is measured over at least two full meander

wavelengths (to smooth out the many variations in the bed). Bed slope should be measured along the thalweg or centre line of flow.

4.2.5. Bed and bank material

Bank material needs to be described in order to check that the template and target reaches are similar. It is usually sufficient to simply classify the bank material as fine or coarse gravel, sand, silt and loam, clay, or a combination of these. The layers of material should be drawn on each cross-section with the thickness of the units indicated.

The particle size distribution of the bed material can also be important. A change in substrate may well be one of the goals of the rehabilitation project. Also, we need to know about bed material for channel design (equations often use median bed material size). The Wolman pebble count method (Kellerhals, 1971) is appropriate for gravel bed streams, while sieving is required for finer bed material. The technique is to simply shut your eyes (or just look away), reach down to the bed and touch it with your finger. Pick up the very first particle that you touched and measure its 'B' axis (ie. that axis that it would roll along on the bed). Take a step, shut your eyes again, and touch another pebble, and measure it. Do this 100 times on a mid-channel bar, or in the bed of the stream. It is important that you do not look!

4.2.6. Vegetation

Vegetation surveys are aided by identifying the 'zone' of the cross-section that is occupied by different vegetation types. Some excellent examples of this are provided in the booklets by Allan Raine and others (eg. Raine and Gardiner, 1997). Figure 5 shows an example of the species that are found on different parts of the bank in a template stream. You may even want to be more specific and identify plants growing on specific depositional sites within the cross-section such as benches, point-bars, and mid-channel bars.

4.2.7. Biota

A survey of the mammals, birds, fish, and macroinvertebrates living in the template reach is invaluable as a reference for the target reach, but is also very expensive and time-consuming to do. Two easier things that are often worth doing are a presence or absence survey of fish (fishing clubs can provide this information) and macroinvertebrates. Alternatively, a survey of fish could be done using electro-fishing techniques. This technique takes about one day per 100–200 m reach. See *Biological site assessment of stream health*, in Catchment review (this volume), for some more ideas on surveying the stream biota.

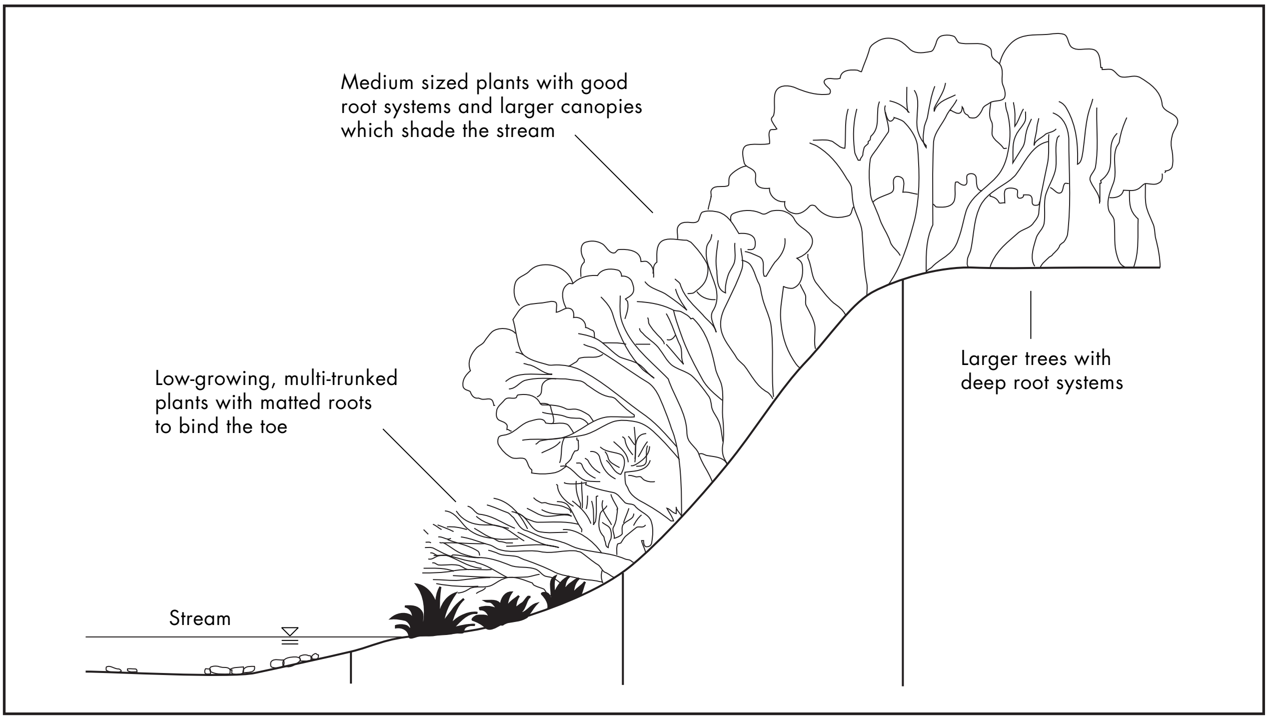

Figure 5. The different types of plants that can be found on different zones of the stream bank (from Raine and Gardiner, 1997).

4.3. Scale adjustments to the reference reach

In reality it is nearly impossible to find a template reach that has the level of catchment similarity required for direct comparison. Usually there are a few differences, eg. the catchment areas or lithologies are different. Streams are never stable in nature. They are continually adjusting to the sequence of flows that they experience. So, the reference reach is a function of its flow history. Perhaps it is recovering from a period of channel enlargement due to a large flood. For these reasons, the template approach is fraught with uncertainty, and you should not expect to get an answer that you can trust completely. This is why the final template of the target reach is created from an amalgam of sources of information.

Where the differences in the template and target catchments relate to issues of scale, then results from the template reach can still be used by scaling the data from the template. In the simplest case, imagine that the reference reach is some 10 km upstream of the channelised and enlarged reach that you are working on. Many stream variables (width, depth, slope, bed material) vary reasonably regularly with catchment area. This means that to estimate the appropriate dimensions for the target reach from those of the template reach we will need to identify how those dimensions (width, for example) vary as catchment area increases. A plot can easily be made of the increase in width with catchment area at several points above the treated reach. By drawing a line through these points and continuing the line to the catchment area of the target reach, the expected (extrapolated) value of width can be read off. The same can be done with depth and slope, although width tends to be the variable that best correlates with discharge (or catchment area).

Bear in mind that many Australian streams do not continue to increase in size downstream after they reach the floodplain section (Nanson and Young, 1981; Woodfull *et al.*, 1996). This can often occur with diversions to anabranches, although it can simply be related to the floodplain becoming a more active part of the channel system. Clearly, we want to avoid constructing much larger or smaller channels than necessary, as they are likely to undergo major changes. These changes might produce undesirable conditions from the perspective of the rehabilitation goals, so it is necessary to take great care when scaling the reference reach.

An example of scaling channel width to catchment size

The lower Yarra River has been widened and straightened in its lower reaches, and has been dredged regularly to maintain these channel dimensions. Melbourne Parks and Waterways was interested in how much the channel would narrow if dredging operations were stopped. They measured off the catchment area on the graphs in Figure 6 to get a feel for the change in channel width and depth if they stopped dredging. They found that the change would be considerable.

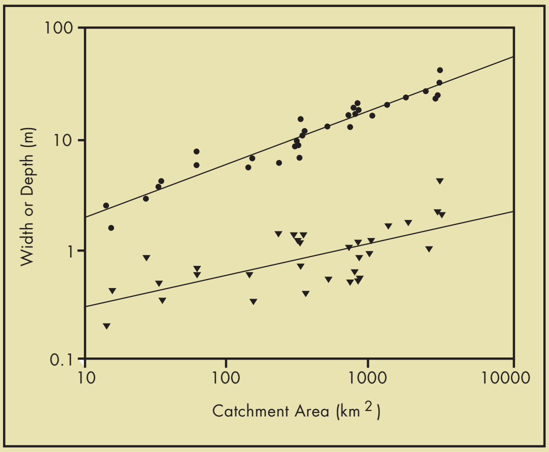

Figure 6. The difference in channel width (dots) and depth (triangles) between the up and downstream reaches of the Yarra River (from Brizga *et al.*, 1996b). Reproduced with permission from S. Brizga & Associates.

The scaling of the reference reach can be done using hydraulic geometry relations (see *Empirical approaches to designing a naturally stable channel*). Also see Newbury and Gaboury (1993) for excellent examples of scaling channel size for catchment area.

4.4. Limitations of the template approach

One overall criticism of the template approach was made by the US National Research Council (1992).

> "*When stream or river management actions are taken without recognising whether the aquatic ecosystem is in dynamic equilibrium or disequilibrium, the manager is gambling with the stream or river rather than ensuring improved ecosystem function and dynamic stability. The well-intentioned but intuitive [template] approach may therefore cause unexpected harm even to species that were meant to be helped.*"

Specific limitations of the template approach are:

- the difficulty in ensuring similar land use, geology, slope, sediment transport and storage and flood conditions between reference and target reaches;

- dubious accuracy of scaling channel morphological features by extrapolation; and

- identifying a suitable reference reach is likely to be difficult in many areas of Australia because of the high level of catchment disturbance. This is particularly true of lowland streams.

EMPIRICAL APPROACHES TO DESIGNING A NATURALLY STABLE CHANNEL

*With contributions from Dr Chris Gippel**

THREE WARNINGS!

1. Is it time for you to be exploring this section yet? It is very tempting to explore the possibility of rebuilding your damaged stream. This is a very common activity around the world, and there are good design guides available for doing it. However, *Step 5: Setting priorities*, in the Stream rehabilitation procedure (Volume 1), emphasises that the first task of stream rehabilitation is to protect the natural assets that remain in streams. We should be considering **improving** stream reaches only after we have protected the assets that already exist. So we should only really be contemplating rebuilding a more 'natural' stream if we are confident that we have already protected the remaining natural assets.

2. The most important thing to realise about applying empirical models derived from other areas to the problem of river rehabilitation is that it is a highly unreliable procedure. Such models should be applied with caution, and with regard to the risks involved. All engineering design work should be done by professionals with experience in this type of work. The information provided here is intended to help you prepare the briefs for the professional, and to have the capacity to assess their analysis and recommendations.

3. Vegetation is an integral part of most stream rehabilitation projects. Vegetation has a profound influence on channel stability and form. Many engineering stream designs ignore vegetation. We cannot ignore vegetation in stream rehabilitation. It must be an integral part of any rehabilitation program.

This part of the manual links to Step 3 and Step 9 of the Stream rehabilitation procedure (Volume 1) How will you design your project to achieve your objectives.

This section of the manual continues the quest for a way to design a more natural stream channel. In developing your template of the target stream reach you can supplement the historical records and the reference reach information with empirical relationships. In other words, when people have looked at large numbers of stable and semi-natural channels around the world, they have found that there are reasonably predictable relationships between stream discharge and channel dimensions (eg. width, depth and meander characteristics). This means that you can use these relationships to suggest what your stream should be like given a particular set of flow, sediment load and vegetation characteristics. This can then form the basis for designing a stream that is reasonably in equilibrium with its inputs. The idea is that this stream will be reasonably stable, and will have a higher potential to be good habitat for organisms.

The Rivercare approach used in northern New South Wales provides a good example of this approach where it defines the design width for a stable, vegetated channel in terms of catchment area (see Raine and Gardiner, 1995). Catchment area in this case is a surrogate for discharge.

This section of the manual covers the following topics:

- An introduction to channel design
- Defining a design discharge
- Using hydraulic geometry equations to design channel dimensions
- Using regime equations to design channel dimensions
- Designing the planform of the channel, and variations in depth.

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1. An introduction to the empirical approach to channel design

The concept of regime channels began in the 19th century as British engineers were designing and building canals in Pakistan and India (Chang, 1988). The basis for regime theory was to describe a cross-sectional geometry for designing equilibrium or 'regime' canals. At any point on the canal, it was regarded as being in 'regime' if there was no net aggradation or degradation at that point for a given design discharge. The equations that described this condition were called regime equations.

In the 1960s, Leopold, Wolman and Miller in the US, and others, noted that there were reasonably consistent relationships between the discharge carried by a natural stream, its sediment character, its catchment area and the size, shape and slope of the channel. They developed what they called 'at-a-station' hydraulic geometry relationships to describe how the cross-section width and depth changed as discharge increased. These relationships were very similar to the regime equations.

Hydraulic geometry also has a catchment-wide perspective. Relationships were derived to characterise, on a catchment-wide basis, how channel morphology changed with increasing discharge downstream, or increasing catchment area downstream. These are known as 'downstream' hydraulic geometry relationships. Later work built on this approach by including other natural channel features such as meander form and pool riffle spacing. Downstream hydraulic geometry relationships are usually simple, in that they predict channel morphology anywhere in a catchment (it is a regional-scale approach) on the basis of only catchment area or channel-forming discharge (or some other convenient discharge index), although some models are more complex and incorporate other variables. Regime equations predict channel morphology at a point (it is a channel reach approach) on the basis of a design discharge, and sometimes combined with the size of the material making up the bed and banks.

The empirical catchment or channel model approach to stream rehabilitation contends that within certain error bands, it should be possible to predict, or reconstruct a channel form that is in dynamic equilibrium with its discharge. This approach should be used in conjunction with other approaches to stream rehabilitation. Before the analysis is carried out, it is necessary to have an understanding of the catchment and river processes that are occurring.

The empirical catchment and channel model method for stream rehabilitation design is based on the premise that we understand the fluvial system well enough to be able to design a stream that would be dynamically stable under natural conditions. This approach is most successful in determining the broad geometry of streams in terms of the average width and depth of the stream, and is less successful at determining habitat requirements, like the proportion or type of cover suitable for a particular fish species.

The empirical downstream hydraulic geometry models of how channels change their morphology as discharge or catchment area increases are misleading because they rarely track the downstream change along a particular stream channel. The sample points are usually distributed all over the catchment. This partially explains the scatter in the relationships. Along the path of an individual stream, the channel morphology is likely to change dramatically only at points of major changes in discharge—at tributary junctions. Between the tributary junctions the channel is likely to be relatively constant (apart from the normal oscillations due to pools and riffles and variations in bank material and vegetation). Rehabilitation projects usually consider continuous, or linked reaches of streams, so it is this step-like downstream change that is more relevant to rehabilitation design.

The empirical model approach is especially unreliable in Australia for three main reasons. The first is that most available models of hydraulic geometry and regime were developed overseas in streams that we either know very little about, or we know are very different from natural streams found in Australia. The second reason is that Australian streams are typically very different hydrologically and geomorphologically to streams in the northern hemisphere. The flow in Australian rivers is usually much more variable, so it is less likely that they are adjusted to a flow of a particular recurrence interval. Rather they may simply reflect the time series of discharge (flow history), with the morphology largely reflecting the timing and magnitude of the most recent catastrophic event. Geomorphologically, Australian rivers drain catchments that are less steep, have lower sediment yields, and transport sediment of a finer particle size than northern hemisphere streams. The final reason is that Australian streams are known to sometimes display an erratic downstream pattern of morphological change. They may effectively disappear into a flood-out, or they may narrow as they enter the floodplain reaches.

Now that you are aware of the basis and risks of the design approaches, it is time to look at how the design procedure can work. The first thing that is required is a design discharge. This is the foundation of the design procedure. The design discharge indicates the dimensions and basic structure of the channel. Once you have the design discharge, you can use the hydraulic geometry regime approaches to decide on the design dimensions of the channel. The design discharge that is usually used for stream rehabilitation design is the bankfull flow. This flow, and ways to determine it are discussed in some detail in the next section.

2. Selecting a design discharge

A key factor for the design of any in-stream structures, and generally for natural channel design, is to select a discharge on which to base the design. When installing an artificial riffle, how do we know how big the rocks should be so that they are not washed away by floods? One commonly adopted principle is to use a tractive stress calculation, such that the tractive stress during bankfull flow is less than that required to move the rocks. Another example may be the selection of an equilibrium channel width for channel realignment.Bankfull discharge or some surrogate is usually adopted as the design discharge for regime equations. Bankfull discharge is typically used as the design flow for in-stream rehabilitation work (not engineering structures like bridges and culverts).

2.1 . Why bankfull? A discussion of bankfull, dominant and channel-forming flows

The computational approach to channel design is based on the relationship of bankfull or dominant flow of a stream and the channel width, depth and slope. The basis of this approach is that major channel-forming activity (erosion and depositional events affecting the long-term form of the bed and banks) occurs during regular (1–2 year) flooding events. The argument is that channels are continually going through destruction and recovery phases, where major floods cause larger-scale channel modification, which is in turn stabilised over subsequent years by the channel-forming flow. Another way of describing the dominant discharge is that it is a single flow that would produce the same channel form as the full range of flows that occur in nature. The basis of using channel-forming flow for channel design is to produce a quasi-equilibrium channel formation similar to that which would naturally develop under similar watershed conditions (Shields, 1996).

To understand the concept of a dominant discharge, we must understand the relationship between a river and its floodplain. When a river deposits sediment it tends to form relatively flat, horizontally orientated surfaces. We adopt the following definitions for these surfaces:

Floodplain: a reasonably continuous surface that is flooded annually, or at least every few years. This surface has been deposited by the present stream.

Bench: a discontinuous surface that tends to be flooded more frequently than the active floodplain.

Terrace: a surface above the floodplain that is flooded only rarely. It was probably deposited in the past. Often it is a former floodplain that has been isolated by stream incision.

Channel-forming flow is considered to be that flow responsible for deposition on the present floodplain. The active floodplain is identified as undergoing net growth over the current stage of the river morphology (Wharton, 1992) and can be identified as freshly deposited material such as a flat deposit within an incised channel or a wider floodplain outside the confines of the channel. The stage of the channel-forming flow, when water depth just reaches the level of the active floodplain, is also referred to as the dominant or bankfull flow. This bankfull flow condition is the most common design flow used when applying the analytical or regime approaches.

Although we use the notion of a dominant discharge in this manual, the notion of a single channel-forming flow is controversial.

Given that flood flows of a moderate magnitude and duration seem to be responsible for channel formation, what changes in the catchment might cause the size of

Problems with the bankfull/dominant discharge concept

By Dr Chris Gippel

Wolman and Leopold (1957) proposed that the process of channel formation was fundamentally associated with bankfull discharge, or the flow which just fills the channel to the top of the banks (bank top). While studies from many areas of the world suggest that, on average, this bank-top discharge occurs every one or two years (Wolman and Leopold, 1957; Brush, 1961; Leopold et al., 1964: p. 220), a wide range of frequencies has been observed, and there is evidence to suggest that bank-top flows occur more frequently as basin area decreases and slope increases (Kilpatrick and Barnes, 1964; Dury, 1965; Harvey, 1969). More frequent sub-bank-top flows do transport bed sediment (Benson and Thomas, 1966), and bankfull has been defined geomorphologically at a level below the bank top (for example, Woodyer, 1968; Riley, 1972; Knighton, 1974; Pickup and Warner, 1976; Richards, 1982: p. 135–145; Knighton, 1984: p. 94–96; Gippel, 1985).

Newbury (1989) suggested that the flow which maintains the important ecological and small-scale morphological characteristics of a channel corresponds to the level where plants show sensitivity to inundation or where rock surfaces are abraded by bedload. It is an oversimplification to assume that there is a unique flow which is competent to perform channel maintenance processes. Implicit in the specification of channel-forming flows in terms of average recurrence interval and percent of time exceeded, is that all flows above the chosen index are important in determining channel morphology.

Bedload transport requires that a threshold stream power be exceeded (Richards, 1982: p. 142), and abrasion marks (Newbury, 1989) or sedimentological features (Nunally, 1967) clearly indicate that this threshold has been passed. However, Pickup and Warner (1976) found that most bedload transport was associated with flows below the level of bank-top discharge. Channel maintenance requires frequent sediment transport and checking of vegetative growth. Above bank-top flows are generally too infrequent to be effective in this role, but they may exert control over the absolute size of the channel. Large, infrequent floods may catastrophically enlarge the channel, but it is the medium-sized flows that gradually rebuild the channel to its characteristic form. Given the marked process discontinuity associated with overbank flow (Richards, 1982: p. 135), it is reasonable to conclude that maintenance of river channel morphology is performed by the range of flows between channel maintenance flow (Newbury, 1989) and bank-top flow. Bedload transport is often supply limited, so that while the cumulative effect of a succession of low-magnitude flood peaks may equal that of a single major flood in term of sediment transport, this is not necessarily the case with channel morphology (Richards, 1982: p. 123). Harvey et al. (1979) found that moderate events that redistribute bed material (lower threshold of channel maintenance flows) occur between 14 and 30 times a year, while the major controlling events (near bank-top flow) occur from 0.5 to 4 times per year. The observations of Pickup and Warner (1976) suggest that discharges more frequent than the modal annual flood dominate bedload transport, but that more extreme events control erosion of cohesive banks.

Thus, it appears that two groups of flows are responsible for creating channel form: a more extreme group that defines channel capacity; and more frequent events that control bedload movement and construction of bedforms (Richards, 1982: p. 142).

these flows to alter, and therefore cause the channel to change its size or shape?

There is limited literature on the effect of land use on bankfull discharge. Most studies focus on peak discharges, annual recurrence interval or channel width—all of which can be related directly or indirectly to bankfull discharge (depending on your confidence in the hydraulic geometry relationships). It is well established that the increase in flood magnitudes across the range of recurrence intervals important for channel formation causes large increases in channel width when a catchment becomes urbanised.

Clark (1987) found that bankfull discharge diminishes with an increase in the proportion of forest cover. This occurs by interception of rainfall and by the increased hydraulic conductivity of the soil as a result of tree roots and soil organisms breaking up the soil. Clark has developed a model based on data from interception, conductivity and local rainfall to predict the peak discharge of various land uses. The results of the model showed that the flood which occurs on average one every two years had a discharge close to the bankfull discharge which had been measured in the field. The bankfull discharge for a catchment under 100% forest cover increased by 2.5 times when forest was reduced to 80% cover, by 3 times when forest was reduced to 50% cover, and by 3.5 times when forest was converted entirely to pasture. These estimates are very large and must be considered maximum effects.

Regime equations ignore the real complexity of the channel forming process—remember they were originally derived for the design of trapezoidal irrigation canals with constant discharge! It is this fundamental problem (assumption of a single dominant discharge) that makes this approach difficult to apply to natural channel design. Despite this, it is currently the best approach for routine channel design. We recommend its use until a better approach is developed. The following section discusses ways to estimate the bankfull flow.

2.2. Estimating the bankfull flow

Bankfull flow can be estimated in three ways:

1. by measurement;

2. by estimating the discharge using an equation; and

3. by estimating flood frequency (ie. the 1–2 year flood).

The following sections will describe these methods. To apply the first two methods you must define a bankfull point in the channel.

2.2.1. Identifying the bankfull point in the field

Given that bankfull is the level of water in the channel, just before the water flows out into the floodplain, how do we measure it? Anyone who has stood on a stream bank looking for textbook geomorphic features knows how frustrating it can be to identify the bankfull level. In reality the channel cross-section is often not easily defined, as illustrated in Table 14.

Bankfull flow can be defined in several different ways. Any of these is appropriate, but the key is to be able to consistently identify bankfull levels to enable inter-catchment comparisons, and to ensure consistency between stream managers. The following criteria for identifying bankfull level have been selected from *Australian Rainfall and Runoff* (Pilgrim, 1987).

- "If no benches exist, use the floodplain level or, if a floodplain is not developed, use the edge of the channel where this is formed by deposition of sediments."

- "If three benches or two definite benches at medium to high stage exist, use the top bench level."

- "If no one bench exits, proceed as follows:

  a) select bankfull level by comparisons with the level at which the nose of the points of the bend upstream and downstream flatten out.

  b) Confirm this by examining the sediments at this level for evidence of numerous recent episodes of deposition, (ie. laminations, flood debris, artefacts etc.) and by seeking information from local landholders regarding frequency of flooding."

- "Where necessary, correlate bankfull levels identified at bends with bankfull levels in straight reaches by running levels between the bends."

- "Bankfull level is taken to be representative of the bench or floodplain surface chosen. The level is taken as near as possible to the stream where the floodplain surface flattens out."

2.3. Using Manning's equation to predict the bankfull discharge

Manning's equation is the most common way of estimating the bankfull discharge. The steps required to predict discharge using Manning's equation are:

- measure channel width and depth and collect data to be able to calculate the cross-sectional area of at least five cross-sections in the reach;

- measure the channel slope (bed slope is suitable);

- estimate Manning's n value (see Table 15); and

- calculate bankfull discharge.

Manning's equation for mean velocity is:

$$v = \frac{R^{(2/3)} S^{(1/2)}}{n}$$

where:

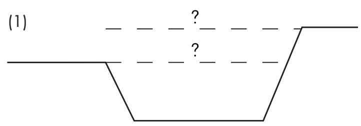
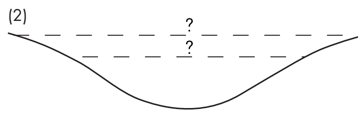
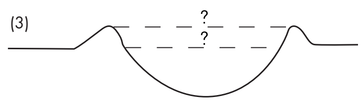
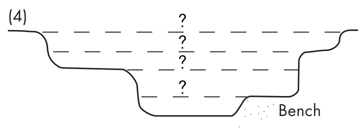
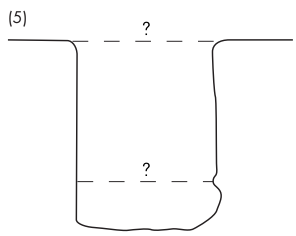
v = depth averaged flow velocity (m/s);

R = hydraulic radius (m), which is the cross-sectional area 'A' divided by the wetted perimeter 'P'. The wetted perimeter for a rectangular channel is 2 times the depth (y) plus the width (w). For wide channels (where $y >$ about 10 times w) the hydraulic radius can be approximated by the depth;

S = energy slope or water surface slope, adopted as the stream bed slope for steady uniform flow; and

n = Manning's roughness coefficient which is discussed in the paragraphs to follow.

Table 14. Situations where the bankfull stage is hard to define.

	1) The floodplain level occurs at a different height on either side of the stream, so there is an upper and lower possible bankfull dimension. An average value can be used.
	2) A convex slope may mark the transition from channel wall to floodplain so it is difficult to decide where to position the bankfull stage.
	3) Levee banks higher than the adjoining floodplain will give a larger bankfull capacity than if the level of the floodplain is adopted as bankfull
	4) Compound channel cross-sections (a number of terrace levels usually created through channel incision), make selection of the correct floodplain terrace difficult.
	5) Severely incised streams and gullies probably never fill to the 'bankfull' stage, so the application of a bankfull design flow to these streams is dubious.

Or for discharge, we simply multiply velocity by cross-sectional area—therefore;

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

where Q = discharge (m^3/s) and A = cross sectional area (m^2).

The key to successfully applying Manning's equation is the use of an appropriate roughness coefficient (n). The primary advantage of Manning's equation over more analytical methods is that the value of n can be predicted quickly. Roughness coefficients such as the Darcy-Weisbach friction factor (f) will tend to be more accurate, but their derivation is time-consuming, and appropriate data for predicting f are not available for many natural flow conditions.

> Since Manning's n seems such a small number, why is it so important to get right?
>
> Manning's n is raised to the power of one (ie. n^1), meaning that it will be directly reflected in the answer to the equation; ie. if you vary Manning's n by ±10% then you will also vary the calculated velocity by ±10%. Compare this with the hydraulic radius R, which is raised to the power of 2/3—less than one. Thus, if R is varied by ±10% then the effect on the velocity will be less than ±10%, and the same is true for the slope which is raised to only 1/2. Although n is a small number it has the greatest influence in Manning's equation.

The best way to choose a Manning's n is to back-calculate it from a known stage and discharge (Kondolf and Micheli, 1995). We rarely have the luxury of a gauged reach, so we must estimate Manning's n from tables or figures. Chow (1959) describes the estimation of Manning's n as more an art than a science and notes that the estimates are prone to wide variation among practitioners. To try and reduce the 'art' component and increase the 'science', we recommend you estimate n by two independent methods and compare the results before selecting a final value. The two methods of estimating n are: 1) estimate the total Manning's n from tables; and 2) estimate different components of n then combine the results to give a final n value. The total n value can be predicted by comparing your stream with pictures of streams of known roughness, such as those found in French (1986), or use tables of values for alternative descriptions of stream types. Table 15 has been summarised from a frequently cited table of Chow, 1959).

The second way to predict Manning's n is to estimate, then combine, its components. The USDA (Gore and Bryant, 1988) recommends use of the method proposed by Cowan (1956) to estimate the value of n:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m$$

where:

n_0 = base value of n for a straight, uniform, smooth channel in natural materials;

n_1 = correction for the effect of surface irregularities;

n_2 = correction for variations in cross-sectional shape and size;

n_3 = correction for channel obstructions;

n_4 = correction for vegetation and flow conditions; and

m = correction for degree of channel sinuosity.

Values for estimating Manning's n using this component method are given in Figure 16. Note that Gordon *et al.* (1992) suggest that the component method is appropriate only for small to mid-sized channels of hydraulic radius less than 5 m. For channels with a larger hydraulic radius, n should be calculated only by predicting the total n value, as presented in Table 15.

2.3.1. Accuracy of Manning's equation

Don't be misled by the implied accuracy of three decimal places for values of n presented in the above tables. Remember, these n values were obtained by back-calculation using stage discharge information, so if you have a channel that is identical to the one measured then, yes, the three decimal places are relevant. Henderson suggests that, at best, the Manning's equation will provide an accuracy of ±1% (Henderson, 1966). However, when we are trying to estimate acceptable n values for natural channels, this variation will probably be up to ±10%. So think about your estimated value of n as ±10% and, if you have time, recalculate using the lower and higher n values and see if these revised values would result in any significant change in your conclusions.

2.3.2. Things to be aware of when using Manning's equation

Generally, Manning's equation works best where the depth is uniform, velocity is constant, and bed and water slope are parallel. Manning's equation is appropriate only for sub-critical flows.

- Estimates of Manning's *n* are subjective, so that if five stream managers are each asked to estimate a Manning's *n* you may get five different numbers.

- Channel roughness varies with depth. For example, as flow depth increases with discharge, the influence that debris located towards the bed of the channel has on the flow resistance decreases. Gregory *et al.* (1985) observed a reduction in *n* from an extremely high value of 1.02 at low flows to 0.31 as the flow increased in an upland stream in the UK. Estimated values of Manning's *n* should be based on a design flow depth.

- The roughness of very weedy and vegetation-choked channels can be very high, especially at low flows; *n* values of 1.0 are common.

- In some cases, the value of *n* has been found to increase with stage. For example, Petryk and Bosmajian (1975) found that in channels that are heavily obstructed by trees and debris the density of obstructions remained roughly constant with rising stage and that the value of Manning's *n* actually increased with discharge.

- It has been suggested (Gippel *et al.*, 1992) that Manning's *n* is not a suitable measure of the roughness provided by a channel with a significant in-stream obstruction component. For example, Gippel *et al.* (1996b) considered that the contribution of in-channel debris to a channel's roughness depends on many factors including the size and shape of the channel, the stage of the flow, bank irregularities and the degree of meandering. Manning's equation was developed for open-channel flow conditions, where the retardation of the flow is primarily controlled by bed roughness elements. In a heavily congested channel the concept of hydraulic radius, on which Manning's relies, may become meaningless. There are, nevertheless, no straightforward alternatives to Manning's *n* for this situation.

Design flow estimation for the Acheron River using Manning's equation

The Acheron River is in central eastern Victoria. At the point where we wish to estimate the design flow, the catchment area is about 500 km^{2}.

Five cross-sections using a line level and staff were surveyed within the target reach. We are interested in water surface slope at bankfull flow. This can be estimated from the bed slope, but a better approximation is the top of the bank itself—it tends to be less variable than the bed. Top-of-bank slope was measured using a level for the entire 400 m length of the reach. The surveyed slope was 0.0018, the estimated Manning's *n* for the reach was 0.04. Manipulated data are presented in Table 17.

Table 17. The data used to calculate the Acheron River design flow using Manning's equation.

Cross- section discharge	Bankfull width	Bankfull depth (average)	Cross-sectional area	Bankfull (m^3/s)
1	17.2	1.48	25.5	31.6
2	16.5	1.38	22.8	27.1
3	15	1.55	23.9	30.5
4	14	1.86	24.7	32.7
5	16.1	1.60	25.8	33.3

Details from these five cross-sections indicate that the bankfull discharge at this reach is about 31 m^3/s.

Table 15. Table of total n values summarised from Chow (1959) as presented in French (1986).

Channel type	Range	Normal
ARTIFICIAL STREAMS:		
Lined or built-up channels		
Concrete	0.011–0.025	0.015
Concrete bottom, float finished with stone sides	0.015–0.035	0.025
Gravel bottom with concrete sides	0.017–0.026	0.020
Gravel bottom with riprap sides	0.023–0.036	0.035
Artificial streams: unlined		
A) Earth, straight and uniform		
1) Clean	0.018–0.025	0.022
2) With short grass, few weeds	0.022–0.033	0.027
B) Earth, winding and sluggish		
1) No vegetation	0.023–0.030	0.025
2) Grass, some weeds	0.025–0.033	0.030
3) Dense weeds or aquatic plants in deep channels	0.030–040	0.035
4) Earth bottom and rubble sides	0.028–0.035	0.030
5) Stony bottom and weedy banks	0.025–0.040	0.035
6) Cobble bottom and clean sides	0.030–0.050	0.040
C) Unmaintained channels		
1) dense weeds as high (ie. heavy foliage)	0.050–0.120	0.080
2) clean bottom brush on sides	0.040–0.080	0.050
3) Same as above at highest stage of flow	0.045–0.110	0.070
4) Dense brush, high stage	0.080–0.140	0.100
NATURAL STREAMS:		
Minor streams (top width at flood stage <33 m)		
A) Streams on plain		
1) Clean, straight, full stage, no rifts or deep pools	0.025–0.033	0.030
2) Same as above, but more stones and weeds	0.030–0.40	0.035
3) Clean, winding, some pools and shoals	0.033–0.045	0.040
4) Same as above, but some weeds and stones	0.035–0.050	0.045
5) Same as above, lower stages, more ineffective slopes and sections	0.040–0.055	0.048
6) Same as no. 4, more stones	0.045–0.060	0.050
7) Sluggish reaches, weedy, deep pools	0.050–0.080	0.070
8) Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075–0.150	0.100
B) Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages		
1) Bottom: gravels, cobbles, and few boulders	0.030–0.050	0.040
2) Bottom: cobbles with large boulders	0.040–0.070	0.050
Floodplains		
A) Pasture, no brush		
1) Short grass	0.025–0.035	0.030
2) High grass	0.030–0.050	0.035
3) Mature field crop	0.030–0.050	0.040
B) Cultivated Areas		
1) No crop	0.020–0.040	0.030
2) Mature row crop	0.025–0.045	0.035
3) Mature Field crop	0.030–0.050	0.040
C) Brush		
1) Scattered brush, heavy weeds	0.035–0.070	0.050
2) light brush and trees, in winter (ie. low foliage)	0.035–0.060	0.050
3) Light brush and trees, in summer (ie. heavy foliage)	0.040–0.080	0.060
4) Medium to dense brush, in winter (ie. light foliage)	0.045–0.110	0.070
5) medium to dense brush, in summer (ie. heavy foliage)	0.070–0.160	0.100

Table 15 (cont'd). Table of total n values summarised from Chow (1959) as presented in French (1986).

Channel type	Range	Normal
D) Trees		
1) Dense willows, straight, summer (dense vegetation)	0.110–0.200	0.150
2) Cleared land with tree stumps, no sprouts		
3) Same as above, but with heavy growth of sprouts	0.050–0.080	0.060
4) heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080–0.120	0.100
5) same as above but with flood stage reaching branches	0.100–0.160	0.120
Major streams		
Top width at flood stage > 33 m—the n value is less than that for minor streams of similar description because the banks offer less effective resistance		
A) Regular cross-section with no boulders or brush	0.025–0.060	
B) Irregular and rough section	0.035–0.100	

Table 16. Values for estimation of Manning's n, from Zipparro and Hasen (1993).

Channel conditions			Values
Material involved	Earth		0.020
	Rock cut	n_0	0.025
	Fine gravel		0.024
	Coarse gravel		0.028
Degree of irregularity	Smooth		0.000
	Minor	n_1	0.005
	Moderate		0.010
	Severe		0.020
Variations of channel cross-section	Gradual		0.000
	Alternating occasionally	n_2	0.005
	Alternating frequently		0.010–0.015
Relative effect of obstructions	Negligible		0.000
	Minor	n_3	0.010–0.015
	Appreciable		0.020–0.030
	Severe		0.040–0.060
Vegetation	Low		0.005–0.010
	Medium	n_4	0.010–0.025
	High		0.025–0.050
	Very high		0.050–0.100
Degree of meandering	Minor (sinuosity 1.0–1.2)		1.000
	Appreciable (sinuosity 1.2–1.5)	m	1.150
	Severe (sinuosity >1.5)		1.300

2.4 . Using flood frequency analysis to predict the bankfull discharge

A common way to check the design discharge (ie. the bankfull or dominant discharge) is to use flood frequency analysis to predict the size of the flood with the return interval of the design flow. The return interval for bankfull flow is usually considered to be around 1–2 years, so your design flow should be within the range of these flows (although see the section *Problems with the bankfull concept* above).

The basis of this method requires the development of a flood frequency curve. Detailed discussions of different methods of preparing and interpreting data for the preparation of flood frequency curves are presented in the standard flood estimation guide for Australia: *Australian Rainfall and Runoff* (Pilgrim, 1987). The following section is a short summary of the most common and simple way to prepare a flood frequency curve. You should consult a hydrology text or *Australian Rainfall and Runoff* for an expansion of the steps. This rapid flood frequency analysis is not a suitable basis for detailed engineering design or flood mitigation work, but is rather an approximation of the order of magnitude of particular return intervals.

Step 1: Is your stream gauged? If your catchment is gauged, that is a real bonus, otherwise find the closest gauged catchment with similar hydrological features such as weather patterns, land use and topography (call this a surrogate catchment).

As an example catchment we will use the Acheron River in Victoria. The Acheron is gauged at one point with a catchment area of about 620 km^2. The target reach we are concerned about is about 10 km upstream of the gauge and has a catchment area of about 500 km^2.

Step 2: Is the gauge record at least 10 years old? If the gauge record spans more than ten years, then the flood frequency analysis is an annual series plot which requires you to identify the annual maximum flood for each of the years on record. The annual maximum flood is the maximum mean daily flow in megalitres (ML).

If the gauge record spans less than ten years, then a partial series plot is probably more appropriate. For details on a partial duration series refer to *Australian Rainfall and Runoff*.

In the first two columns of Table 18 we present the gauging record from 1946–1981 for the Acheron River, from *Victorian Surface Water Information to 1982*.

Step 3: Arrange the annual flood series in descending order. The annual flood series should be ranked in descending order from 1, the largest flood, to the last flood recorded (see Table 18).

Step 4: Calculate the plotting position for observed floods. The plotting position (*PP*) is calculated from the annual flood series, ranked in descending order, according to the equation:

$$PP(m) = \frac{m \pm \alpha}{N + 1 - 2\alpha} \times 100$$

Where:

m = rank of the flood in the series (largest flood has rank $m = 1$)

N = number of years of the record

α = a constant (adopted as 0.4 (Cunnane, 1978; McMahon and Srikanthan, 1981)).

Therefore, the plotting position is given by

$$PP(m) = \frac{m - 0.4}{N + 0.2} \times 100$$

For the Acheron River, the plotting position is presented in Table 18.

Step 5: Plot the flood frequency curve according to the plotting position from step 4 on log-normal graph paper as shown below (the upper curve on Figure 7).

Step 6: Fit a curve to the data points. To be able to use the flood frequency curve we must fit a curve to the data points. This can be done roughly by freehand, or by selecting a straight line through the data points. A straight line fitted through the data points assumes that the logarithm of the flood peaks is normally distributed (Newbury and Gaboury, 1993). Alternatively a Log Pearson type 3 distribution can be used to fit a curve to the data.

Table 18. Calculating the average annual flood on the Acheron River (*PP* = plotting position).

Step 2		Step 3		Step 4
Year	**Maximum annual flood discharge (ML/day)**	**Floods in order of size**	**Rank (*m*)**	***PP*(*m*)%**
1946	2,940	10,000	1	1.6
1947	3,900	9,610	2	4.4
1948	3,330	8,490	3	7.1
1949	5,260	8,050	4	9.9
1950	2,020	7,940	5	12.7
1951	6,190	7,520	6	15.4
1952	10,000	7,150	7	18.2
1953	8,050	6,870	8	20.9
1954	4,230	6,530	9	23.7
1955	8,490	6,340	10	26.5
1956	7,940	6,190	11	29.2
1957	4,490	6,130	12	32.0
1958	9,610	5,370	13	34.8
1959	6,530	5,310	14	37.5
1960	7,520	5,260	15	40.3
1961	2,310	5,220	16	43.0
1962	2,600	5,140	17	45.8
1963	2,570	5,050	18	48.6
1964	4,230	4,780	19	51.3
1965	3,960	4,490	20	54.1
1966	4,320	4,320	21	56.9
1967	1,600	4,230	22	59.6
1968	6,340	4,230	23	62.4
1969	2,260	4,200	24	65.1
1970	5,050	3,960	25	67.9
1971	6,130	3,900	26	70.7
1972	1,580	3,330	27	73.4
1973	5,310	3,260	28	76.2
1974	7,150	2,940	29	79.0
1975	5,140	2,600	30	81.7
1976	3,260	2,570	31	84.5
1977	5,220	2,310	32	87.2
1978	4,200	2,260	33	90.0
1979	4,780	2,020	34	92.8
1980	6,870	1,600	35	95.5
1981	5,370	1,580	36	98.3

The Log Pearson III is usually recommended for general use. The method for fitting this curve is presented in *Australian Rainfall and Runoff*.

From a curve fitted by eye to Figure 7 (upper curve), it appears that there is a probability of 50% that a peak flow of 5,000 ML/day will be exceed in any one year. The annual return interval for this flood is 100/50 or 2 years. In other words, a flood of 5,000 ML/day or greater will occur 50 times in 100 years. This flow should be approximately the bankfull flow.

Bankfull flow is often related to a return interval of between 1 and 2 years (and therefore between 50 and 67%

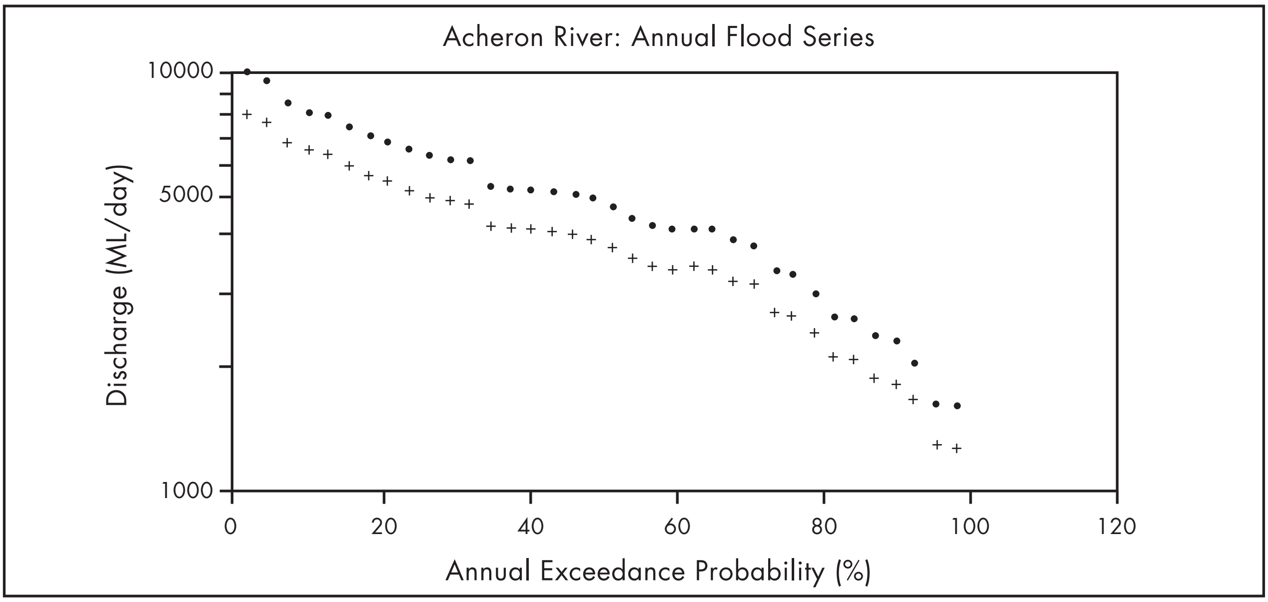


Figure 7. Annual flood series for the Acheron River at both the gauged (the upper curve with dots) and target reaches (lower curve with crosses).

probability of occuring in any one year). Although the return interval can be up to 3–4 years, it is important to gain an appreciation for the size or frequency of flood which causes bankfull condition. Relate this known flood event back to a return interval.

Step 7: Calibrate the annual flood series details for the actual reach. Given that in most cases the gauge record will not be located within our target reach, it is important to correct the peak annual flow details for the target catchment. There are several methods of predicting flow away from the gauged section, such as flood routing estimations, or by extrapolating between gauges and extrapolation based on catchment area as suggested by Newbury and Gaboury (1993). Where the catchment area between the target reach and gauged reach does not vary by more than about 50%, and the dominant catchment landforms do not change, this last method can be used as a quick approximation. For the Acheron River, the gauged catchment is 620 km^2, and the catchment for the target reach is approximately 500 km^2. So, assuming the unit area flood peaks between these two catchments, the flood peaks at the target reach will be 500/620 = 80% of those measured at the gauge (this assumption of identical unit area flood peaks is erroneous for high frequency events). Figure 7 shows the annual flood frequency for both the gauged and target reaches. From this figure the discharge for annual return period of 2 years is approximately 4,000 ML/day (or 46 m^3/s) and for an annual return period of 1 year, the peak discharge is 1,200 ML/day (14 m^3/s).

Step 8: Compare the expected range of annual exceedance probability with the predicted design discharge. We can now compare the design flow predicted using Manning's equation in the previous section with the typical range expected (between 1 and 2-year flood magnitude).

For the Acheron River, the bankfull flow for a return interval of 1 year is 13 m^3/s and for 2 years is 46 m^3/s.

The bankfull flow predicted from the previous section using Manning's equation was 31 m^3/s. Hence, for the Acheron River our design flow is probably somewhere between 20 and 50 m^3/s. This level of accuracy is as good as can be expected from these approaches.

If the bankfull design flow was not similar to the 1 to 2 year flood, what would it mean? The fact that the bankfull discharge does not correspond to a 1–2 year return interval flood may simply mean your stream is not 'average', or it could indicate non-equilibrium channel form such as an over-wide or incised stream. If your design flow is not within the expected range this should be a trigger for further investigation.

Once the design flow is established, the average design width, depth and slope can be determined based on hydraulic geometry and regime equations.

3. Hydraulic geometry equations and regime equations

This section describes two related approaches to designing channel dimensions: hydraulic geometry and regime equations.

3.1. Using hydraulic geometry equations to design channel dimensions

3.1.1. Simple hydraulic geometry

The downstream hydraulic geometry methodology was pioneered by Leopold and Maddock (1953) from studies of a large sample of rivers in the Great Plains and south-west area of the United States. In this simple approach, the dependent channel variables, width (w), mean depth (d), mean velocity (v) and slope (S), are related by simple power functions to an index of discharge (Q), usually channel forming discharge. Leopold and Maddock (1953) did not consider channel slope in their analysis.

$w = aQ^b$

$d = cQ^f$

$S = kQ^m$

The coefficients *a, c,* and *k* and the exponents *b, f,* and *m* are empirically derived. Given a design discharge (ie. bankfull as estimated above) one can predict the expected size and shape of the channel.

Downstream changes in channel geometry can be investigated by linking information from a number of sites within a stream system (Gordon *et al.,* 1992: p. 309). Leopold and Maddock (1953) cited downstream coefficients of $b = 0.5$ and $f = 0.4$.

Chong (1970: p.882) concluded that "…rivers in different geologic, physiographic and climatic regions tend to behave in much the same way…", but later, Park (1977) who examined worldwide hydraulic geometry exponent data from 72 streams from a variety of climates concluded that there was a great deal of variation in the relationship between channel morphology and discharge or catchment area.

3.1.2. Some general guidelines for simple hydraulic geometry

(Note that the higher the exponent, then the faster the rate of change downstream.)

- Streams in humid areas tend to have medium to high width exponents (0.4–0.8) and medium depth exponents (0.2–0.6).

- Tropical streams tend to display low to medium width exponents (0.2–0.4), and low to medium depth exponents (0.2–0.6).

- A distinction can be drawn between the hydraulic geometries of perennial streams and ephemeral streams in the semi-arid environment. Perennial streams exhibit exponent values similar to that of humid temperate streams, whereas ephemeral streams tend to have low width exponents (<0.3).

- A single tidal estuary study by Langbein (1963) showed different exponents to those of non-tidal streams. Width exponent was high (0.6–0.8) and the depth exponent was high (0.6–0.8).

- Huang and Nanson's (1997) work on four streams in the Illawarra region found that values of the exponents *b, f,* and *m* varied considerably between streams and in some cases even exceeded the full range of values obtained internationally. When considering gravel bed and sand bed streams separately, the exponents for average depth (*f*) in sand channels were close to the modes observed for worldwide data, while the exponents for width (*b*) were extreme outliers.

- For the Acheron catchment in Victoria, Gordon used channel maintenance flow for the development of geometry relationships rather than the bankfull discharge (which is higher) (Gordon, 1996). The hydraulic exponents were found to be $b = 0.48$ and $f = 0.35$, which are within the range of the worldwide values.

- For the Hunter Valley, Gippel (1985) found that when catchment area was used as the independent variable, the exponents were $b = 0.52$, and $f = 0.23$ for pool sites and $b = 0.48$ and $f = 0.34$ for riffle sites.

- Large data sets are required to establish hydraulic geometry equations with any precision (meaning that three or four measures down a stream system may not be enough to predict a downstream trend).
- Channels which have non-vegetated banks can be roughly two to three times wider than those with banks that are densely vegetated.
- In sand-bed channels, bed vegetation can cause a significant increase in channel width and decrease in flow velocity without causing much change in depth.
- The possible range of variation within the channel width caused by bank vegetation is less than that caused by channel bed vegetation.

3.1.3 . Limitations of simple hydraulic geometry

Hydraulic geometry suffers from numerous limitations:

- Its simple form based on one variable (discharge or catchment area) is appealing, but it ignores all the other factors that control channel form.
- There is always a high degree of scatter in downstream hydraulic geometry plots.
- Regional hydraulic geometry relationships have been developed for only a few areas of Australia.
- There are difficulties in defining the bankfull channel.
- There are difficulties in selecting a consistent and meaningful discharge index. Channel forming discharge in northern hemisphere streams may have little relevance to channel formation in Australian streams.

3.2. Using regime equations to design channel dimensions

The approach of traditional dimensional regime equations is to establish a statistical relationship between dependent variables (width, depth, slope) and independent variables (discharge, median bed material size, bed load transport) (Wharton, 1992). The regime formulas take the general form:

$$w = k_1 Q^{k2} D_{50}{}^{k3}$$

$$d = k_4 Q^{k5} D_{50}{}^{k6}$$

$$S = k_7 Q^{k8} D_{50}{}^{k9}$$

Where:

w = bankfull width

d = bankfull depth

S = average thalweg slope

k_1–k_9 = coefficients and exponents that are constant for a given data set from which the relationship has been derived.

Hence, the regime approach assumes that flow and bed material size are the critical variables to predicting *w, d*, and *S*; in many regime equations bed material size is excluded (as in at-a-station hydraulic geometry relationships). Regime relationships are developed from a collection of streams which often have similar geomorphological and hydrological controls. The major limitation to regime relationships is in trying to apply the regime equations to stream types that are not clearly represented by the streams used to develop the regime equation.

When estimating the channel width, k_2 is usually about 0.5 (same as downstream hydraulic geometry relationships), and k_3 is usually excluded. This means that the width is proportional to $\sqrt{Q}$, implying that as the discharge doubles the average channel width increases by about half a channel width.

It is important to note that the correlation coefficient for regime relationships is generally higher for the prediction of width, and is lower for the prediction of average depth. The correlation coefficient is usually much lower (indicating a greater scatter of data points or higher variability) when used for predicting bed slope.

The use of regime equations for predicting bed slope often gives poor results.

3.2.1. Which equation should you use?

Research into regime relationships by Dr Graham Jenkins, Neranjala Fernando and Robin Black at Queensland University of Technology on two, small, ephemeral Brisbane (rural) streams indicated that vegetation is a significant control on stream geometry (Jenkins *et al.,* 1997). The streams investigated were Bullock Head Creek (sand bed) and Moggill Creek (gravel bed, cohesive banks). The coefficients developed by Hey and Thorne (Table 20) were found to best represent the hydraulic geometry of these streams.

Work by the Department of Land and Water Conservation on northern coastal New South Wales rivers also indicated that the Hey and Thorne coefficients were the most applicable for gravel bed streams in that region.

The Brisbane City Council's 'Hydraulic Geometry of Brisbane Streams: Guidelines for Natural Channel Design' (Ian Drummond and Associates, 1996) recommends the application of Hey and Thorne coefficients for gravel bed streams, and Simons and Albertson coefficients for sand bed streams (see Table 19).

Table 19. Recommended regime equations for south-eastern Queensland streams (from Conrick and Ribi, 1996).

Bed	Banks	Recommended regime relationship
Coarse (gravel)	Coarse (gravel)	Hey and Thorne (1986)
Coarse (gravel)	Cohesive	Hey and Thorne (1986)
Sand	Sand	Simons and Albertson (1963)
Sand	Cohesive	Simons and Albertson (1963)
Cohesive	Cohesive	Simons and Albertson (1963)

Non-cohesive material
For non-cohesive material (ie. no clay content) the channel-forming process is thought to be related to erosive forces, which are in turn related to boundary shear-stress and particle size. Hence, a regime channel is one that is more or less balanced between erosion and deposition during bankfull flows. Regime relationships developed from a data set of streams with non-cohesive beds and banks tend to give reasonable correlation. This may be because of the relatively straightforward physical processes of erosion in non-cohesive materials.

Cohesive material
Stream forms in cohesive material are not so easy to predict, possibly because of the complex chemical processes which give clay its cohesive properties. There is an extensive literature which looks at the erosive properties of cohesive material (Enger *et al.,* 1968; Partheniades, 1971; Mehta *et al.,* 1989a; Mehta *et al.,* 1989b). However, the complex properties of cohesive material make analysis of the erosion process much more difficult than for non-cohesive material. A paper by Brekhovskikh *et al*. (1991) shows that erosion of cohesive sediment could even be influenced by the presence of benthic organisms.

Simons and Albertson (1963) worked on US and Indian canals. They differentiated between bed and bank materials, and as such the regime relationships they developed in 1963 are still some of the best we have for cohesive bed and banks, and sand bed with cohesive bank streams.

So which equations should you use?
The best approach for using regime relationships is to develop your own equations from a locally derived database. It obviously takes a fair bit of time and effort to develop a reliable database, so the quick alternative is to calibrate existing relationships with your stream. Collect data (Q, w, d, S, vegetation type and density) from a series of equilibrium cross-sections and compare the measured data with the results you obtain using the equations in Table 20. The physical conditions used to derive these equations are described in Table 21.

Table 20. Coefficients for regime relationships (from Shields, 1996).

Coefficients for equations of the form:		$w = k_1 Q^{k2} D_{50}^{k3}$				$d = k_4 Q^{k5} D_{50}^{k6}$		$S = k_7 Q^{k8} D_{50}^{k9}$			
Reference	Data	Domain	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
Simons and Albertson(1963)	US and Indian Canals	Sand bed and banks	6.34	0.5		0.572	0.36		0.000072	–0.296	
		Sand bed and cohesive banks	4.71	0.5		0.484	0.36		0.000269	–0.296	
		Cohesive bed and banks	3.98	0.5		0.407	0.36				
Hey and Thorne (1986)	UK rivers	Gravel bed rivers with:									
		I) grassy banks with no trees or shrubs	4.33	0.5		0.47	0.37	–0.11	$0.00049k_7$*	–0.43	–0.09
		II) 1–5% tree/shrub cover	3.33	0.5		0.47	0.37	–0.11	$0.00049k_7$*	–0.43	–0.09
		III) 5–50% tree/shrub cover	2.73	0.5		0.47	0.37	–0.11	$0.00049k_7$*	–0.43	–0.09
		IV) > 50% shrub cover or incised flood plain	2.34	0.5		0.47	0.37	–0.11	$0.00049k_7$*	–0.43	–0.09

$k_7^* = D_{84}^{0.84} Q_S^{0.10}$, where Q_S is the bed material transport rate in kg/s at water discharge Q and D_{84} refers to the bed material in mm.

where;

Q = dominant discharge (m³/s)
D_{50} = median bed-material size (mm)
w = bankfull width (m) (wetted perimeter for depth (m) Simons and Albertson (1963))
d = mean bankful
S = slope (m/m)

Table 21. Physical conditions used to derive various regime equations (from Hey, 1988 and Shields, 1996).

Reference	**Data source**	**Median bed size material (mm)**	**Banks**	**Discharge (m^3/s)**	**Sediment concentration (ppm)**	**Slope (m/km)**	**Bedforms**	**Bank vegetation**
Simons and Albertson (1963)	US and Indian Canals	0.318–0.465	sand	2.83 – 11.32	<500	0.135 – 0.388	ripples to dunes	light to moderate
		0.06 – 0.46	cohesive	0.15 – 2500	<500	0.059 – 0.34	ripples to dunes	not specified
		0.029 – 0.36	cohesive	3.88 – 14.43	<500	0.063 – 0.114	plane	light to heavy
Hey and Thorne (1986)	Meandering UK rivers	14 – 176	–	3.9 – 424	Q_S computed to range up to 114	1.1 – 21	plane	as specified

4. Channel design details

The redesign of channel geometry has particular application to streams which have undergone dramatic morphological changes through response to land-use practices or due to direct human interference with the stream form (channelisation or straightening). To redesign a channel we need to consider both the channel geometry (cross-section variables) and channel planform. This section summarises the commonly adopted methods of channel cross-section design and the following section details the design of channel plan form.

4.1. Channel depth variation

To maintain hydraulic variability in redesigned channels, the depth must vary downstream and across channel. Depth irregularities will form naturally in the redesigned channel if scour velocities are high enough, however for cohesive or armoured channels it is advisable to incorporate depth variation at the design stage (Brookes, 1989).

Pools naturally form at locations with the highest scour velocities (bends). Apmann's (1972) equation and Hey and Thorne's (1986) equation can be used to estimate this pool depth (measured from bankfull height).

Apmann's equation for depth at bend is:

$$d_b = d[(3.5W/r_0)/(1-(1-W/r_0)^{3.5})]$$

and Hey and Thorne's equation for gravel bed streams is:

$$d_b = 0.20Q^{0.36} D_{50}^{-0.56} D_{84}^{0.35}$$

where:

d_b = depth at bend or maximum depth (measured from bankfull height)

d = average depth from regime equation

W = average width from regime equation

r_0 = radius of curvature of outer bank (see Figure 4)

D_{50} = diameter of sieve which 50% of bed material passes

D_{84} = diameter of sieve which 84% of bed material passes

Here are some other geometry equations produced by Hey and Thorne which are useful as guides in design.

- Riffle width (*RW*)(to approximate width at point of inflection between bends) (not to be used for incised streams)

$RW = 1.034\ W$

- Riffle depth (*Rd*) (used to define minimum depth, measured from top of bank) (not to be used for incised streams)

$Rd = 0.951d$

- Riffle maximum depth (measured from top of bank)

$Rd = 0.912\ d_b$

4.2. Designing channel planform/sinuosity

Where suitable reference sites exist, it is recommended that the template approach be used to design meander planform. Reinstatement of the pre-disturbance course using the template method is a commonly adopted basis for small stream rehabilitation design (Brookes, 1987). The pre-disturbance course can often be determined through historical research and by looking for old meander paths on aerial photography.

Planform should be empirically designed only when the historical channel position is unknown or impractical to resume. Planform is inherently linked to slope, such that meanders are established through a floodplain according to the degradation and accretion of sediment. It is impossible to design a stream planform that will be immediately stable. Streams with re-constructed planform will experience degradation and accretion before a stable planform is reached.

There are two basic approaches to designing stream planform:

1) slope first; or

2) alignment first.

4.2.1. Slope first

The slope is determined by way of regime equations presented previously, or preferably through the measurement of slope of a known previous course. Regime relationships generally give poor estimations of slope but are useful for quick order-of-magnitude approximations. In terms of a previously known course, slope is approximated by measuring the channel length (thalweg) from historical records (topographic maps, aerial photos etc).

The next step is to lay out a new channel course using a piece of string scaled to the design length on a map (Shields, 1996). When attempting this approach it is important to be mindful of the erosive effect of low radii of curvature, so it is useful to calculate ranges of these values.

4.2.2 . Alignment first

The alignment-first approach designs a planform based on meander arc length and stable radii of curvature (see Figure 4). The bed slope is then compared with a stable reference stream. The meander arc length commonly ranges from 4 to 9 times the average channel width, and is commonly presented as:

meander arc length $z = 2\pi W$

where W is the average bankfull width, either measured or from empirical equations.

The prediction of radius of curvature also seems to be driven by stream width. Newbury and Gaboury (1993) noted that for gravel-bed streams in Manitoba, Canada, the average radius of curvature of the meander bends is 2.4 times the bankfull width. For stable stream planform the radius of curvature should be between 1.5–2.5 times the average width.

Radius of curvature = 1.5 to 2.5 W

5. A worked hypothetical application of the regime approach

In this example we shall:

- collect relevant stream data; $Q_{1.5}$, vegetative cover, bed material. D_{50}, historical stream alignment;
- identify the regime equations which are suitable for your stream type (slope, bed material etc; we use Hey and Thorne for gravel bed streams and Simons and Albertson for sand bed streams) by referring to Table 20 and Table 21;
- use the design flow to predict channel geometry by applying the regime equations; and
- design the planform and the pool depth variation for the stream.

Step 1: Stream details

A gravel bed stream has been realigned (due to road works) in a straight course for 1,500 m leading and 500 m after a road bridge. The stream is rapidly eroding; this is thought to be due to increased velocity due to straightening. The relevant stream characteristics are:

- gravel bed, $D_{50} = 2$ mm;
- from the unchannelised section on the stream the bankfull discharge relates to approximately $Q_{1.5} = 100\ m^3/s$;
- vegetation = minor shrub cover, some trees, say 20% of bank has tree cover, the rest is grassed; and
- average bankfull width of unchannelised section ~ 25 m (20–30 m).

Step 2: Select equation

Select Hey and Thorne equation: type III stream: 5–50% tree/shrub cover.

Step 3: Predict channel geometry

$w = 2.73Q^{0.5}$

Therefore, average stable width of the new channel should be about $w = 27$ m (the width of the unchannelised reach is 25 m, reasonably close to the predicted width).

$d = 0.47Q^{0.37}\ 2^{-0.11}$

Therefore, the average depth $d = 2.4$ m.

Step 4: Design planform

The old stream planform was determined by aerial photographs and historical record. This planform is unsuitable for the rehabilitated stream because of realignment for the bridge and road. A new planform design is required. A bed slope measured by comparing the thalweg to valley length measured from a topographic map was 0.001 before realignment, the current slope is 0.0022.

Meander arc length should be $2\ \pi\ 27$

therefore average meander arc length = 170 m

Radius of curvature (r_0)should be in the range:

$r_0 = 1.5 \times 27 = 40$ m

$r_0 = 2.5 \times 27 = 67$ m

Undertake iterative design to get acceptable slope

Target slope is 0.001, current slope is 0.0022 (distance = 2,000 m)

therefore drop = 4.4 m

for new slope, total channel length should be around = 4,400 m

The design approach is to lay out an approximate new stream planform, then check the radius of curvature and meander length to ensure the final shape is likely to be stable.

Step 5: Design pool depth variation

Design pool depth at each bend using Apmann's equation

Pool depth = $d_b = d[(3.5W/r_0)/(1-(1-W/r_0)^{3.5})]$

Where $r_0 = 40$ m, pool depth is 5.8 m.

Where $r_0 = 67$ m, pool depth is 4.0 m.

6. Limitations of the empirical model approach

The shortcomings of the empirical model approach are that the hydraulic geometry and regime equations reflect the data base from which they were derived (Hey and Heritage, 1988). Hence, for hydraulic geometry equations to be of use, the reference streams from which they were derived must be similar to the target channel to be rehabilitated.

The implication of this criticism of the regime approach in Australia is that there has been limited confirmation of specific regime equations for any stream types. Therefore, regime equations should either be used cautiously on Australian streams, or verification of hydraulic geometry variables should be undertaken on similar streams of a stable form.

Potential impacts associated with channel design depend heavily on the site conditions before rehabilitation. For example, in the case of a completely armoured (say concrete) urban drainage channel which has been redesigned, the concrete has been removed and the new earth channel remeandered there are going to be at least some short-term erosion and deposition problems until the channel stabilises itself.

It is not possible to estimate the magnitude of the secondary effects without considering each rehabilitation project on a reach-by-reach basis, but in terms of conservative designing, consider the following to be potential impacts.

- Bank erosion.
- Development of knickpoints.
- Bed erosion.
- Loss of infrastructure such as bridges.
- Meander migration.
- Catastrophic widening.

THE CHANNEL EVOLUTION APPROACH TO REHABILITATION DESIGN

This part of the manual links to Step 3 (How has your stream changed) Step 4 (What are your stream's main problems and assets), Step 6 (What are you strategies) and Step 9 (How will you design your project to achieve your objectives) in the Stream rehabilitation procedure (Volume 1).

The concept of how streams evolve is very important for stream rehabilitation. This is the basis for working out the trajectories of assets and problems in Steps 3 and 4. An understanding of how the stream will develop over time is also vital for working out rehabilitation strategies (Step 6) and designing the details of your rehabilitation (Step 9) so that your final plan is working with the natural recovery of the stream.

For descriptions of the evolutionary development of gullies, incised streams, sand slugs etc. see the geomorphology examples in the Common stream problems section of this volume.

Streams are rarely stable over long time scales. Geomorphologists now realise that channels are continually adjusting their form in response to changes in the processes that shape them. This is particularly the case with streams that are subjected to periodic cycles of cut and fill. While many streams incised following the phase of major disturbance by Europeans, there is evidence that this has happened many times before Europeans arrived. Thus, we know that channels evolve, or go through distinct cycles of incision, widening and migration, then deposition, possibly followed by a new equilibrium form. By correctly classifying the stage of this process that the stream is in, it is possible to make predictions about whether the channel is likely to enlarge in the near future, or slowly contract. If it is in the phase of down-cutting or widening, then it is a poor candidate for rehabilitation because the works are likely to be destroyed.

As well as the traditional models of channel evolution devised by Schumm (eg. Schumm, 1969), more ambitious classification systems have been based on the evolution of stream systems (eg. Rosgen, 1996). A catchment characterisation system based on the evolution of channel geomorphology has been developed at Macquarie University (funded by LWRRDC) known as the River Styles approach. The approach is detailed in a three-part series titled *Geomorphology and River Ecology in South-eastern Australia: an Approach to Catchment Characterisation* (Brierley *et al.*, 1996). The following section summarises some aspects of the River Styles approach.

The channel evolution approach to rehabilitation design places the current stream condition into a longer-term geomorphological process perspective. This allows assessment of natural recovery potential.

1.1 The 'River Styles' classification scheme

Geomorphic units are the building blocks of river styles, and explaining their character, distribution and assemblage provides the key to the explanation of river character and behaviour. So far the method has been based mainly on observations of unregulated non-urban New South Wales streams, but may have a much wider application.

The context for the development of the river styles method is that the traditional view of an equilibrium based river, formed and maintained by some dominant discharge condition may not apply to Australian streams. The example of the disequilibrium provided in Brierley *et al.* (1996) is the Bega River. Before European settlement, stream morphology was based on chains-of-ponds and swamps which had developed through a cut-and-fill process involving multiple phases of incision spaced thousands of years apart. Since European settlement, the valley floors have gullied following vegetation clearing and channel disturbance. The gullied streams will not return to their pre-disturbance equilibrium condition, rather they will stabilise over time to a new incised form. So, while a bankfull or dominant discharge may be responsible for the final shape of the modified streams, the evolutionary process from chains-of-ponds to incised streams does not conform to the traditional stream evolution process.

Within this context of synchronous incision of south-eastern Australian streams, the key to stream rehabilitation is to assess the stage of post-disturbance evolution for each river, and determine the likely future condition (Brierley *et al.,* 1996).

The process of catchment characterisation in the river styles methodology is based on a nested hierarchical approach proposed by Frissell *et al.* (1986), which is applied at three independent scales:

- Catchment scale

  Review of catchment scale considerations such as catchment size and shape, elevation, drainage patterns and geology.

- Reach scale

  Reach scale elements are based on sediment budgets, ie. the reaches ability to store, accumulate and transfer materials as well as their role as sediment source zones.

- Geomorphic unit scale

  Geomorphic unit attributes are those features sculpted from rock or depositional forms as rivers rework their bed material. Instream habitat character is determined largely by hydraulic interaction with these geomorphic units such as in pool and riffle formation, the development of bars and scour holes, sheets of sand in a sediment slug, and meander cut-offs in lowland reaches.

Brierley *et al.* (1996) suggested a five-stage approach to the catchment characterisation procedure;

- **Stage 1:** Compile baseline data.

  Relevant data are collected for each of the above three scales.

- **Stage 2:** Data analysis.

  The present river behaviour is explained on the basis of the collected data in stage 1.

- **Stage 3:** Prediction of recovery potential.

  Future river behaviour is predicted on the basis of geomorphic process zone framework (ie. on the basis of recent changes), sediment storage (ie. sediment balance drives the stream forming process), and theoretical river behaviour (use traditional notions of stream evolution to predict future stream behaviour).

- **Stage 4:** Determine target condition; prioritisation of catchment management issues.

  On the basis of predicted behaviour in stage 3, river management actions can be prioritised.

- **Stage 5:** Identification of suitable river structures.

  Stream rehabilitation works can be designed on the basis of the priorities from stage 4.

More details and applications of the River Styles approach are provided in the following publications:

- Brierley, G. (1999). River Styles: an integrative biophysical template for river management. In: Rutherfurd, I.D. and Bartly, R. (eds) Proceedings of the second Australian Stream Management Conference, pp. 93–100.

- Fryirs, K. (1999). The recovery potential of River Styles in the Bega catchment, NSW: a catchment based framework for prioritisation of river rehabilitation strategies. In: Rutherfurd, I.D. and Bartly, R. (eds) Proceedings of the second Australian Stream Management Conference, pp. 279–286.

- Ferguson, R. (1999). Know your catchment! The importance of understanding controls on river styles and their distribution in catchment management. In: Rutherfurd, I.D. and Bartly, R. (eds) Proceedings of the second Australian Stream Management Conference, pp. 249–256.

PREDICTING THE SCOUR PRODUCED WHEN YOU PUT THINGS INTO STREAMS

Natural streams are untidy: they are full of woody debris, have trees sticking into the stream, the banks are often undercut, and the flow varies from local high velocity zones over rocks and around logs, to still water conditions in deep pools. The channel meanders across the floodplain, varying in shape from a deep, narrow trench where it is hard up against the floodplain wall to a broad, shallow stretch between meander bends. Most human impact on streams, such as channelisation, increasing sediment loads, and removing snags and vegetation, has reduced in-channel complexity, making them less messy and more uniform. **Much stream rehabilitation effort is directed at making streams messy again by reintroducing structures, vegetation or woody debris, which creates habitat complexity and velocity variation in the stream.**

The habitat features detailed here are based on the creation of hydraulic, depth, and substrate diversity in response to an in-stream obstruction. The basic hydraulic response to an in-channel obstruction is a scour hole created at high flows which persists at low flows, creating low-flow habitat.

The purpose of this section of the manual is to help you to predict where scour will occur if you put something into a stream, and how much scour and deposition there is likely to be. This is important, not only for predicting the effectiveness of your proposed works, but also for predicting potential undesirable consequences of the work (see Step 8: Are your objectives feasible? of the Stream rehabilitation planning procedure, Volume 1). This section describes the general erosion and deposition effects of placing any object into a stream. It then goes on to provide some methods for predicting the approximate depth of scour that can be expected. The final section considers the position of scour around objects.

If there is flow around an object the local turbulence will cause scour. The scour creates hydraulic and depth variability, and the bar formed downstream of the scour is usually coarser than the normal bed material, creating substrate variability.

1. What happens when you put something into a stream?

To achieve a high species richness in a rehabilitated reach, there must be a complex in-stream habitat. One indicator of complex habitat is a large range of flow velocities in the reach at any one time. Consider a stream as a rectangular channel; the average velocity is equal to the flow rate divided by the cross-sectional area ($V = Q/A$). If we constrain the channel by putting a groyne into the flow or a full-width structure across the bottom of the channel, the cross-sectional area decreases, so the average velocity increases. The opposite is true if we expand the cross-sectional area with large pools: then the average velocity decreases. In general, for every increase in flow velocity at one point there must be a corresponding decrease elsewhere. If we look at velocity on a smaller scale, say where rocks or logs are put into the channel, we see that there is little effect on the overall velocity of the channel, but that the velocity conditions around the obstruction will range from much higher than the average velocity to still water behind the object. Hydraulic diversity is also increased by the scour hole and depositional bars that form downstream of instream works. Fish and other aquatic creatures (platypus, macroinvertebrates) are dependent on complex velocity conditions for suitable conditions for feeding, reproduction and resting.

2. Increasing pool habitat

One of the limiting habitat features for degraded streams is a lack of pool habitat. For example, habitat features (pool area, riffle area, pool volume, bed material size, spawning gravel area, and average maximum depth) and fish populations were measured in a 1.5 km rehabilitated reach of a small (width 9–12 m) coastal stream in Oregon, USA. The rehabilitation strategy was the construction of 22 full-width gabion or rock and log structures, and 10 partial-width structures and boulder clusters. Within two years of installation, the area of pool habitat in the rehabilitated reach had increased by 53%. During the same period pool areas in an untreated reach had increased by only 23% (House and Boehne, 1985). Unfortunately, the effect of habitat change on fish numbers was inconclusive due to flow conditions and evaluation techniques (House, 1996).

There are two forms of pool created by in-stream structures. The first is simply a backwater pool, created by full-width structures that act like low dams across the stream. The second is a permanent scour hole created downstream of structures by turbulent flow. Both pools increase in size as the crest of the structure gets higher.

2.1. Backwater pools

Backwater can be formed upstream of partial or full-width structures during flood flow because of their constricting effect on the channel cross-section. During low flow, backwater pools are created only behind full-width structures.

The depth of backwater pools is a function of the height of the structure and the bedload and suspended load of the stream. In streams with substantial sediment transport, the low velocity conditions in the backwater will encourage bedload to be deposited and fill the backwater pool. This ability of structures to catch sediment is called the trap efficiency. Thus, in streams with a large bedload the pool may fill with sediment which can greatly reduce its biological value.

2.2. Pools formed by scour

Scour can be defined in various ways, depending on whether it is occurring on a reach or local scale. For stream rehabilitation projects, scour can be considered a localised erosion of the stream that occurs on the rising or falling limb of the hydrograph. Depending on the sediment transport characteristics of the stream, the scour hole is either filled with sediment or remains a permanent bed feature. Permanent scour holes are also referred to as bed degradation. Scour due to structures that obstruct the channel is caused by the flow being constricted around the obstruction, causing a localised increase in velocity near the structure. This high-velocity flow has a turbulent, rapid expansion phase downstream of the structure (called eddy scour). A scour hole is created either by the high velocity around the obstruction, as in the case of scour under a snag, or from an eddy downstream of the structure, such as the scour at the tip of a groyne.

3. Substrate variability and scour holes

Use of in-stream structures increases substrate variability, and it is believed that this enhances the in-stream habitat value. Scour holes are created by turbulent flow (around or over an obstruction), mobilising the bed material. Coarse bed material is deposited in a bar just downstream of the scour hole, but finer material will stay in suspension for longer and is therefore separated from the coarse material. The result is that, downstream of an in-stream structure, a bar is formed of material that is coarser than the normal bed material.

It is well established that salmonid fish prefer 'washed' gravels for spawning. Salmonids lay their eggs in a 'redd' buried just under the gravel surface (Swales and O'Hara, 1980). Coarser gravels aid aeration of the redd and the removal of waste products. It is not known if the spawning of Australian fish is improved by the presence of 'washed' gravel, but it is known that many Australian fish species rely on their eggs adhering to a surface, eg. Australian grayling, freshwater hardyhead, Macquarie perch and possibly Murray cod and trout cod (Koehn and O'Connor, 1990). For these species, it is advantageous to provide gravel which is free of fine material so the eggs can adhere to the gravel. The freshwater catfish actually make nests in the river gravel by disturbing the substrate, presumably to remove the fines from the gravel before spawning. So although the spawning mechanisms of Australian fish differ from those of salmonids, Australian fish are likely to benefit from a more variable substrate, such as that formed downstream of instream works.

In addition to the direct impact on fish through improved spawning conditions, increasing the variability of substrate will also increase the habitat potential for macroinvertebrates (Swales and O'Hara, 1980). Overseas research indicates that benthic macroinvertebrates can represent the major food supply to bottom-feeding forage fish (De Silva *et al.,* 1980; Starnes and Starnes, 1981; in Gore, 1985). In general, the highest productivity and diversity of aquatic macroinvertebrates in lotic systems have been found in riffle habitats with medium cobble (256 mm diameter) and gravel substrates (Hart, 1978; Gore and Judy, 1981; in Gore, 1985). To increase the species richness of macroinvertebrates (and of the fish that feed on them) it is advantageous to have variable substrate material, and particularly the coarse bed material downstream of instream structures.

How depth, hydraulic and substrate variability are influenced by in-stream structures is conceptualised in Figure 8.

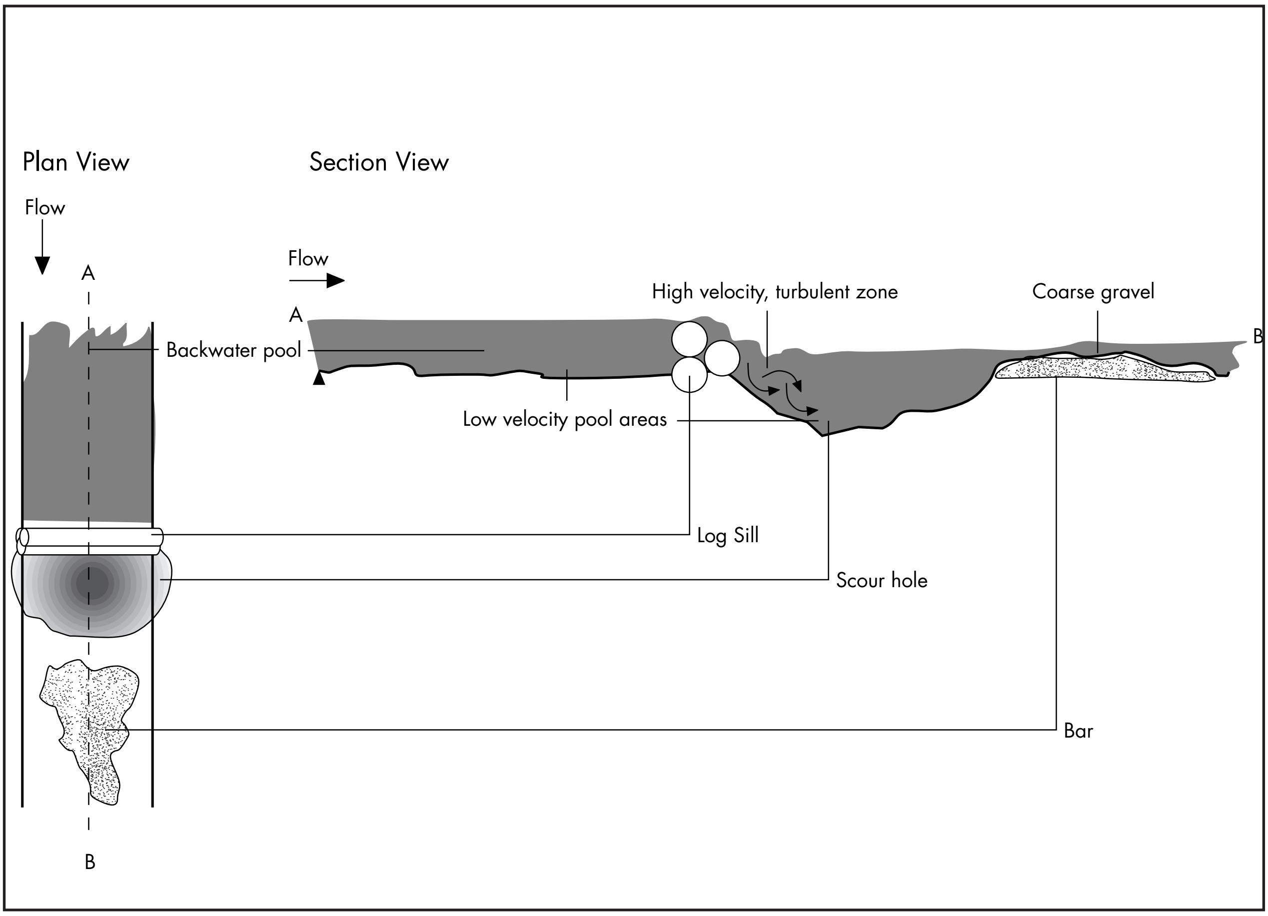


Figure 8. Local changes in depth, velocity and bed material resulting from an instream structure.

4. General hydraulic effects of instream structures

4.1. Predicting the size of scour holes

For stream rehabilitation, it would be very useful to be able to predict the size and location of scour holes so that we know if structures will be threatened, or by how much pool area will be increased. Unfortunately, we are unable to do this with any great confidence. There is a general lack of agreement between investigators as to which factors are most important in determining scour depths (Copeland, 1983) although there is general agreement that the greatest amount of scour occurs under clear-water scour conditions (Richardson and Richardson, 1993; Yasi, 1997). A wide range of models has been produced for predicting the scour pattern around groynes.

A simple technique for estimating the scour downstream of in-stream structures or disturbances like bridge piers, groynes, and abutments is the Farraday and Charlton (1983) method detailed below. For structures such as large woody debris or boulders that are likely to be submerged, the scour will be less than that predicted by this method. This method is included to provide guidance on how much protection that may need to be provided for structures placed in streams.

> **Note:** Placing objects in streams can produce dramatic and unwelcome erosion and deposition. For example, agencies have incurred legal trouble for revegetation that constricted flow and caused bank erosion. It is always wise to seek professional advice. These notes provide only a general guide. We recommend seeking professional advice in any project where scour could cause a problem.

4.1.1. The Farraday and Charlton method

The basic equations used in this method are given below:

$$y_2 = 0.38(V_1 y_1)^{0.67} D_{50}^{-0.17} \quad \text{(for sand bed channels)}$$

$$y_2 = 0.47(V_1 y_1)^{0.8} D_{90}^{-0.12} \quad \text{(for gravel bed channels)}$$

$$y_2 = 51.4 n^{0.86} (V_1 y_1)^{0.86} T_c^{-0.43} \quad \text{(for cohesive bed channels)}$$

where:

y_2= mean depth of the total scour measured from the water surface (m);

y_1= design depth equal to A_1/T_1 (m) (usually adopted as bankfull depth);

V_1 = design flow velocity (m/s) (either measured or estimated using Manning's equation—see *Selecting a design discharge*, in Natural channel design, this volume);

D_{50} = size of bed material such that 50% of the material is smaller by mass (sieve sampling or field sampling for coarse beds);

D_{90} = size of bed material such that 90% of the material is smaller by mass (sieve sampling or field sampling for coarse beds);

n = Manning's roughness coefficient (see *Selecting a design discharge*, in Natural channel design, for a method to calculate Mannings n);

T_c = critical tractive stress for scour to occur for given bulk density and soil type (read from Table 22);

T_1 = mean top width for the design flow (m) (usually taken as bankfull width); and

A_1 = mean bankfull flow area for the design flow (m) (usually taken as bankfull cross-sectional area).

Table 22. Critical tractive stress for cohesive bed material. (First select the column based on the voids ratio and bulk density; second, select N/m^2 for that column given the soil type.)

Voids ratio	2.0–1.2	1.2–0.6	0.6–0.3	0.3–0.2
Dry bulk density (kg/m^3)	880–1,220	1,200–1,650	1,650–2,030	2,030–2,210
Saturated bulk density (kg/m^3)	1,550–1,740	1,740–2,030	2,030–2,270	2,270–2,370
Soil type	**Critical tractive stress (N/m^2)**			
Sandy clay	1.9	7.5	15.7	30.2
Heavy clay	1.5	6.7	14.6	27.0
Clay	1.2	5.9	13.5	25.4
Loam clay	1.0	4.6	10.2	16.8

The depth of scour is influenced by the direction of attack of flow to the obstruction. Table 23 provides a list of multipliers for different attack angles.

Table 23. Multiply by this amount to estimate the critical depth of scour.

Location	**Multiplier**
Nose of groynes or abutments	2.0–2.75
Flow striking the bank at right angles	2.25
Flow parallel to bank	1.5–2.0

The field procedure for estimating total scour depth using the Faraday and Charlton method follows.

1. Determine the nature of the bed material—either sand bed, gravel bed or cohesive bed and select the appropriate equation.
2. Calculate, estimate or measure the parameters for the equation.
3. Calculate scour depth.
4. Estimate the 'maximum' scour depth using the multipliers in Table 23.
5. Estimate the depth of scour below the original bed surface (y_s) as:

$$y_s = y_2 - y_1$$

The predicted maximum depth should be used to give an order of magnitude only—in this case we can say that the expected maximum scour-hole depth generated from bankfull in a stream such as this flow is around 1 m.

An example calculation of scour

Consider a small, mid-catchment, ephemeral stream that has a moderate slope and a degrading bed. The rehabilitation strategy calls for the construction of a rock weir approximately 1.0 m high. It is hoped that this structure will stabilise the bed and form a large permanent pool to maintain fish populations during the periods of no flow.

Details:

uniform incised channel which is assumed to be rectangular in shape

width (w): 20 m

bankfull depth(y_{bf}): 1.5 m

slope (S): 0.005

roughness: channel has patches of cumbungi reed, and there are two large trees which have fallen into the channel and obstruct about 15% of its cross-section. Estimated Manning's n before treatment: 0.06

sinuosity: 1.2

hydraulic radius (R): A/P = (20 × 1.5)/(20 + 1.5 + 1.5) = 1.30 m

design height of full width structure (z): 1.0 m

D_{50}: 12 mm

D_{90}: 22 mm

Step 1: Determine the nature of the bed material—either sand bed, gravel bed or cohesive bed and select the appropriate equation (in this case it is the gravel bed equation).

Step 2: Calculate, estimate or measure the variables for the equation.

$V_1 = 1.4$ m/s

Step 3: Calculate scour depth.

$y_2 = 0.47(1.4 \times 1.5)^{0.8} 0.022^{-0.12}$

$y_2 = 1.345$ m

Step 4: Estimate the 'maximum' scour depth using the multipliers in Table 23.

Flow is parallel to the bank so the multiplier for estimating total scour depth is between 1.5 and 2.0—call it 1.8. Thus the maximum scour depth is 2.4 m

Step 5: Estimate the depth of scour below the original bed surface (y_s) as: $y_s = y_2 - y_1$

2.4 – 1.5 = 0.9 m (So, the scour pool will be about 0.9 m deep.)

4.2. Predicting the location of scour holes

Unfortunately, we cannot accurately predict scour hole size and orientation. However, we can qualitatively predict the location of the scour hole and the consequences that it may have on the stability of the in-stream structure by considering the general shape of the structure and how it intercepts flow. Different scour holes can be formed at high and low flows, because of different angles of deflection and different backwater lengths. Table 24 summarises the variables that affect the formation (and consequently habitat potential) of a scour hole downstream of an instream structure.

The formation of scour holes is also affected by the conditions in the stream. The following stream characteristics can be important.

- Bed material—streams with coarse bed material will tend to armour the scour hole, limiting scour formation (eg. Figure 9).

- Tractive stress—tractive stress is a measure of the ability of a stream to resist initial movement of bed material. As the depth of flow increases, so the tractive stress increases until the stream banks overtop and the tractive stress drops off because of the momentum transfer between fast-flowing water in the main channel and slow-flowing water on the floodplain. Streams in a deep trench (incised streams or gullies) have limited out-of-bank flow, and thus generate a much greater tractive stress and erosive capacity (hence it is difficult to stabilise a stream that is actively incising).

- Velocity and depth—supercritical flow over a structure will tend to produce a much more turbulent downstream condition and more scour than subcritical flow over a structure.

- Sediment load—high bedload streams (and aggrading streams) will fill scour holes on the falling stage of a flood (Figure 10).

- Downstream control—the erosive capacity will be reduced if a structure is placed in the backwater of a downstream control (eg. a constriction like a culvert).

Figure 9. Armouring in the bed of Lockyer Creek, in Queensland.

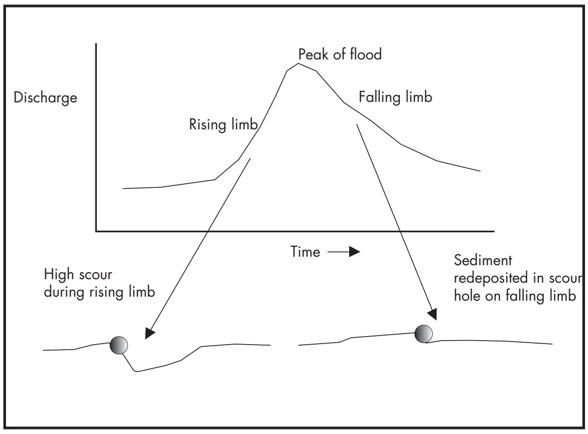


Figure 10. The sequence of scour over a flood in streams with a high sediment load. On the rising arm of the flood a scour hole develops downstream of the structure. During the falling arm, deposition will fill the hole.

Table 24. Variables that influence the position and type of scour that occurs around an obstruction.

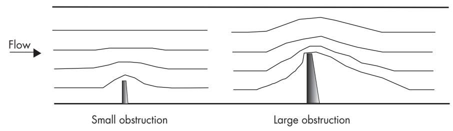
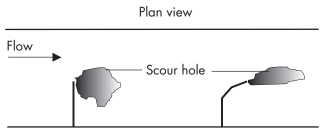
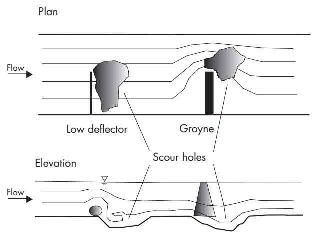
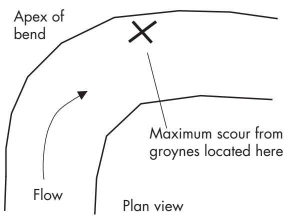
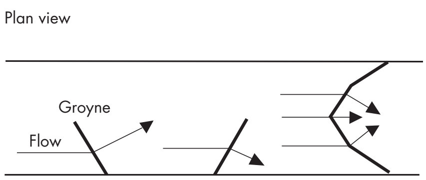
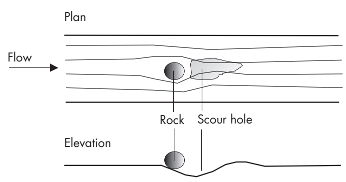
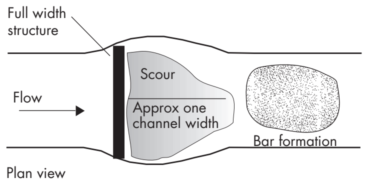
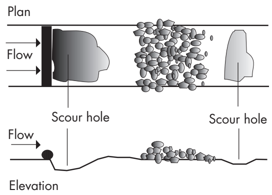
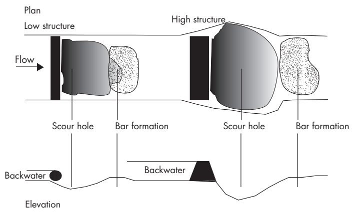
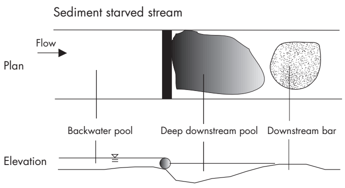
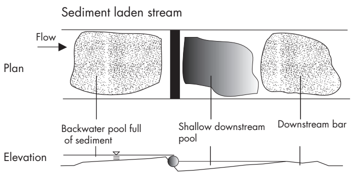
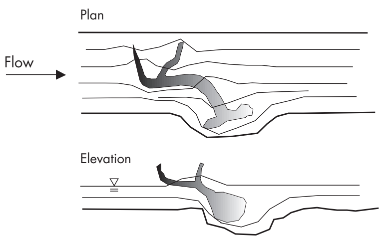
Illustration **Partial-width structures**	**Concept**
	Percent obstruction—the more of the cross-section that a structure obstructs, the greater the increase in local velocity and downstream turbulence and the greater the scour (plan view).
	Trailing edge—the scour hole forms at the tip of a structure, but just downstream. A trailing edge will push the scour hole toward the centre of the channel (Dyer *et al.*, 1995).
	Degree of submergence—the more a structure is overtopped, the less scour there will be at the tip and the more on the downstream side.
	Location of partial width structure—studies by Copeland(1983) and Przedwojski, (1995) suggest that the maximum secondary scour depth and extent occurred at groynes sited immediately downstream of the meander apex, rather than at groynes at the entrance and exit from the bend.
	Angle of structure—fully emergent structures (such as groynes) produce only slight variations in the downstream scour hole with angles less than $\pm$ 15° to the flow direction. However, structures that are submerged at high flow (low deflectors) redirect overtopping flow at 90° to the submerged structure. Thus, a submerged structure angled downstream, will redirect flow toward the bank, and a structure angled upstream will redirect flow toward the centre of the channel. A concave weir which has two arms pointing upstream will redirect flow to the centre of the channel. This deflection ceases when the object is less than 30° to the bank.
	Unattached structure—structures unattached to the banks, such as boulders placed in the stream, form a scour hole downstream of the structure.
See (Drummond *et al.*, 1995).	Effect of multiple structures—a large proportion of the work published on groyne erosion has been done on single groynes and its applicability to field situations was thought to be limited. However, work by Suzuki (1987) and Dyer (1995) has suggested that each structure can be considered as a single object subject to the flow conditions from the structure immediately upstream, and that the relationships developed for predicting the erosional effects of single structures can be applied to multiple structures.

Table 24 (cont'd). Variables that influence the position and type of scour that occurs around an obstruction.

Illustration **Full-width structures**	**Concept**
	Eddy scour—scalloping of the bank downstream of a full-width structure is common. This usually extends about one channel width downstream of the structure and is caused by turbulent flow expansion as the water passes over the structure.
	Downstream face angle—a gently sloping downstream face (eg. rock chutes) will generally not produce a scour hole because energy is dissipated on the face of the structure and not on the downstream bed. This contrasts with structures such as log sills that have a steep downstream angle, and often considerable scour.
	Height—higher structures will create a larger backwater, and the increased height will lead to a larger downstream scourhole (Breusers and Raudkivi, 1991)
 	Trap efficiency—the lower velocity conditions of the backwater behind full-width structures allows deposition of suspended sediment. If a reach is treated with a series of full-width structures, the cumulative sediment trapping action can starve downstream reaches of sediment, resulting in clearwater scour. However, in streams with high sediment loads, the backwaters are likely to fill with sediment and subsequent bedload will pass over the full-width structures.
	Complex structures—Complex structures such as large woody debris (LWD) can span a section, or all of the channel. They are sometimes fully attached to the bed, but usually fall into the channel on an angle, allowing flow both over and under the snag. LWD also has a complex array of branches that protrude into the flow and often catch other debris. The net effect of LWD in the stream is much like the addition of a combination of complex engineered structures. There is often scour under, downstream, and at both ends of LWD.

HOW CHANGING THE CHANNEL CAN AFFECT FLOODING

If you put snags back into a stream, build benches that constrict a channel, or revegetate the channel, what effect will this have on flood height and flood duration? Conversely, will removing those willows in the stream dramatically reduce flooding? These are fundamental questions for stream rehabilitators. This section, with worked examples, provides some guidance on the effects that doing things in streams has on flood levels.

At the end of this section you will be able to roughly estimate how changing things in a stream will affect how high floods get, and how long they stay high.

Note. Predicting hydraulic effects is a complex task. Here we provide general information so that you can understand the possible effects of your actions in the stream. It is essential to get professional assistance if changing flood levels are likely to lead to damage.

To assess the likely effect of in-stream work on flooding we need first to understand some basic open-channel hydraulics so that we can tell if flow is subcritical, calculate the critical depth for a given discharge and predict roughness coefficients so that we can estimate the discharge.

1. Open-channel flow: general concepts and useful formulae

As a stream manager needing to predict the hydraulic effect of instream work you must understand the concepts of backwaters, flow conditions, the energy equation and Manning's equation. The following section is a summary of these open-channel flow concepts. Their application to predicting hydraulic effects will become clear as we work through some examples of stream rehabilitation projects in the following section.

1.1. What is a backwater?

An integral concept of flooding is the notion of a backwater. If you increase the water level upstream of stream works you have created a 'backwater'. A backwater is the difference between the upstream water level with the structure and the water level without it (Neill, 1973). Any structure or roughness that creates a backwater is known as a control point (because it controls upstream water depth).

Backwaters are important because they control flooding. Imagine that we have built a dam across a river, and you are in a boat, measuring the velocity of the water in the reservoir. The water velocity at the dam wall (known as the control point) will be zero. As you travel upstream of the wall, the water velocity gradually increases until the river is flowing at its normal velocity, unaffected by the dam. The distance from the dam wall upstream to where the flow is unaffected by the dam is the backwater. Backwaters are produced by every structure in a channel, not just dams. The upstream extent of the backwater depends on how much the water level is raised at the control point. With a dam, you know the effect on water level. The problem comes when trying to predict the rise in water surface from some in-channel structure like a piece of large woody debris. We will use the subsequent hydraulic tools to roughly predict the increase in water level from any obstruction in the channel.

Note. Many people believe that backwaters are created only by dams that span the channel. In reality, anything that resists flow produces a backwater during subcritical flows. Examples are channel constrictions, logs, bushes, rock chutes, culverts a wide shallow reach etc. All these features can 'back the water up'.

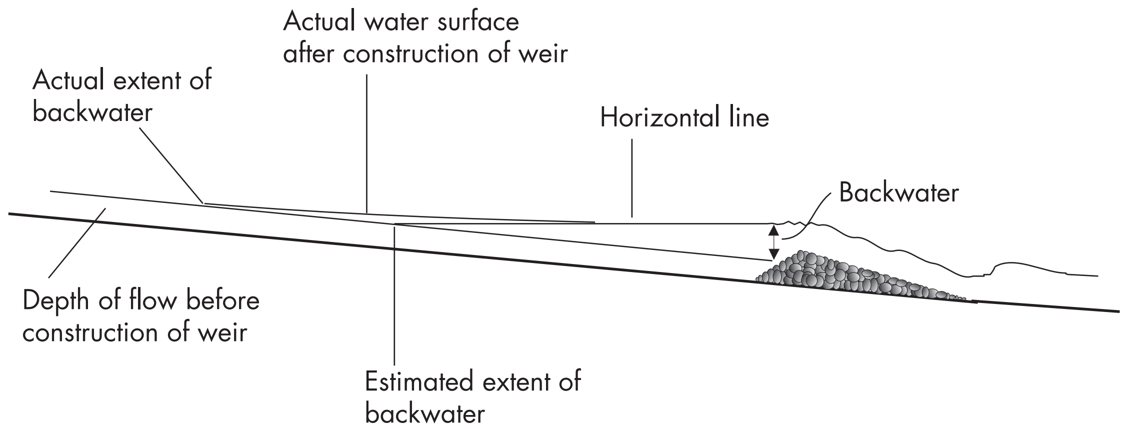


Figure 11. As a rule of thumb, to predict the upstream extent of a backwater, take a horizontal line upstream from the water level at the control point (ie. the structure). Be aware that this will underestimate the actual extent of the backwater.

A rule of the thumb for predicting the absolute minimum upstream extent of an in-channel backwater is to take a horizontal line upstream from the water level at the control point to where it intersects a line of the normal depth of flow for that discharge. The point where the line intersects the normal depth of flow is the minimum upstream extent of the backwater. In reality, the backwater profile forms a curve that extends further upstream than this point (see Figure 11).

Predicting the true backwater curve is a specialist hydraulic task. However, rehabilitators need to be aware of the principles involved and their relevance to rehabilitation projects. In many cases, the variability of hydraulic and morphological conditions in the channel means that refined calculations of the extent of the backwater are complicated (Neill, 1973) and do not provide much more information than quick approximations.

Hand (or spreadsheet) calculation methods for predicting backwater extent include the direct step and graphical integration methods and are fully described in texts such as Chadwick and Morfett (1993). The methods are quite time-consuming but relatively easy to master. Alternatively, computer programs like Mike 11 or HECRAS can provide detailed information on the effect of in-channel work, but the time spent collecting and entering the data should be commensurate with the risks associated with the flood hazard.

1.2. Energy

We can approximate the effect of changing the cross-sectional area of a stream (say with a full or partial-width structure) by considering the continuity of energy just before the constriction. We can present this continuity as the basic energy equation (or Bernoulli equation), which is used to calculate different flow conditions between two points in the stream as shown in Figure 12. This equation is essential for predicting flood effects of instream structures and it is easy to understand.

$$\frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + \text{ energy loss}$$

where the variables are as defined in Figure 12.

Large errors can be made in calculating the extent of a backwater. First, it is difficult to identify control points, and second, errors in predicting the increased water levels at the control points are amplified in estimating the extent of the backwater. The water level at the control point is difficult to predict accurately without using hydrodynamic modelling (ie. HECRAS or Mike 11). Say, for example, the predicted increase in height at a constriction through a culvert was 0.5 m; for a low-gradient stream (say a slope of 0.0005), the influence of this backwater would be a minimum of 1 km (0.5/0.0005) upstream. Consider the difference in extent of the backwater if the water level at the obstruction was incorrectly estimated, and was, in reality, only 0.35 m. The upstream extent of the back water would then be only 700 m. For a low-gradient stream, calculations of the extent of the backwater can be wrong by kilometres because of relatively minor errors in the calculation of water depth at the control point.

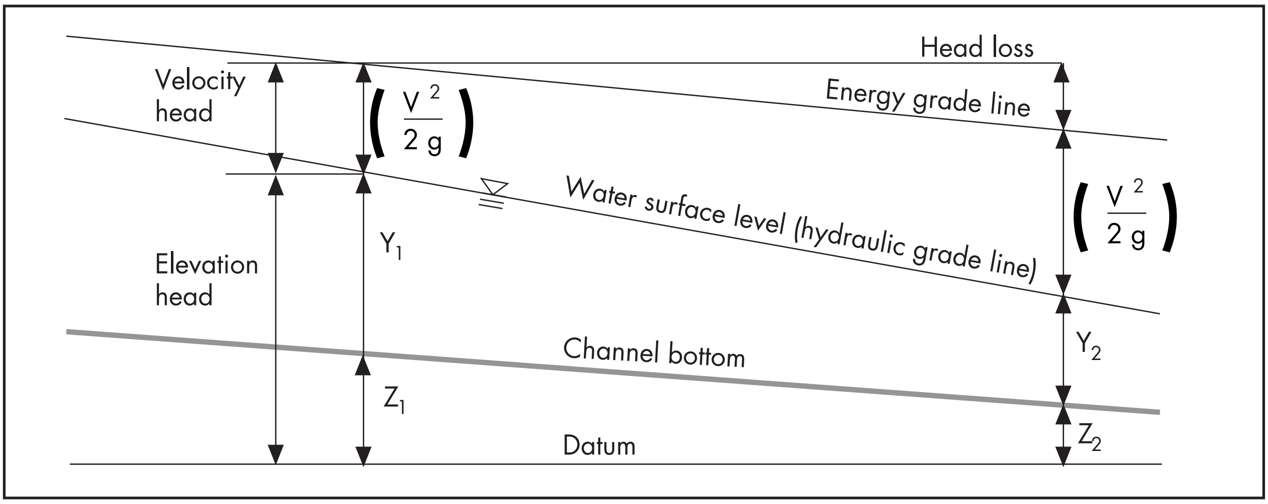


Figure 12. An illustration of the terms in the basic energy equation.

The energy equation has two basic parts: the velocity head ($v^2/2g$), which describes the energy due to flowing water, and the elevation head ($y + z$), which describes the energy due to the elevation of water. If we compare the energy equations for two different locations on the stream, friction and trubulence will also cause losses of energy. To simplify calculations, such energy losses are usually ignored and, if the distance between the points of interest is short and there is no abrupt change in depth of water ('hydraulic jump', discussed in next section), this approach does not seriously affect the conclusions drawn.

The energy equation is used in the following section to predict backwater depth resulting from full-width structures and channel narrowing.

1.3. Flow conditions

Two important points can be made about flow conditions, obstructions and flooding: 1) as a general rule, we will not create backwaters when the flow is supercritical; and 2) the depth of flow at a channel obstruction that is creating a backwater is the critical depth. We need first to understand what are the supercritical and critical flow conditions, and to have a way of calculating them for a given discharge.

For a given discharge, we can construct a specific energy diagram (Figure 13) from the basic energy equation in the previous section. If we consider a channel cross-section, the energy varies with flow depth. The specific energy diagram shows that, for any given energy, there are two possible velocity and depth combinations with either supercritical or subcritical flow conditions. The division between subcritical and supercritical flow is the inflection point of minimum energy where critical flow occurs. The depth at which this occurs is called **critical depth**. During critical flow conditions the flow is unstable and usually quickly becomes either subcritical or supercritical.

A handy equation to find the critical depth of a rectangular channel for a given discharge is

$$y_c = \left(\frac{q^2}{g}\right)^{1/3}$$

where:

y_c = the depth for critical flow (m), and

q = the discharge per unit width of a rectangular channel, ie. total discharge divided by width (Q/w) for a rectangular channel. We will use this equation later.

To better understand subcritical, critical and supercritical flows, consider a rock thrown into a flowing stream. Water propagates disturbances as waves, and when a rock is thrown into a stream the velocity of the disturbance wave (known as the celerity) is a function of water depth. We can tell if flow is supercritical or subcritical by comparing the flow velocity and celerity.

The ratio of the flow velocity to the celerity is called the Froude Number (Fr):

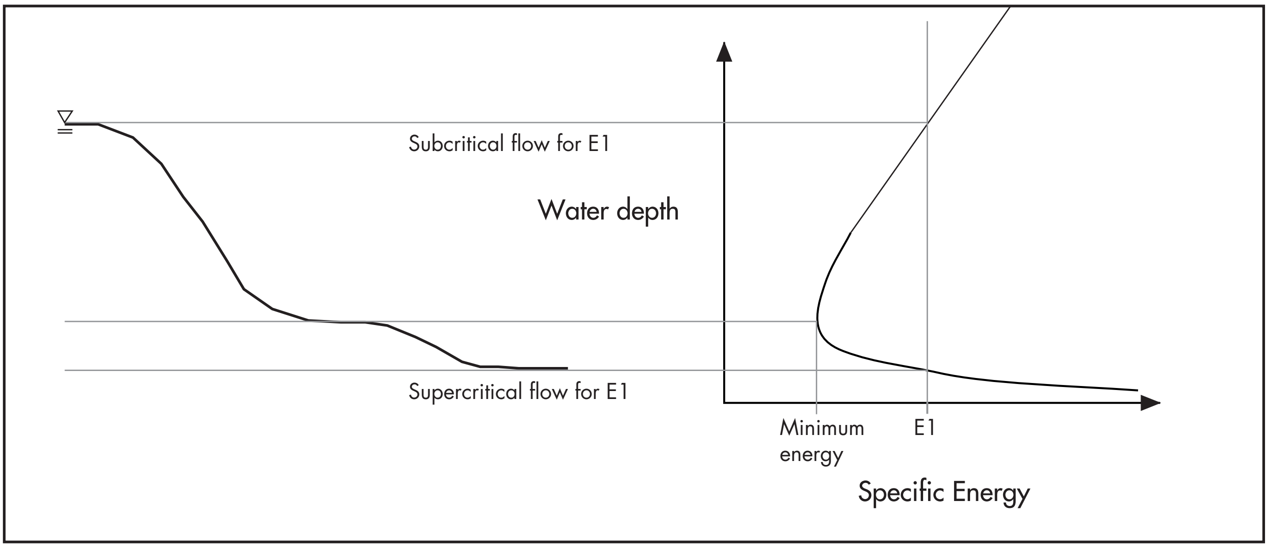


Figure 13. A typical specific-energy curve, showing the relationship between flow type and water depth. For a given specific energy (eg. E1), there are two possible combinations of depth and flow type.

$$Fr = \frac{v}{\sqrt{gy}}$$

where

v = depth averaged flow velocity of the stream (m/s);

g = acceleration due to gravity (9.8 m/s^2); and

y = flow depth (m).

The term $\sqrt{gy}$ is the disturbance wave celerity.

Consider again the rock thrown into a flowing stream. The velocity of the disturbance waves (celerity) relative to a stationary observer on the bank will depend on the flow velocity of the stream. If the flow velocity is greater than the celerity ($Fr > 1$), then flow is said to be supercritical and waves from the rock will not travel upstream. When the flow velocity and the celerity are equal, a stationary wave front will form at the disturbance and the flow condition is described as critical ($Fr = 1$). If the flow velocity is less than the celerity then the flow is subcritical and the disturbance wave from our rock can travel upstream ($Fr < 1$).

Critical flow occurs where the channel cross-section has been reduced, such as at full width structures and channel constrictions. It is the occurrence of critical flow that controls the upstream water level and backs-up water. This is because there is, for a given discharge, only one critical flow depth (Figure 13). Since there is only one critical flow depth for a given discharge, if we know the discharge it is relatively easy to work out how high the backwater will be (ie. somewhat more than critical flow depth). A subsequent section on predicting backwater effects gives two worked examples of backwater depths due to critical flow: one is for flow over a weir, the other is for a channel constriction.

1.4. Using Manning's equation to predict changes in discharge through increased roughness

Critical flow occurs when a backwater is created by a channel obstruction such as a full or partial width structure. In these cases, it is the local constriction in the channel area that acts as the control point and produces a backwater. If we reduce the channel capacity on a reach scale rather than at a point, flow conditions are affected by the cumulative influence of roughness and drag from the boundary material and elements such as logs or boulders in the channel. There is no one critical control point, but rather the water level increases for a given discharge because the channel capacity has been reduced by the addition of roughness elements. This situation could arise from revegetation of a channel, the reintroduction of snags, or placing several small structures in a reach of stream. In such cases, we use a uniform flow equation and define the change in channel capacity from in-stream works in terms of a changed channel 'roughness'. The method entails comparing the pre-rehabilitation channel roughness with an estimated post-rehabilitation channel roughness and either the change in channel capacity or the change in water level for a given discharge. Various methods for calculating flow conditions are available, including those developed by Chezy (1789), Manning (1889) and Darcy-Weisbach (1850).

Manning's equation is the easiest and most widely used method for quantifying the hydraulic effects of channel conditions. It was developed for uniform flow conditions and assumes that the water surface profile and energy gradient are parallel, and that the cross-sectional area, hydraulic radius and depth remain constant throughout the reach. In terms of reaches with a significant amount of natural variation in roughness, these assumptions are clearly not valid. However, Manning's equation allows a useful first approximation of changes in channel roughness to be made (Gippel *et al.,* 1996b).

Refer to *Selecting a design discharge,* in Natural channel design, this volume, where Manning's equation is discussed in more detail.

1.4.1. Composite channel

For stream rehabilitation we are usually concerned about increased flood levels. The foregoing discussion of Manning's equation shows that it is easy to calculate discharge from a single channel but when flows become deep, the channel tends to be poorly defined and may be made up of different component channels like the floodplain and main channel, or even of different parts of the same channel which have quite distinct roughnesses (say if the upper bank of the stream is heavily vegetated but the lower section is bare). The several methods for predicting the discharge from what is termed a 'composite channel', are discussed and compared by Stephenson *et al.* (1991).

The basic method for calculating discharge in a composite channel is to break the channel up into sub-channels, such as the main channel and the floodplain, then combine them into a long Manning's equation. The main problem in estimating discharge for composite channels, relates to what happens at the boundaries of the composite sections, where low velocity flow from the floodplain interacts with high velocity flow in the channel. Where flows of different velocity come together, they create a shear stress as adjacent high and low velocity water particles interact. In reality there is no clear dividing line of low and high flow, rather a transition from one to the other. We simplify the situation by assuming a vertical boundary at the interface of different channel sub-sections (Figure 14). The velocity or discharge can be worked out for the composite channel by applying Manning's equation and treating it as a combination of the different channel sub-sections. The imaginary boundary is not included as part of the hydraulic radius (ie. the wetted perimeter is only where the water is in contact the bed or bank). The likely error in using this method to predict stream discharge is up to +20% for very shallow floodplain flow (floodplain depth/channel depth <0.1), and the error falls to about +5% when the floodplain depth is about half the channel depth. Note that these errors do not work in both directions (ie. they are not ± errors). The method always overestimates the discharge, because the energy losses at the interface between the channel sections are ignored.

A worked example for a composite channel comprising a bench built in an incised channel is given below in *Examples of increased roughness*.

An alternative approach to predicting discharge through vegetated, composite channels is presented by Darby and Thorne (1996), in which Darcy friction factors are predicted and applied in a finite difference model (the channel cross-section is cut into many slices). Application of the technique to the prediction of a stage discharge relationship for the River Severn, England provided

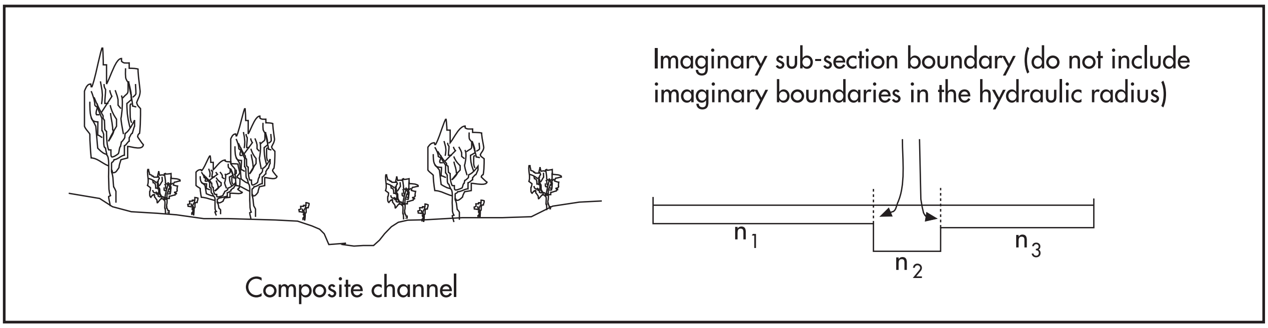


Figure 14. An example of a composite channel. To calculate discharge, you separate the channel into sub-sections with an imaginary vertical line at the channel interface.

discharge estimates that were mostly within 10% of measured values. This technique has not been applied for vegetation other than grasses. It is probably the best method available at present for incorporating the effects of vegetation on flood stage, but it is too complex to use for routine management problems.

1.5. Is it really a control point?

Remember that a control point is anything that creates a backwater. We have now covered two types of control points. The first is the easiest to identify and is created by a reduced channel cross-sectional area. The second is the increased water level due to reach-scale increase in roughness.

If your stream rehabilitation work is to create a backwater, then it in turn must not be within the backwater of a control point further downstream. For example, culverts often act as a control point during high-flow conditions, so if in-channel works are just upstream of a culvert they may have only limited effect on the water depth (Figure 15).

The simplest way to see if you might be working in a backwater zone is to walk downstream a kilometre or two, checking for changes in bed level, narrow deep-channel

The bank queue: an example of a backwater

Backwater from constriction: Consider the queue that forms when only one bank teller is operating. The bank teller acts as the control point and creates a 'backwater' of people queuing to be served.

Lower downstream water level: There is no 'control point' after the teller so it is much quicker to get from the bank teller back out the door of the bank.

First teller working in a backwater: If there are two bank tellers but the first is checking your identification and the second is processing the transaction and handing out the money, it wouldn't matter how fast the first teller was. The line can move only as quickly as the second teller can process the transaction, so by removing the first teller we do not reduce the backwater of people. In this case the first teller is operating within the backwater of the second teller, so the first teller is having no effect on the size of the 'backwater of people'.

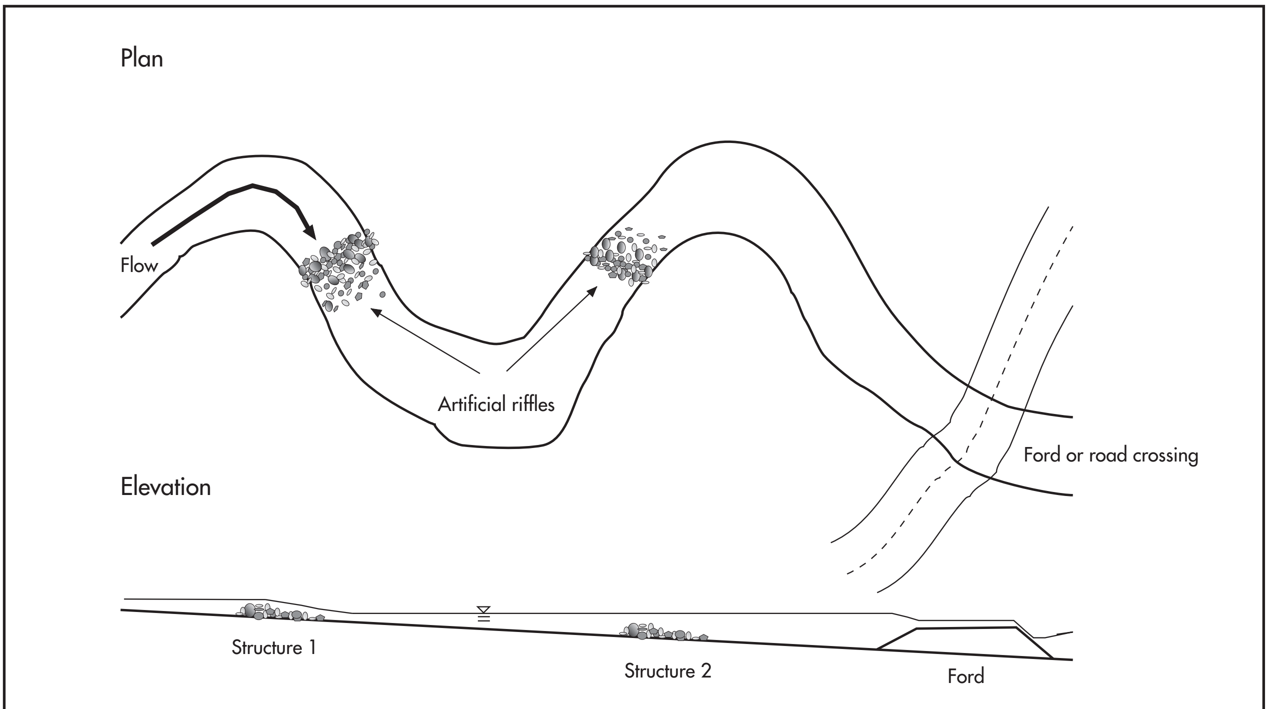


Figure 15. There is no need to be concerned about increasing flood levels if in-channel work is within the backwater of a downstream control point (ie. your structure height plus the critical depth must be below the water level caused by the downstream control). In this case, structure 1 creates a backwater, but structure 2 does not, because it is in the backwater of the road culvert.

sections (ie. constrained channel), culverts, dense vegetation, bridges, low-level crossings and other possible control points. You should apply the methods in the following sections to see if any of these potential controls are creating a backwater in your reach. If you are working in a backwater, you can assume that your rehabilitation work will have no effect on flooding.

The water level downstream of an obstruction will be lower, because once the stream has passed the control point there is no restriction backing up the water (eg. just downstream of structure 1 in Figure 15). This raises the important point that if, during high flow, the water level downstream of the suspected control point is not lower, then either it is not really a control point, or further downstream there must be some other control point, or a combination of roughness elements, that is causing the water to back up (eg. structure 2 in Figure 15).

2. Predicting backwater effects

2.1. Type of flooding

Now that we have covered the basic elements of open-channel hydraulics, we can combine elements to predict the effect of in-channel work on flooding.

First, we have to identify what 'type' of flooding we are concerned about and what sort of in-channel modification the stream rehabilitation project will use. We can then provide various methods for predicting if flooding will be affected and by how much.

It is important to define what we mean by a 'flood'. When river managers talk about 'increased flooding' they usually mean one or other of the following:

- Increasing the maximum flood stage for an extreme event (1 in 20 ARI flood or greater). For example, such and such a treatment will increase flood levels so that more of the town will be inundated by a 1 in 20-year flood.

- Increased frequency of nuisance flooding (that is, the channel capacity is reduced so that out-of-bank flows occur twice instead of once a year).

- Increasing the duration of floods (ie. floods tend to stay on the floodplain for longer).

2.1.1. Extreme event floods

Flooding occurs because the amount of water produced by a storm is greater than the discharge capacity of the stream. During large floods, the floodplain usually carries most of the flow, and only a relatively small proportion of the flood is carried in the main channel. For example, 5–15% of peak discharge (depending on where in the catchment you look) of a 50-year flood on the Murray River will be carried within the main channel, and the rest on the floodplain. The proportion of flow in the channel is likely to increase in smaller streams. Note that most stream rehabilitation work is done in and around the channel, so that since extreme event floods are dominated by floodplain flow, the impact of stream rehabilitation on major floods is not likely to be great.

An exception would be where the channel has been reconstructed to carry extreme flows, eg. artificial channels such as urban streams, or streams with full levee protection. In these cases we can consider the whole reconstructed channel as a compound low-flow and high-flow channel (see example calculation of Artificial bench formation, toward the end of the section).

Increased frequency of minor floods

Increased frequency of out-of-bank flows, or nuisance flooding, is generally the type of flooding that farmers are most concerned about, because it directly impedes access to the floodplain and is considered to reduce the productivity of floodplain farms. In this type of flooding most of the flow remains in the main channel. These small floods can occur several times in one year but are usually restricted to 1 to 5-year events depending on the channel conditions. A clean, straight channel has a greater flow capacity than a natural meandering channel full of woody debris. Stream rehabilitation work is usually undertaken in and around the channel, so it is this type of flood that stream rehabilitation work might affect. The examples in the following section concentrate on flow that is just out-of bank.

Increased flood duration

Flood duration is a significant issue for both the environment and farm protection; for example, a 2-day inundation of a white clover crop will lead to a loss of more than 6% of the annual yield (Maher, personal communication). Equally, some flood persistence is essential for the spawning of several fish species. The time that a flood stays on the floodplain is a function of the discharge capacity of the channel and floodplain, and of the storm event that creates the flood. Predicting increased flood levels for minor or extreme events is quite simple, because it is a function of how much the flow exceeds the discharge capacity of the channel and floodplain, but to determin 'how long' flow is going to exceed capacity is a more complicated story. To predict increases in flood duration from stream rehabilitation projects we need to conduct flood routing for different events before and after the stream rehabilitation work. The flood routing must take into account the changed channel and floodplain capacity.

The conclusion from the Wannon River example is that the smaller capacity channel would have little effect on the frequency of flooding, but a significant effect on flood duration. However, it is unreasonable to compare out-of-bank flow duration for different channel conditions without considering the various types of storms that lead to flooding.

To predict the effect of in-channel work on flood duration you must route a series of flood events of different sizes and types through the treated reach. To do this, you must be familiar with a hydrological flood routing model and have real flow records to compare the effect of pre-and post-rehabilitation conditions on flood duration. The prediction of changed flood duration is not covered further in this manual. However, we do emphasise that **the duration of small floods can be much more important for rehabilitators to consider than the big floods that people usually worry about.**

An example of flood duration for different channel capacities of the Wannon River, Victoria

The flood duration for different channel capacities have been estimated for the Wannon River, Victoria (data provided by Peter Hill) as part of an assessment of a proposal to remove large woody debris (LWD) from the channel (Sinclair Knight Merz, 1997). The effect of reducing or increasing the channel capacity by 25% was investigated in terms of the number and duration of out-of-bank flows. The prediction was based on hydrograph records from 1970 to 1995. The channel capacity is 5,300 m^3/s and, during 1970–95 there were 29 out-of-bank flows. If we **increased** the channel capacity by 25%, to 6,625 m^3/s (say by removing all LWD and straightening the channel), then there would have been only 24 out-of-bank flows during the period. If we **reduced** the channel capacity by 25%, to 3,975 m^3/s (by adding LWD, or remeandering), then the number of out-of-bank flows during the same period would have increased to 34. Therefore, for the period considered, a 25% increase or decrease in the channel capacity resulted in an average change in flood frequency by one more (smaller channel) or one less (larger channel) out-of-bank event every 4 years. This seems to be a small effect on flood frequency in comparison to the significant alterations required to change the channel capacity by 25%.

However, if we look at the **duration** of out-of-bank flow for the three channel capacities, as shown on Figure 16, the out-of-bank flow obviously lasted longer for the smaller channel. It is important to note the relative effectiveness of channel capacity change for different flood events. There appears to be no direct relation between duration of out-of-bank flow and channel size. Consider event No. 21. For the 3,975 m^3/s channel, flow was out-of-bank for 16 days, while the same event in a 6,625 m^3/s channel flow would resulted in out-of-bank flow for just 2 days. This event probably had sustained high flow rather than a sharp peak, or a series of storms that maintained the discharge between 3,975 and 6,625 m^3/s for most of the event. For the small channel, almost all of the event was out of bank (only just) and for the large channel almost all of the event was in-channel (only just). Compare this extreme result with a short, sharp storm shown by event 19, where for a channel capacity of 3,975 m^3/s the out-of-bank flow lasted for 14 days, only 2 days longer than for the 50% larger 6,625 m^3/s channel. For this event, a fair proportion of the flow was probably carried by the floodplains for both the small and large channels, So it is the combined channel and floodplain capacity, not just the channel capacity, that influences the flood duration for this event.

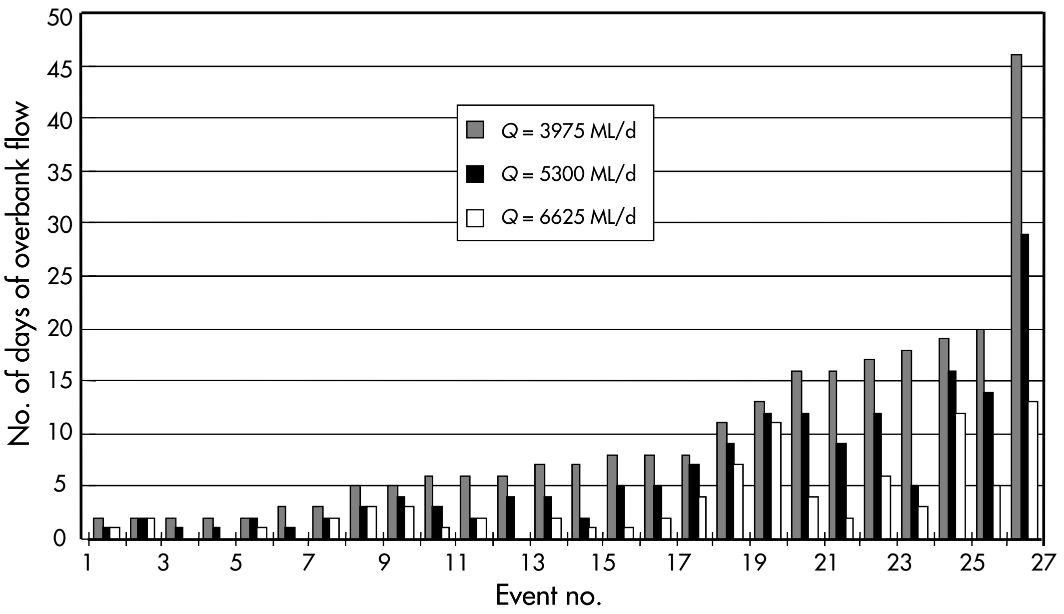


Figure 16. The relationship between overbank flow duration and channel capacity, demonstrated by the flood record for the Wannon River.

Of the three types of flooding that we generally consider (extreme events, increased frequency, and increased duration), stream rehabilitation is most likely to affect increased frequency and duration. The Wannon River example has shown us that we can predict the increase in flood frequency or duration by using historical flow data. Flow data are usually not available, so the approach taken in the following sections is to consider how stream rehabilitation works affect the water level at bankfull condition (that is, does it create a backwater?). Alternatively, we can assess by how much the channel capacity is modified by the work.

The following assessment of the potential increase in water levels is divided into three types of channel obstruction:

- full-width structures such as low weirs;
- partial-width obstructions such as groynes, retards and channel narrowing; and
- general channel roughness such as in-channel revegetation.

2.2. Flooding from full-width structures

The effect of a full-width structure is to reduce the channel cross-sectional area. If the reduction in area is large enough, the structure can control the water depth by forming critical depth conditions over the structure. For a given discharge the minimum depth of flow over a structure will be the critical depth.

Full-width structures that are low compared with the flow depth will be overtopped by a depth of water greater than critical depth and will be 'drowned out'; that is, they will have no direct effect on the local surface water profile other than that due to increased roughness (Figure 17A). As the structure increases in height, it will reach a point where the upstream water level is unchanged, but the depth of flow over the structure is at critical depth (y_c) (Figure 17B). This is the point of maximum structure height with no backwater increase. The depth of water over the structure cannot be lower than critical depth, so if we increase the height of the structure past this point, then the upstream water depth must increase so that critical depth is maintained over the structure (Figure 17C). Only the conditions presented in Figure 17C will produce a backwater from a full-width structure.

We can consider Figure 17C in terms of the energy equation from section 1.2 *Energy*, above. Assuming no energy loss, the energy at point (1) is the same as the energy at point (2):

$$\underbrace{y_1 + \frac{v_1^2}{2g}}_{\text{point (1)}} = \underbrace{y_c + \frac{v_c^2}{2g} + z}_{\text{point (2)}} \qquad (1)$$

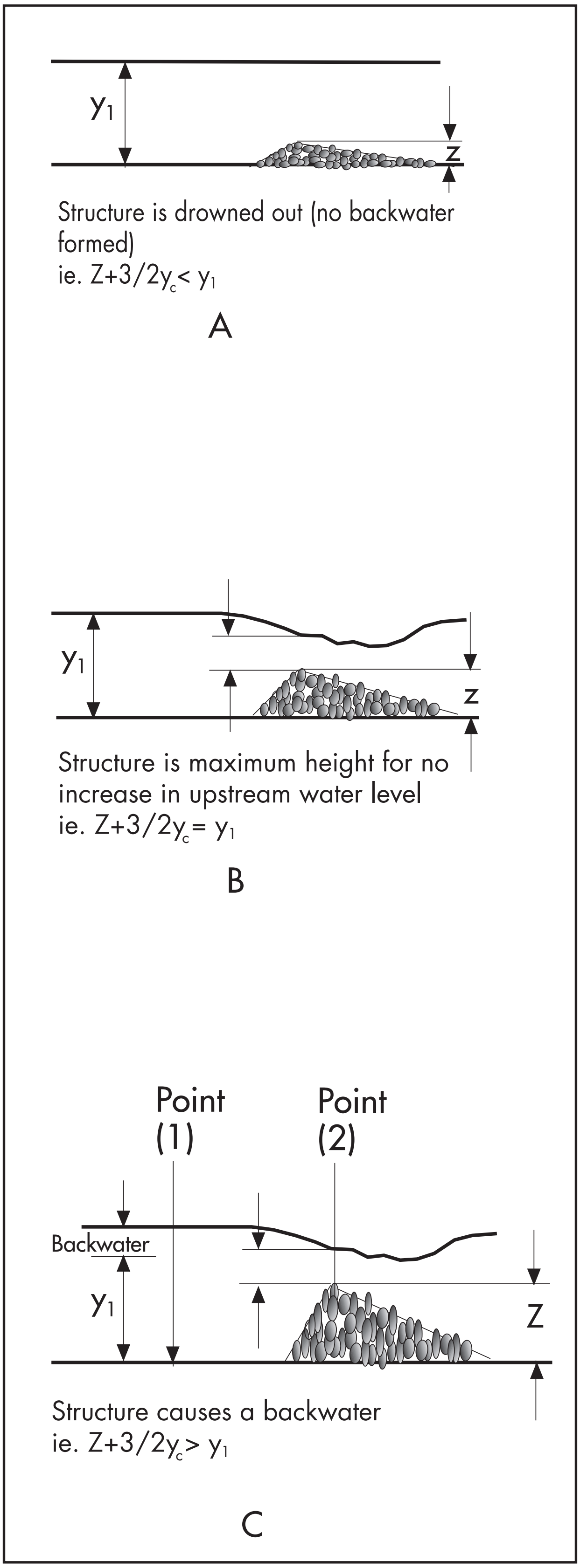


Figure 17. The effect of a full-width structure on water depth. In A, a low, full-width structure is overtopped with subcritical flow, and has little effect on water depth. In B, there is critical flow over a slightly higher structure, but there is still little effect on depth. The structure in C is higher still, and creates a backwater.

For critical depth at point (2) the Froude number = 1:

$$Fr = \frac{v_c}{\sqrt{g y_c}} = 1$$

To get rid of the square-root sign, square both sides of the equation:

$$\frac{v_c^2}{g y_c} = 1^2 = 1$$

Multiply both sides by $y_c/2$ so that we get the velocity head term in the same form as in the left-hand side of equation (1):

$$\frac{v_c^2}{2g} = \frac{y_c}{2}$$

To make the left-hand side look like part of the right-hand side of equation (1) add y_c to both sides of the equation.

$$y_c + \frac{v_c^2}{2g} = \frac{3}{2} y_c \tag{2}$$

Do you recognise the left-hand side of equation (2)? It is the velocity head and elevation head in equation (1). Substitute the right-hand side of (2) into the appropriate part of (1).

$$y_1 + \frac{v_1^2}{2g} = \frac{3}{2} y_c + z \tag{3}$$

Upstream of where a full-width structure creates a backwater, the water has a greatly reduced velocity, such that the velocity head term ($v_1^2/2g$) in (3) becomes small when compared with the elevation head term (y_1). To prove this to yourself, assume a velocity of 0.5 m/s upstream of the full-width structure. The velocity head term $v_1^2/2g$ becomes $0.5^2/(2 \times 9.8) = 0.013$ m, hence the velocity head contributes just over 1 cm to the total energy head upstream of the structure. We are lucky if we can measure the water level to within ±5 cm, so the effect of the velocity head can be neglected.

So equation (3) now becomes;

$$y_1 = \frac{3}{2} y_c + z \tag{4}$$

If we consider Figure 17B, the case of maximum height of the full-width structure without affecting water level, and equation (4), then the maximum height of the structure (so that no backwater is created) is the design depth of flow (bankfull) minus 3/2 times the critical depth for the bankfull discharge.

To avoid a backwater make sure $Z \leq y_{bf} - 3/2\, y_c$

This result is for ideal conditions. In reality there are energy losses, channels are not rectangular, and structures are rarely 'ideal'. By using the ideal case we will be overestimating backwater levels. Consider this over estimation as a 'safety factor'.

Progress so far...

We can predict that a backwater will form at a full-width structure, and how high the backwater will be, if we know the structure height (z), design depth (bankfull depth), and the critical depth (y_c) calculated from the discharge at design depth. We will use the following example to illustrate how it is done.

A worked example of predicting the effect of a structure on flooding

Here is a fully worked example of how to predict the influence of a structure on flooding. The following data will be used in the example:

The stream for our example is a small, mid-catchment, moderate-sloped ephemeral stream that has a degrading bed. The rehabilitation strategy calls for the construction of a rock weir about 1.0 m high. It is hoped this structure will stabilise the bed and create a large permanent pool to maintain fish populations during the periods of no flow.

Details:

- uniform, incised channel which is assumed to be rectangular in shape
- width (w): 20 m
- bankfull depth(y_{bf}): 1.5 m
- slope (S): 0.005
- roughness: channel has patches of cumbungi reed, and there are two large trees which have fallen into the channel and obstruct about 15% of its cross section. Estimated Manning's n before treatment: 0.06
- sinuosity: 1.2
- hydraulic radius (R): $A/P = (20 \times 1.5)/(20 + 1.5 + 1.5) = 1.30$ m
- design height of full width structure (z): 1.0 m

Step 1: Design depth

Structures will have a variable influence on depth depending on the flow. Consider a log sill across a stream: at low-flow it acts as a dam, but at high flows you often cannot tell where it is because it is drowned-out. Our first step must be to determine what flow is important in terms of secondary effects. For example, we may be concerned about changes to the flow depth around bankfull level, or we may care about some higher flow which threatens infrastructure such as when levees are overtopped. As the flow depth increases above the height of the structure, the effect of the structure on flow is reduced because the proportion on the channel cross-section that it takes up is reduced. The minimum depth we are usually concerned about is bankfull, because changes to flow conditions below this discharge are pretty well contained in the channel. So for this example our design depth is the bankfull depth.

For our example stream the design depth = 1.5 m

Step 2: Is the flow supercritical?

You will recall that supercritical flow is low depth, high velocity (remember supercritical flow is like superman—faster than a speeding bullet). If the flow is supercritical at bankfull discharge and the full-width structure is not higher than bankfull, then no backwater will be created.

As supercritical flow passes over a structure, it will have a local increase in water depth, but by definition of supercritical flow, this disturbance will not propagate upstream (Figure 18). In this case the full-width structure acts simply as a bed roughness feature.

Only steep gradient, shallow streams are likely to have supercritical flow during bankfull conditions. For most streams, the flow will be subcritical (deeper then critical depth) during bankfull conditions.

For our example stream:

Use Manning's equation to calculate the bankfull velocity

$$v = \frac{R^{(2/3)} S^{(1/2)}}{n}$$

$$v = \frac{1.3^{(2/3)} 0.005^{(1/2)}}{0.06}$$

so $v = 1.4$ m/s

Now

$$Fr = \frac{v}{\sqrt{gy}}$$

when y = our design depth or bankfull (y_{bf}) = 1.5 m

$$Fr = \frac{1.4}{\sqrt{9.8 \times 1.5}}$$

For our stream, $Fr = 0.37$ which is less than one. Our flow is therefore subcritical and we need to proceed to the next step

Step 3: Will the water depth increase when the structure is built?

Recall from earlier (equation 4) that if the structure influences the upstream water depth, then flow over it will be at critical depth (Figure 18) and the upstream water level will be 3/2 times the critical depth plus the structure height (Chadwick and Morfett, 1993).

The accurate prediction of flow depths requires detailed analysis of the channel and the shape of the full-width structure. For a quick estimation we assume the channel is rectangular, and the full-width structure is horizontal, with a flat surface like a broad-crested weir. Using different shapes of full-width structure will have only a small effect on water levels. The small variation in water level is within the error bounds of this process so it is not worth investigating alternative weir structures. So long as the weir is not steeply angled into the channel like a V-notch weir the predictions here are appropriate.

For our example stream:

The bankfull velocity calculated in the previous step = 1.4 m/s,

area $A = 30$ m^2

therefore bankfull discharge (Q_{bf}) = 42 m^3/s

The critical depth for this flow is;

$$y_c = \left(\frac{q^2}{g}\right)^{1/3}$$

remember that the discharge per unit width for a rectangular channel $q = Q/w$, ie.

$$y_c = \left(\frac{(42/20)^2}{9.8}\right)^{1/3} = 0.76 \text{ m}$$

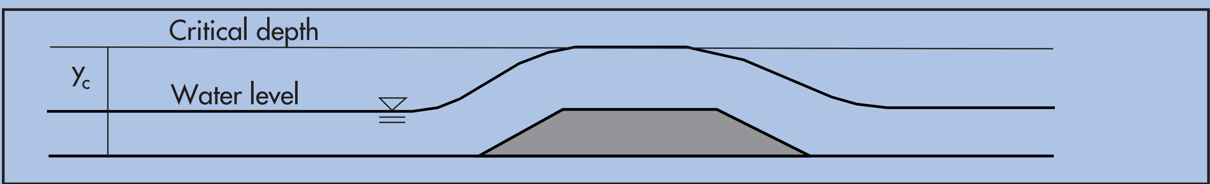


Figure 18. Structures lower than critical depth will not form a backwater for supercritical flow.

Therefore, the maximum height upstream is $H = 3/2 \times 0.76 =$ 1.15 m

The total water depth is 1.15 + the weir height = 2.15 m. However, bankfull depth is only 1.5 metres so this structure will cause an increase in water level at bankfull depth.

Remember that to avoid an increase in bankfull depth, the maximum height of the structure is (1.5 – 1.15) = 0.35 cm

For our example we want to know what is the increase in water level because of the structure. To do this we need to look at the interaction of the floodplain and channel.

Step 4: Calculate the increase in water depth

We know from step three that if the channel continued to extend past the bankfull level, the new depth would be 2.15 – 1.5 = 0.65 m above the old bankfull level (Figure 19A). However, in reality once we reach bankfull height the flow spills out into the floodplain so the discharge is shared between the floodplain and the channel (Figure 19B). If the flow is shared, then the in-channel flow is less than before, because some of this flow is carried on the floodplain. The discharge is split between the channel and the floodplain, the depth of flow over the structure is still critical, but will be lower than calculated because the proportion of flow in the channel is lower. To work out the water depth for this composite channel we need to work out the new critical depth for the reduced channel discharge.

If our floodplain rises gently from the bankfull level at a gradient of 1% (ie. a 1 m increase in height for every 100 m distance from the channel), then we can work out the cross-sectional area of the floodplain flow as a function of the depth of flow.

Remember the equation for Froude number:

$$Fr = \frac{v}{\sqrt{gy}}$$

$$v = Q / A$$

so

$$Fr = \frac{Q}{A\sqrt{gy}}$$

We know the discharge—it is our pre-rehabilitation bankfull discharge $Q = 42$ m^3/s—but the area must now also take into account the floodplain. The depth y will be our new water depth and, because this is critical depth over the full width structure, $Fr = 1$.

The cross-sectional area (A) is a function of the water depth and channel shape,

$A = wy + [100(y - 0.5)(y - 0.5)]$

(0.5 is the difference in height between the top of the weir and the top of the channel).

The first part is the area of the channel up to the full height of water, and the second, the area of the floodplain on both sides of the channel, where the area of one floodplain would be approximately half the height of water above the channel (y – 0.5) times the extent of water on the floodplain (y – 0.5 times 100 (ie. 1% slope)).

So, for critical depth of the channel and floodplain system

$$Fr = 1 = \frac{42}{(20y + 100(y - 0.5)(y - 0.5))\sqrt{9.8y}}$$

We solve this equation by trial and error for y to produce an Fr of 1

Trial	y (m)	Fr
1	0.6	1.33
2	0.7	0.89
3	0.65	1.09 (close enough to a critical flow of 1)

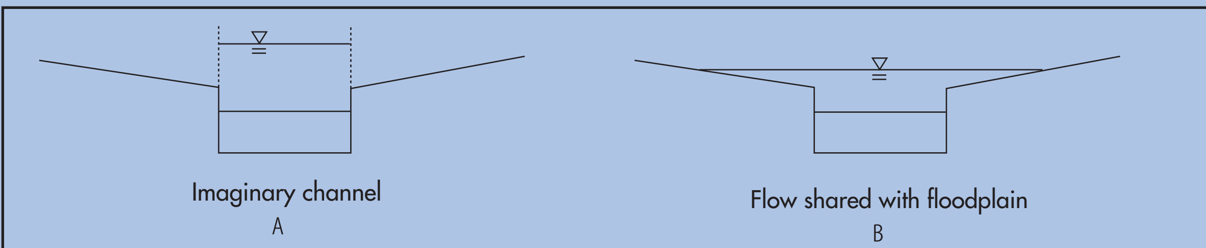


Figure 19. How flow is shared between channel and floodplain.

So the critical depth over the full-width structure is 65 cm: therefore, the depth in the channel just upstream is 3/2 x 0.65 = 0.98 m: ie. the increased water level from the full-width structures is about (0.98 – 0.5) 0.5 m when the floodplain flow is also taken into account.

Step 5: Is this increased depth important?

If your full-width structure is likely to increase local water depths, you need to consider the implications of the increase in water depth and at what point it becomes a significant concern. For this example we will say that the increase in depth is acceptable, but we are concerned about how far upstream the influence will extend.

Step 6: What is the extent of the backwater?

Estimate the backwater extent by assuming a horizontal line from the water level just upstream of the weir until it reaches design flow depth (ie. bankfull).

For our example,

The design flow depth is y_{bf} (y = 1.5 m)

the backwater is (1.98 – 1.5) ~ 0.5 m

the channel slope is 0.005 (assume the water surface without the structure would have the same slope as the bed)

so the upstream extent of the backwater = 0.5/0.005 m

upstream extent is 100 m, but remember that the real extent will be further upstream than this quick approximation.

Step 7: How much sooner will it now flood?

We have shown how to roughly estimate the increase in water level for a given discharge when we place a full-width structure in the channel, but an equally valuable question is how much more frequently will out-of-bank flow (ie. flooding) occur because of the structure? To answer this question we need a time-series of stream flow so we can compare the frequency of the current bankfull condition with the new bankfull condition. In reality, such data are rarely available, but it is still valuable to compare pre-rehabilitation and post-rehabilitation bankfull discharges.

For our example stream,

the pre-rehabilitation discharge is 42 m^3/s

from steps 3 and 4 above. The maximum post-rehabilitation in-channel (ie. bankfull) discharge will occur when the water level is at bankfull level and we have critical flow over the full-width structure. Therefore, the depth of flow just upstream of the full-width structure is 3/2 times the critical depth, or y_c = 2/3 (bankfull depth – structure height)

$$y_c = \left(\frac{q^2}{g}\right)^{1/3} = \frac{2}{3}(y_{bf} - z)$$

The only unknown is discharge, so we can solve the following by trial and error to give the new bankfull discharge for a critical depth of 0.33

$$y_c = \left(\frac{(Q/20)^2}{9.8}\right)^{1/3} = \frac{2}{3}(1.5 - 1) = 0.333$$

We solve this equation by trial and error for Q

Trial	Q (m^3/s)	y_c
1	30	0.61
2	10	0.29
3	12	0.33 (this is the discharge for critical depth)

Therefore, by placing a structure 1 m high in a 1.5 m deep channel, the channel will now flow bankfull at just 12 m^3/s upstream of the structure, whereas before the treatment the discharge was 42 m^3/s before bankfull conditions were achieved.

In summary, we can estimate whether or not a full-width structure will have an influence on water depth by comparing the structure height plus 3/2 times the critical depth with the design height (bankfull). If we see that out-of-bank flow will occur we can predict the new depth of water for simple cross-sections (including floodplain), based on critical depth over the full-width structure.

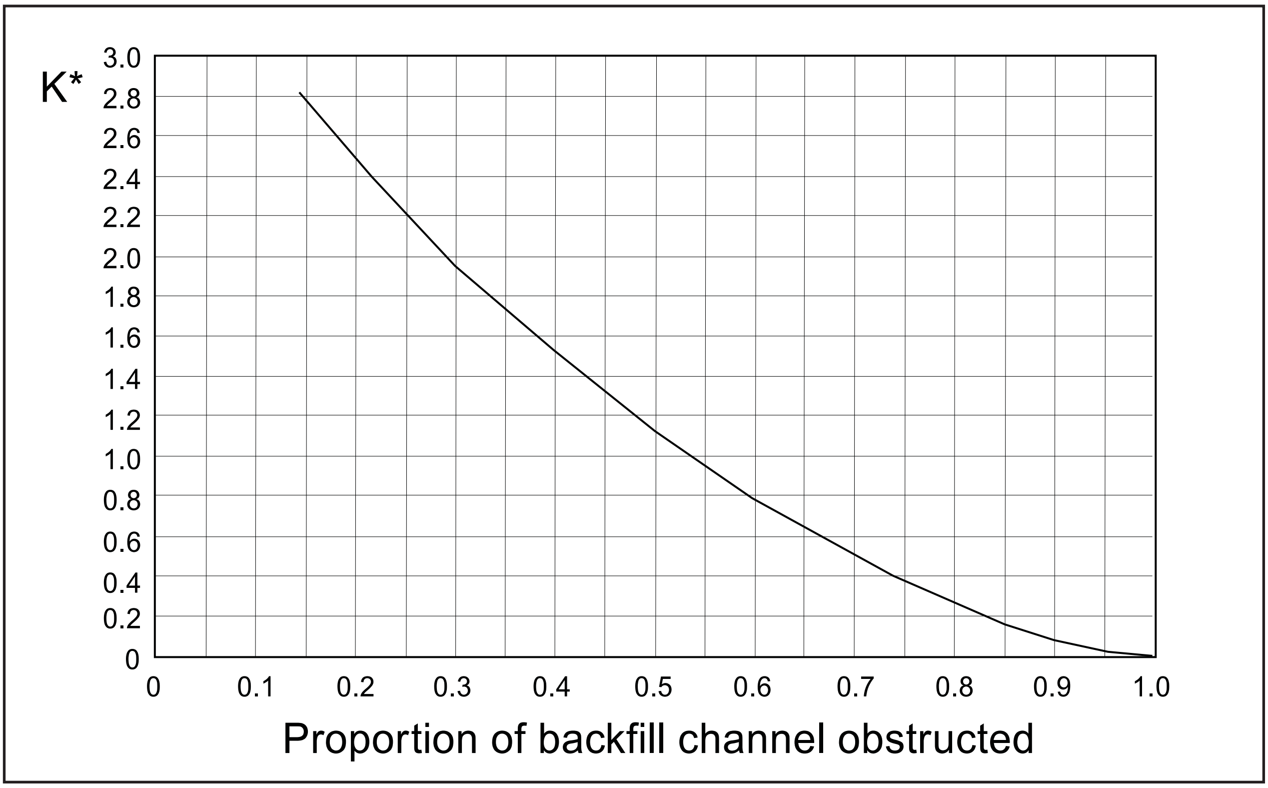


Figure 20. Backwater coefficient (K^*) for a given proportion of obstruction (modified from Bradley, 1970). Please note that this curve is an approximation only. Various corrections can be made to the curve to improve its accuracy (see Bradley, 1970, figure 6, p 14).

2.3. Increased flooding from channel constrictions

Local channel constrictions may affect the water profile. We can constrict the channel using a number of different stream rehabilitation tools, such as full height groynes or by narrowing the channel. In some cases, the constricted channel can act as a control and produce a backwater. We consider only structures that extend to the full depth of flow, so if you make channel changes that will be submerged during high flow their effect on flow depth can be treated as reach-scale roughness elements, as covered in the next section.

We will consider two cases where the channel is constricted;

- point type constriction (eg. a large, impermeable groyne extending into flow)
- gradual type constriction (eg. channel has been narrowed to bankfull height by depositing imported fill)

2.3.1. Point type constriction

Consider a large structure such as a groyne extending into the channel. The flow is rapidly contracted, and a backwater upstream can be produced (Figure 21). A quick approximation of backwater depth can be achieved by using a formula of Bradley (1970) for estimating backwater created by bridge abutments:

$$h = 3.28K^* \times \alpha \frac{v^2}{2g}$$

where

h = backwater level or increase in water level (y) due to the constriction;

K^* = the total backwater coefficient (see below) ;

α = the velocity correction coefficient (assumed value of 1.15 after Henderson, 1966);

v = the velocity in the constriction (for that type of structure); and

g = acceleration due to gravity (9.81 m/s^2).

The total backwater coefficient K^* is comprised of a base value (K_b) estimated from Figure 20 for the percent of channel opening, with additional corrections for the degree of eccentricity, skewness of structure to flow and the effect of bridge piers. For a quick approximation, it is acceptable to set the value of K^* to the base value (K_b).

A worked example of how to calculate the backwater created by a groyne

Using the same stream as for the example in the previous section, we will replace the full-width structure with a groyne that extends 4 m into the channel. This gives a channel opening of 80% or 0.8 (ie. 16/20) of the full width. From Figure 20 this gives a K_b value of 0.55, which we will adopt for the K* value.

$\alpha = 1.15$

Calculate v as the average velocity through the opening using Manning's equation assuming the flow depth to be bankfull at the obstruction.

$$v = \frac{R^{(2/3)} S^{(1/2)}}{n}$$

The hydraulic radius is now (16 × 1.5/(16 + 1.5 + 1.5)) = 1.26

$$v = \frac{1.326^{(2/3)} 0.005^{(1.2)}}{0.06}$$

so $v = 1.4$ m/s

Now calculate the backwater

$$h = 3.28k^* \times \alpha \frac{v^2}{2g}$$

$$h = 3.28 \times 0.55 \times 1.15 \frac{1.4^2}{2 \times 9.8}$$

$h = 0.207$ m, or a backwater of 21 cm (that is, the water surface elevation upstream of the groyne increases by 21 cm).

2.3.2. Gradual channel constriction

The smooth transition from a wider to narrower cross-section can result in critical flow depth at the new cross-section if the channel has been sufficiently constricted. (Figure 22). The production of a backwater in this case is the same mechanism as for a full-width structure. In both cases the structure reduces the channel cross-sectional area, critical flow depth occurs in the constriction, and a backwater is formed upstream of the constriction.

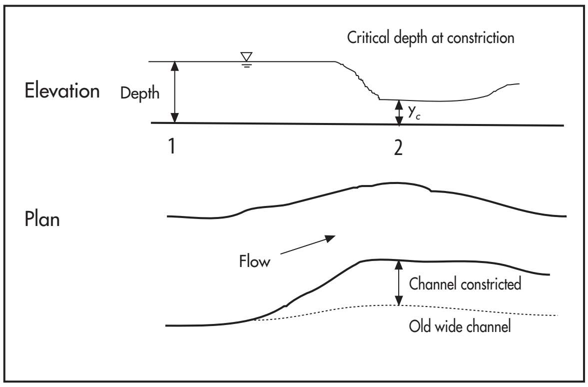


Figure 22. Channel constriction can create a backwater.

For points (1) and (2) in Figure 22, a backwater will be formed when point (2) is narrow enough to create critical flow depth.

Assuming no energy loss, the energy equation relating point (1) and (2) is:

$$y_1 + \frac{v_1^2}{2g} = y_c + \frac{v_c^2}{2g}$$

From the full-width structures section above this can be rewritten as:

$$y_1 = \frac{3}{2} y_c$$

An example of the method is shown in the next box.

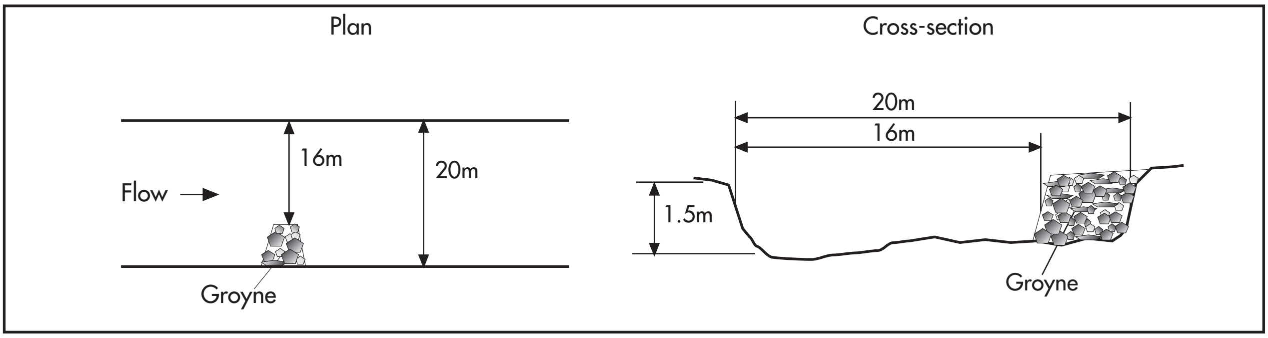


Figure 21. The dimensions of the groyne and channel under consideration.

A worked example of the backwater from a gradual constriction

In this example, we will consider the channel from the full-width structure example above. However, instead of a full-width structure we will gradually narrow the channel from 20 m to 10 m. We will see if: 1) if a channel constriction will produce a backwater; 2) how big will the backwater be for the pre-rehabilitation bankfull flow; and 3) how much has the bankfull flow capacity been reduced.

Step 1: Design depth

For the analysis of floods, adopt bankfull depth as the design depth.

For our example stream:

the design depth = 1.5 m

Step 2: Is the flow supercritical?

As with full-width structures, no backwater will be created at a channel constriction if the upstream flow is supercritical.

For our example stream:

Use Manning's equation to calculate the pre-rehabilitation bankfull velocity

$$v = \frac{R^{(2/3)}S^{(1/2)}}{n}$$

From the full-width structure section

$$v = \frac{1.3^{(2/3)}0.005^{(1/2)}}{0.06}$$

so v = 1.4 m/s

Now

$$Fr = \frac{v}{\sqrt{gy}}$$

when y = our design depth or bankfull (y_{bf}) = 1.5 m

$$Fr = \frac{1.4}{\sqrt{9.8 \times 1.5}}$$

then for our stream Fr = 0.37 which is less than one. Therefore, our flow is subcritical and we need to go to the next step.

Step 3: Will a backwater form?

We assume that the flow is of critical depth at the narrowed section of channel, then the water level upstream is y_1 in the equation .

$$y_1 = \frac{3}{2}y_c$$

For our example stream:

Bankfull velocity (without the channel narrowing) = 1.4 m/s,

A = 30 m^2

therefore bankfull discharge (Q_{bf}) = 42 m^3/s

We need to calculate the critical depth for this discharge at the narrowed section of channel.

$$y_c = \left(\frac{q^2}{g}\right)^{1/3}$$

Remember that the discharge per unit width q = total discharge (Q)/width (w), therefore:

$$y_c = \left(\frac{(42/10)^2}{9.8}\right)^{1/3} = 1.22\text{ m}$$

Therefore, the maximum height upstream is $y = 3/2 \times 1.22 =$ 1.82 m.

1.82 m is greater than the bankfull depth of 1.5 m, so narrowing the channel will create a backwater that is 0.32 m above the water surface in an unmodified channel.

Step 4: Calculate the increase in water depth

Note from step 3 that the critical depth for our constricted channel is less than the channel depth (ie. 1.22 m < 1.5 m). This means that, at the constriction, the water level is actually below the bankfull level, but just upstream it will rise to 3/2 times the critical depth to be about 30 cm above bankfull level (182 – 150 ~ 30 cm). Because all flow is within the channel at the constriction (ie. critical depth < bankfull depth) there is no need to calculate a new critical depth and corresponding water depth like the full-width structure example. For this case, the channel would have to be constricted from 20 m to 7.5 m before the critical depth exceeds the bankfull depth and we need to calculate a new critical depth including floodplain flow, like we did for the full-width structure example.

Step 5: Is this increased depth important?

Consider the influence of the effect of an increase in the local water level, and what it may affect. For the sake of our example we will say that 30 cm is of concern, so we will consider the upstream extent.

Step 6: What is the extent of the backwater?

Estimate the backwater extent by assuming a horizontal line from the water level just upstream of the constriction until it reaches bankfull flow depth.

For our example:

The design flow depth is bankfull ($y = 1.5$ m)

the backwater is 0.32 m

the channel slope is 0.005 (assume the water surface has the same slope)

so the upstream extent of the backwater = 0.32/0.005

upstream extent is 64 m

remember that this is the absolute minimum extent of backwater

Step 7: How much sooner will it now flood?

We have shown how to roughly estimate the increase in water level for a given discharge when we constrict the channel but an equally valuable question is how much have we reduced the channel capacity by constricting it? The answer is the same as for step 7 in the example of calculating the backwater for a full width structure.

For our example stream:

the pre-rehabilitation discharge is 42 m^3/s.

From steps 3 and 4 above, the maximum post-rehabilitation in-channel (ie. bankfull) discharge will occur when the water level is at bankfull level and we have critical flow through the constriction. Therefore, the depth of flow just upstream of the full-width structure is 3/2 times the critical depth, or $y_c = 2/3$ (bankfull depth)

$$y_c = \left(\frac{q^2}{g}\right)^{1/3} = \frac{2}{3} y_{bf}$$

the unknown is discharge, so we can solve the following by trial and error to give the new bankfull discharge

$$y_c = \left(\frac{(Q/10)^2}{9.8}\right)^{1/3} = \frac{2}{3} \times 1.5 = 1.0$$

We solve this equation by trial and error for Q

trial	Q (m^3/s)	y_c
1	40	1.17
2	25	0.86
3	30	0.97 (close enough)

Therefore, by constricting the channel width from 20 m to 10 m, the channel will now flow bankfull at 30 m^3/s whereas before the treatment the bankfull discharge was 42 m^3/s.

2.4. Flooding from increased channel roughness

In the case of reduced channel capacity from increased roughness, individual roughness elements (eg. individual snags) do not produce a noticeable backwater, but the cumulative effect of the elements reduces the capacity of the channel, and water depth is subsequently increased for a given discharge. If we think about stream energy being either kinetic energy (related to flow velocity) or potential energy (related to flow depth), channel roughness causes kinetic energy loss through turbulent flow around the roughness elements. Hence, a greater energy in the form of flow depth is required for the same discharge to compensate for the lost kinetic energy.

How can roughness create a backwater?

Remember our bank teller backwater? Imagine if all the staff members in the bank stood in a line to introduce themselves, shake your hand and say 'have a nice day', after you completed your transaction. It takes only a moment to greet each customer, but the cumulative effect of this job creation scheme slows your exit from the bank, and could create a backwater of people. In this case your exit from the bank is controlled by human 'roughness elements' rather than the speed of the teller. The roughness is a general roughness rather than a point control.

The best condition to maximise flow conveyance is a clean straight channel with no roughness features, and limited hydraulic diversity (Figure 23). Most stream rehabilitation strategies improve the instream habitat by increasing the hydraulic diversity of the flow. By increasing the hydraulic diversity we introduce more roughness into the flow, so the discharge capacity of the stream decreases. Urban streams like the one in Figure 23 have been constructed for a design discharge based on a design roughness. If we undertake instream work we will increase the channel roughness and effectively reduce the channel capacity. The stream rehabilitation strategy can be designed so that channel roughness is not increased beyond a pre-determined maximum acceptable limit. An example where this strategy has been adopted is Wildcat Creek,

Figure 23. To achieve maximum flow conveyance, many streams have been cleared and straightened, as in this example of Downfall Creek in Brisbane.

Richmond, California, where vegetation is permitted to grow within the flood control levees until it reaches a density at which it is deemed to be affecting a design flood stage (a Manning's n of 0.07). At this point the vegetation is thinned.

For stream rehabilitation we need to be able to predict the decrease in the channel capacity due to introduced elements. The most straightforward way to achieve this is by predicting the likely change in Manning's n from the proposed work. (Manning's equation and a method for predicting n were introduced in *Selecting a design discharge*, Natural channel design, this volume). The problem with this approach is that the use of Manning's n assumes an average roughness over the channel reach, so the drag force associated with large isolated roughness elements (ie. snags) is not well represented unless we consider the roughness at many cross-sections that are close together, such that the distance over which the average roughness is applied is small. This level of computation can be achieved with computer models, but to undertake these calculations by hand would be very time-consuming. Detailed analysis is usually required only for limited cases and for urban streams, so a general reach average roughness is probably going to be suitable for most stream rehabilitation work.

2.4.1. Rules of thumb for estimating increased flooding due to increased channel roughness

Some basic rules on the hydraulic influence of channel obstructions have been suggested by researchers. An example is the 10% rule of Gippel *et al.* (1992), who suggested that if less than 10% of the channel cross-section was obstructed by LWD then the effect on stage would be negligible. This rule was derived from a flume study by Young (1991) and supported by field work. To apply the 10% rule consider a slice across the stream. If less than 10% of the area of the slice is blockage (eg. LWD), then the blockage will not cause a local control point that can affect water levels, but rather will act as a roughness element.

The work by Gippel *et al.* (1992) suggested that up to three obstructions could be placed in line with the streamflow without causing the cumulative backwater effect that would result if the backwaters from individual obstructions were added together (see Figure 53 in *Management of large woody debris* in Intervention in the channel, this Volume). This is due to the wake effect behind an in-channel object, which shields a downstream obstruction from the direct force of the flow. The same could be said for a groyne or retard field where the first structure has a pronounced effect on flow hydraulics but subsequent structures simply maintain rather than add to the altered flow conditions. Gippel's 10% rule is applied for isolated obstructions. However, if stream rehabilitation occurs on a reach scale it is convenient to consider reduced channel capacity in terms of an increase in the average reach roughness. The following examples illustrate how to do this using Manning's equation. Shields and Gippel (1995) provide a more accurate approach for assessing the hydraulic effect of LWD.

2.4.2. Examples of increased roughness

Let us consider three examples of stream rehabilitation works in which general roughness will increase:

- bendway weirs are added to an upper catchment stream
- an artificial bench is formed to move the point of attack away from an eroding bend (this differs from the constriction example because the bench does not extend the full height of the channel)
- revegetation of the banks of the channel in Figure 23.

Calculating the effect of increased roughness caused by bendway weirs on channel flow capacity

This is a real example, from a rehabilitation site on Pappinbarra Creek, a tributary of the Nambucca River on then north coast of New South Wales.

The stream has the following characteristics:

width = 25 m

depth = 0.8 m

bed slope = 0.01

sinuosity ≈1.2 at the point of works

bed material = gravel and cobble $D_{50} \approx$ 20 mm

bendway weirs = logs ~ 0.3 m diameter, that extend about 8 m into the channel

Step 1: What is the design depth?

As previous for examples, we will adopt the bankfull height as the design depth; ie. y = 0.8 m.

Step 2: What is the pre-rehabilitation Manning's *n*?

To select a pre-rehabilitation Manning's n we will compare n values from Chow's table, and from Cowan's method (see *Selecting a design discharge* in Natural channel design, this volume for a discussion of Manning's n and the relevant tables).

From Chow's table: we have a 'natural stream: clean, winding, some pools and shoals, some weeds and stones', normal n value = 0.045

According to Cowan's method, we can estimate components of Manning's n for bankfull flow.

Material	n_0	0.028	(coarse gravel)
Irregularity	n_1	0.005	(minor irregularity)
Cross-section	n_2	0.000	(gradual cross section variations)
Obstructions	n_3	0.000	(no obstructions)
Vegetation	n_4	0.010	(low vegetation)
Meandering	m	1	(low sinuosity)

Manning's $n = (n_0 + n_1 + n_2 + n_3 + n_4)m$

Therefore, for this channel during bankfull conditions Manning's n from Cowan's method is 0.043

The Chow and Cowan Manning's ns compare well: n is set at 0.045

Step 3: Predict design discharge

Use Manning's equation predict the pre-rehabilitation discharge for the design depth:

For our example stream :

$$v = \frac{R^{2/3}S^{1/2}}{n}$$

and $Q = VA$

so

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

$$Q = \frac{(25 \times 0.8)\left(\frac{25 \times 0.8}{25 + 0.8 + 0.8}\right)^{2/3} 0.01^{1/2}}{0.045}$$

So the pre-rehabilitation $Q_{bf} = 36.7\ m^3/s$

Step 4: Estimate a new Manning's *n*

We need to estimate a post-rehabilitation Manning's n using both the Chow table and Cowan method.

From the Chow table we now have a natural channel: minor stream type 4: 'clean, winding, some pools and shoals, more stones', which conforms to a Manning's n of 0.05

Using the Cowan method: we are likely to change the 'relative effect of obstructions' (n_3) from negligible to minor, say $n_3 =$ 0.015: which gives a new Manning's n of 0.058.

Both Manning's n values appear reasonable, but we'll adopt the conservative value of 0.058.

Step 5: Predict the new stage

We calculate a post-rehabilitation water level for the pre-rehabilitation design discharge (Q_{bf}); ie. if the design depth was bankfull before the treatment, what will it be after the treatment? We calculate this new water level based on a post-rehabilitation n value from step 4.

For our example stream:

$$Q = \frac{(wy)\left(\frac{wy}{w + 2y}\right)^{2/3} S^{1/2}}{n}$$

$$36.7 = \frac{(25y)\left(\frac{25y}{25 + 2y}\right)^{2/3} 0.01^{1/2}}{0.058}$$

Solving for depth (y) by trial and error:

trial	y (m)	Q (m^3/s)
1	0.9	34.52
2	1.0	40.95
3	0.94	37.0 (close enough)

So when flow is around bankfull height we can expect an increase in water depth through the reach of around 14 cm (0.94 – 0.80 m). The steep slope of the stream means that this increase in depth will not extend far upstream (0.14/0.01 = 14 m).

In reality, the out-of-bank depth will not be the full 14 cm, because once flow becomes out-of-bank, it quickly spreads and the effective area of the channel is much larger. To calculate the actual flow depth, we have a composite channel where the Manning's n and shape of the main channel are very different from the roughness and shape of the floodplain. This condition of a composite channel is presented in the next artificial bench example below.

Step 6: What is the new channel capacity?

Another way to think about the effect of stream rehabilitation work is not how much it increases the depth of flow, but how much the channel capacity is reduced.

For our example:

For the Nambucca River, the pre-rehabilitation bankfull depth is 38.5 m^3/s. Use the new Manning's n to work out a post-rehabilitation bankfull discharge.

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

$$Q = \frac{(25 \times 0.8)\left(\frac{25 \times 0.8}{25 + 0.8 + 0.8}\right)^{2/3} 0.01^{1/2}}{0.058}$$

The post-rehabilitation discharge capacity is 28.5 m^3/s, so the construction of bendway weirs has reduced the channel capacity from 38.5 to 28.5 m^3/s or about 25%.

Calculating the effects of artificial bench formation on channel flow capacity

A common treatment for an over-wide channel or shallow low-flow channel within a wide incised trench is to construct an artificial bench to narrow the channel. This treatment is a particularly common approach when flow-retarding devices are constructed on the bench to protect an eroding bank. From a hydraulic point of view, the original rectangular channel has been transformed into a two-stage channel with low-flow confined to the new narrower channel, and high flow carried both in the new channel and over the artificial bench.

We can consider a real example on the Wilson River on the north coast of New South Wales, a stream in which clearing and gravel extraction have caused dramatic over-widening. The Wilson River is a wide expanse with shallow water most of the time, ie. a biological desert. The aim of the rehabilitation project for this site was to narrow the channel using logs to define the new channel boundary and excavate gravel from the point bar to backfill behind the toe protection. The bench has been revegetated and mesh fencing installed on it to encourage deposition of fine sediment and further natural regeneration of vegetation.

Channel characteristics

Slope = 0.003

Bed material = relatively uniform coarse gravel D_{50} ~ 20 mm

The pre-rehabilitation channel was approximately 110 m wide and 3 m deep. The rehabilitation strategy narrowed the channel to approximately 60 m with a log wall 1.2 m high. The area behind the log wall was filled with material from the opposite point bar. Figures 24 and 25 show that the channel has been converted from one rectangular channel into a two-stage channel, where the roughness over the fully vegetated bench is much greater than in the channel.

To determine the hydraulic effect of this rehabilitation strategy, we shall consider the channel in two stages. Note that to construct the bench, the opposite point bar was excavated by an average depth of 0.55 m to win enough fill.

Step 1: Design depth

For our example, at the rehabilitation site the channel is incised, and a natural levee has formed to give a bankfull height of 3 m, but we assume that just upstream the channel is slightly less incised and no levee has formed so that the bankfull depth is only 2 m. We will adopt 2 m as our design depth, because it is at 2 m depth that the channel will flow out-of-bank just upstream of the work.

Step 2: Predict Manning's *n*

We need to predict a Manning's n for the clean channel (this is the same for the pre- and post-rehabilitated channel), and a Manning's n for the vegetated bench.

For our example:

To predict Manning's n, we use the Chow table and Cowan method.

From the Chow table, the clean channel is natural channel, type 4, so $n = 0.045$

The rough bench is: floodplain type 5: heavy stands of timber, a few downed trees, little undergrowth, branches in flood stage: $n = 0.12$.

Using Cowan's method, we get:

	n	Clean channel;	Bench
Material	n_0	0.028	0.028
Irregularity	n_1	0.005	0.005
Cross-section	n_2	0.005	0.005
Obstructions	n_3	0.000	0.040
Vegetation	n_4	0.010	0.050
Meandering	m	1.000	1.000
Total n	n	0.048	0.128

To be conservative we will select the slightly higher n values from the Cowan method (ie. 0.048).

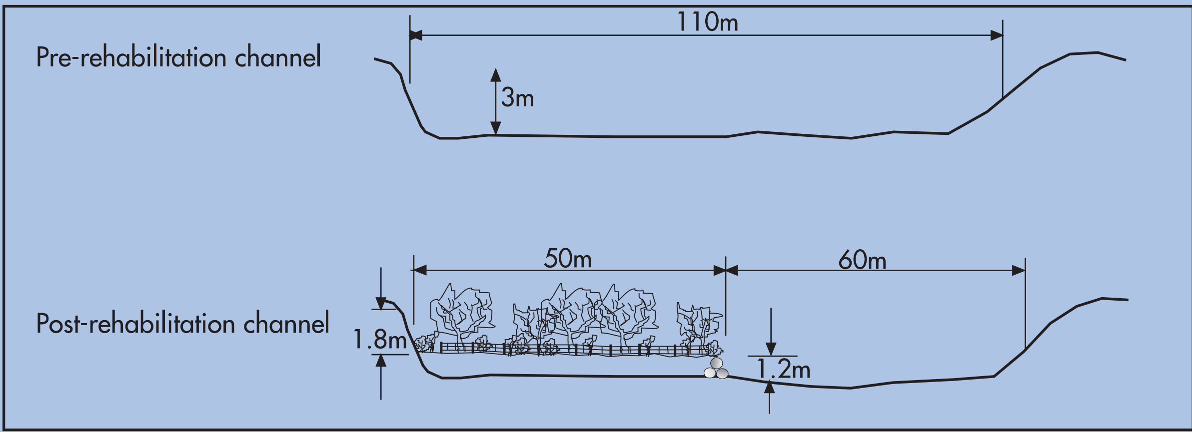


Figure 24. The creation of an artificial bench on the Wilson River.

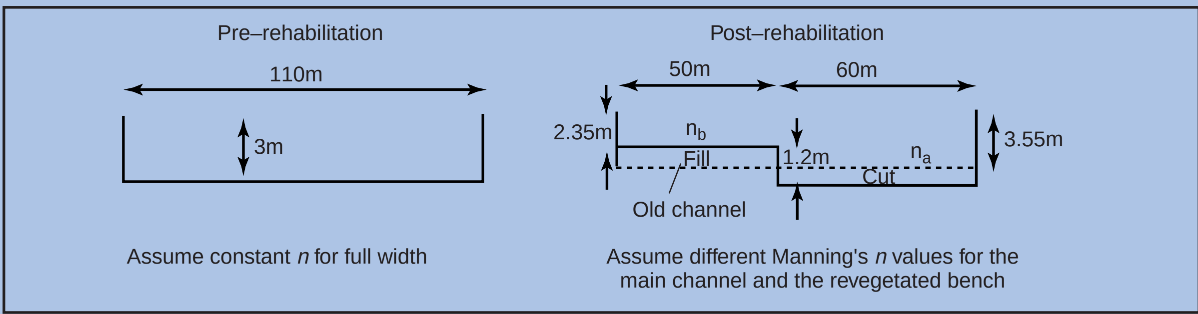


Figure 25. A schematic diagram of the sediment moved to form the Wilson River bench.

Step 3: Pre-rehabilitation discharge

Use Manning's equation to work out the pre-rehabilitation bankfull discharge;

For our example:

$$v = \frac{R^{2/3}S^{1/2}}{n}$$

and $Q = VA$

so

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

$$Q = \frac{110 \times 2\left(\frac{110 \times 2}{110 + 2 + 2}\right)^{2/3} 0.003^{1/2}}{0.048}$$

Therefore, for our design depth, $Q = 390$ m³/s

Step 4: What is the depth of the design flow in the rehabilitated channel?

To predict the depth of the design flow in the post-rehabilitation channel we simply combine the two sections of the channel and solve for the depth by trial and error.

For our example:

If the depth of water in the main channel is y, then the depth over the bench is $y - 1.2$ m.

$$Q = S^{1/2}\left(\frac{A_1 R_1^{(2/3)}}{n_1} + \frac{A_2 R_2^{(2/3)}}{n_2}\right)$$

Note that the wetted perimeter for the sections is only that depth that is in contact with bank or bed material (ie. not the water interface between the two sections).

$$390 = 0.003^{1/2}\left(\underbrace{\frac{(50(y-1.2))\left(\frac{50(y-1.2)}{50+y-1.2}\right)^{2/3}}{0.128}}_{\text{Bench section}} + \underbrace{\frac{(60y)\left(\frac{60y}{60+y+1.2}\right)^{2/3}}{0.048}}_{\text{Clean channel section}}\right)$$

By trial and error we calculate the post-rehabilitation depth for our design discharge of 390 m^3/s.

trial	y (m)	Q (m^3/s)
1	2.6	359.9
2	2.9	437.0
3	2.7	384.9 (close enough)

Therefore, the water level in the rehabilitated reach will be a depth of 2.7 m in the clean channel section and 1.5 m (2.7 −1.2) over the bench. However, recall that we excavated the channel to a depth of 0.55 m to win material for the bench, so the water level relative to the pre-rehabilitation level is (2.7 – 0.55) 2.15 m. The increase in water level relative to the original depth is 15 cm.

Therefore, by narrowing the channel and creating a vegetated bench we have increased the local water level by approximately 15 cm.

Step 5: What is the extent of the backwater?

At the rehabilitation site the banks are about 3 m high, but just upstream they are only about 2 m high. The minimum extent of this 15 cm backwater is 0.15/0.003, or 50 m.

Step 6: What is the new channel capacity?

We can also consider the effect of stream rehabilitation in terms of the reduced capacity of the channel. As in the previous examples, use the new Manning's n to work out a post-rehabilitation bankfull discharge.

For our example:

$$Q = S^{1/2}\left(\frac{A_1 R_1^{2/3}}{n_1} + \frac{A_2 R_2^{2/3}}{n_2}\right)$$

remember that the depth we will be using is the overall 2 m depth plus the 0.55 cm excavation of the channel at this site so the main channel depth is 2.55 m and the depth over the bench is
0.8 + 0.55 = 1.35 m

$$Q = 0.003^{1/2}\left(\frac{(50 \times 1.35)\left(\frac{50 \times 1.35}{50 + 1.35}\right)^{2/3}}{0.128} + \frac{(60 \times 2.55)\left(\frac{60 \times 2.55}{60 + 2.55 + 1.2}\right)^{2/3}}{0.048}\right)$$

so the new discharge for 2 m flow depth is 347 m^3/s, compared with the pre-rehabilitation discharge of 390 m^3/s for the same depth

Calculating the effect of revegetating channel banks on channel flow capacity

Consider the channel in Figure 23. If we were to revegetate the banks of this channel, how would it affect flood levels? Studies have been conducted to enable prediction of Manning's *n* on the basis of tree density and plant type; eg. the trunk of a tall eucalypt will have a lower roughness than a dense shrub. For simplicity and consistency we will make a quick approximation using the same method of predicting Manning's *n* as in the previous examples.

We will consider the channel as a composite, three-part channel, with the centre of the channel being the concrete-lined section with two equal sections on either side as shown in Figure 26. We will assume a stream bed slope of 0.005.

Step 1: Design depth

Increases in flow depth below bankfull will not affect anyone, so let's adopt the bankfull condition as our design depth, ie. design depth = 3 m

Step 2: Predict Manning's *n*

We need to predict a Manning's n for the clean channel (this is the same for the pre- and post-rehabilitated channel), and a Manning's n for the vegetated 'floodplain'.

Using Chow's table we get the following n values

Clean channel	Pre-rehabilitation 'floodplain'	'Floodplain' after revegetation
Concrete 0.015	Floodplain: short grass: $n = 0.030$	Floodplain: medium to dense brush: $n = 0.1$

Using Cowan's method we get;

	n	Clean channel	Pre-rehabilitation 'floodplain'	'Floodplain' after revegetation
Material	n_0	0.010	0.020	0.020
Irregularity	n_1	0.000	0.005	0.005
Cross-section	n_2	0.000	0.000	0.000
Obstructions	n_3	0.000	0.000	0.040
Vegetation	n_4	0.000	0.005	0.050
Meandering	m	1.000	1.000	1.000
total n	n	0.010	0.025	0.115

To be conservative, we adopt the highest values: ie

clean channel $n = 0.015$

pre-rehabilitation floodplain $n = 0.030$

post rehabilitated floodplain $n = 0.115$

Step 3: Pre-rehabilitation discharge

Use Manning's equation to work out the pre-rehabilitation discharge for the design height:

$$Q = S^{1/2}\left(\frac{A_1 R_1^{2/3}}{n_1} + \frac{2A_2 R_2^{2/3}}{n_2}\right)$$

Where area (1) is for the concrete channel and area (2) is for the grassy banks

the profile of the grassy banks is taken as illustrated in Figure 26 (ie. not a rectangle).

So,

$$Q = 0.005^{1/2}\left(\underbrace{\frac{(3\times 1.8)\left(\frac{3\times 1.8}{3+0.5+0.5}\right)^{2/3}}{0.015}}_{\text{channel section}} + 2\underbrace{\frac{(\frac{1}{2}9\times 1.3)\left(\frac{\frac{1}{2}9\times 1.3}{9}\right)^{2/3}}{0.030}}_{\text{revegetated banks}}\right)$$

Therefore, for our design depth, $Q = 51.8$ m³/s

Step 4: What is depth of design flow in rehabilitated channel?

As in the previous example we put the predicted Manning's n for the new channel into the equation and predict the new depth by trial and error.

$$Q = 0.005^{1/2}\left(\frac{(3y)\left(\frac{3y}{3+y+y}\right)^{2/3}}{0.015} + 2\frac{(\frac{1}{2}9(y-0.5))\left(\frac{\frac{1}{2}9(y-0.5)}{9}\right)^{2/3}}{0.115}\right)$$

By trial and error we calculate the post-rehabilitation depth for our design discharge of 51.8 m³/s.

trial	y (m)	Q (m³/s)
1	2.0	43.9
2	2.5	64.8
3	2.2	51.9 (close enough)

So, increasing the channel roughness by revegetating the grassy banks will produce an increase in depth of 2.2 –1.8 = 40 cm.

We can see in Figure 23 that there is a culvert at the downstream end of our treatment reach. We need to determine the flow at which the culvert will create a backwater. At the water depth at which the culvert creates a backwater, the effect of the vegetation on flow depth will be limited. This is because the vegetation will be in the velocity backwater from the culvert. For example, if the culvert creates a backwater for flow depths any shallower than 40 cm below the bankfull depth, then the proposed revegetation will have only limited impact on water depth. From the previous calculations, the revegetated channel will (roughly) flow bankfull for the flow that was previously 40 cm from the top of the pre-rehabilitation channel. If the culvert created a backwater in the pre-rehabilitation channel when the water was 40 cm or more from the top of the bank, then the revegetation will have only a limited effect on flow depth.

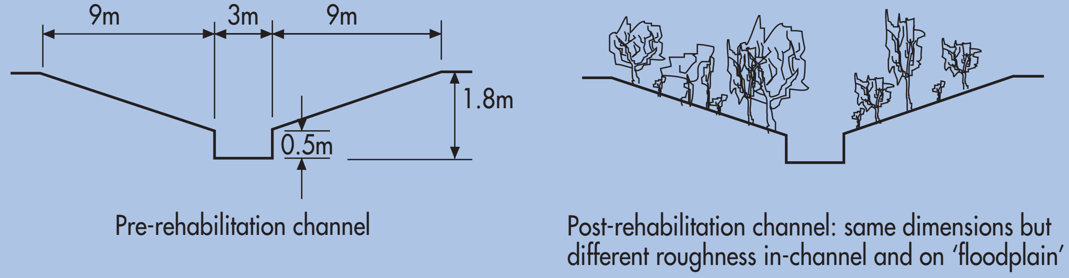


Figure 26. A schematic of the pre- and post-rehabilitation channel for Downfall Creek.

EVALUATION TOOLS

- **Evaluation**

EVALUATION

Evaluation is an extremely important step in the rehabilitation procedure. With no formal check on the success of a project, it is difficult to improve the techniques we use, because we don't even know if they need improving. Through evaluation we can also learn more about little-known aspects of stream systems, such as the habitat preferences of fish. The regular monitoring involved in evaluation also means that damage, or flaws in the project, can often be detected and fixed, where otherwise they may have gone unnoticed.

Although there is no doubt that evaluation is extremely useful, it is extremely rare. This is largely because no one likes to find out that their hard work resulted in failure, especially not to admit it in public. Even if you do decide to bite the bullet and evaluate your work, thorough evaluation can be time-consuming, expensive, and difficult.

There are ways of getting around these dismal-looking problems. Realistically, a stream rehabilitation project should be seen as an experiment (Kondolf and Micheli, 1995). Then there is no shame in admitting that one or all goals were not met. There is a lot to be learnt from failures. Also, not all evaluations need be difficult and expensive (although this tends to be the case for the more informative designs). By limiting your ambitions, it is possible to do a quick and easy evaluation.

This chapter is an extension of Step 10: *How will you evaluate your project?* in the Stream rehabilitation planning procedure in Volume 1. The chapter consists of three sections. *Fundamentals of evaluation design* will give you a basic understanding of why people are fussy about the design of evaluations. *Planning the evaluation of a rehabilitation project* presents 11 tasks that help you develop your evaluation plan. This section also provides information for Step 7 of the Rehabilitation procedure in Volume 1: *Setting objectives*. Finally, *Evaluation case studies* presents several real examples of evaluation.

1. Fundamentals of evaluation design

Even if you do decide to opt for a simple type of evaluation, it is good to understand and appreciate the reasons why a thorough evaluation can be tricky and time-consuming. This basic knowledge will also help you understand the limits of any evaluation.

The two basic questions we ask in every evaluation are: 1) "has something really changed"; and 2) "is the change that we are seeing really caused by our actions, or is it caused by something else?" Natural systems are always undergoing change, because they are constantly responding to changes in numerous environmental influences (eg. temperature or rainfall). Any impact of our actions is superimposed onto this constant background of change. Designing an experiment to identify what changes are related to our intervention is a specialised and laborious task that entertains the days of scientists. For a more detailed discussion of experimental design see Gordon et al. (1992), or Underwood (1996). The main purpose of this section is to introduce you to some principles of experimental design that will help you to appreciate why scientists are so careful about it. It also aims to encourage you to think very hard about experimental design before being tempted to measure things.

Is there a difference between monitoring and evaluation?

Yes. Monitoring is the collection of information about the effectiveness of a treatment. Evaluation is the assessment of that monitoring—that is, deciding what the results of your monitoring tell you about the success or failure of the project. Thus, many projects are monitored but never evaluated, because nobody does anything with the monitoring information.

First some definitions:

Evaluation plan	The detailed plan of how you do your experiment—what you measure, when, how often, etc.
Treatment or intervention	This is the thing that you do to the stream (in this case, some stream rehabilitation activity).
Control	This is a sampling site or reach which as similar as possible to the rehabilitation site in every way, except that it is not rehabilitated. The control site is compared with the rehabilitation site as a way of checking that any changes are a result of the rehabilitation, rather than some other unconnected event affecting the whole stream.
Uncontrolled experiment	Does not refer to a lack of discipline, rather it refers to a project that has no control site or reach.
Replication	This is repeat sampling to identify the inherent variability in the system. You can have replicates on many scales—replicate rivers to see if the results can be applied to different streams; replicate study sites within a river to see of all reaches react in the same way; replicate samples over time, to measure the temporal variability, and replicate sub-samples within a sample, to measure spatial variability. Thus, when you sample, you might take 10 samples from the reach instead of one, or 10 samples from 10 streams at the same time.
Sample	A measurement of some sort. It could be anything from the average depth of erosion at a site, as measured by erosion pins, to a measure of water quality, or a survey of the invertebrate population at a site.
Sub-sampling	Sometimes, a sample is made up of many sub-samples. For example, if you wanted to know the rate of erosion at one site, you might use several erosion pins. The sub-samples would be the individual pins, and the sample would be the average rate of erosion around all the pins at the site. This means you can estimate how much variation there is at any one site.

1.1. Natural variation

Natural systems are always in a state of change. There are regular fluctuations such as daily and seasonal change, and more random variation in response to chance occurrences, such as a flood, or a particularly warm winter. Variation also occurs spatially. For example, plant species found in the upper catchment are usually different from those in the lower reaches. Some species of macroinvertebrate live on large, clean rocks while others in the same stream will live in the finer sediment between rocks. It is the temporal and spatial variation intrinsic to natural systems that makes experimental design critical to successful evaluation of your project. If your experimental design is the skeleton of the evaluation plan, then your sampling methodology is the meat on the bones.

1.1.1. Spatial variation

Ideally, if you wanted to know what macroinvertebrates were present in a stream, or the particle size distribution on a gravel bar, you would count every individual animal or stone. That way, you could be sure the result of your survey accurately represented what was really present in the stream. Obviously, this will almost never be possible. Instead, you must take samples—a net-full of invertebrates, or a shovel-full of sediment. You then count the animals or stones in that sample, and assume that the sample is representative of the entire population of invertebrates, or all the sediment in the gravel bar. This is all very well, so long as the macroinvertebrates are distributed evenly through the stream, and the size of the gravel does not vary across the bar. Here you are out of luck. Macroinvertebrates are not distributed evenly—different species will live in different habitats, and even within the same habitat some areas may be more densely populated than others. Gravel is not distributed evenly across a bar—the upstream end tends to be coarser sediment, and there is also the possibility of armouring. The solution to this problem is to take several sub-samples from different parts of the stream at that site. From these, you can calculate an average, which we assume to be representative of the entire invertebrate population at the site, or the entire gravel bar. This also allows us to calculate how much variation there is in invertebrate species or particle size at a single site.

You need to take enough sub-samples to have covered the variation at a site, so that the average does represent what is really present in the stream. If you do not manage this, the chance variation between samples could mask changes in the stream, or make you think changes have occurred where in fact the stream remains unchanged. To continue the macroinvertebrate example, variations in water flow, and the size and type of rocks on the bed of the stream, will mean that the macroinvertebrates are not evenly distributed across the stream. If you accidentally collect your sample from an area of fast-flowing water one week, and from slow water the next, you may get very different samples. This will not be because the types and density of macroinvertebrates in the whole stream have changed, but because you accidentally sampled different populations. This means that taking only one or even a few sub-samples may not give an accurate picture of the stream as a whole. This is shown schematically in Figure 27.

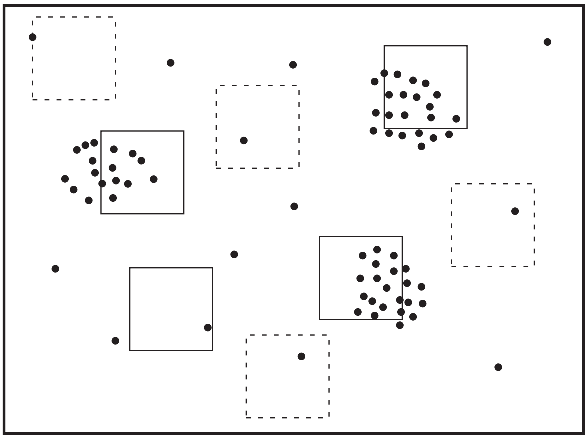


Figure 27. Where you are sampling a population with a lot of spatial variation, taking only a small number of sub-samples may be a bad estimate of the average. In one sampling run (solid squares), the average density is considered to be much higher than the next time (dashed squares), despite the same population being sampled (from Underwood, 1996). Reproduced with permission from Blackwell Science.

Where variation is predictable, you can 'stratify' your sampling. For example, you might separate your macroinvertebrate sampling into pools and riffles, because you know there will be different animals present in each habitat.

When taking samples or sub-samples, it is very important to chose each randomly. It is almost impossible for a person to be totally objective. While you may think you are choosing 'representative' sites, you may accidentally collect data which are more likely to show the effect you would like to be present. This does not imply deliberate falsification of results, just the very human trait of seeing what you want to see. Random sampling is one of the basic assumptions of many statistical tests, so it is particularly important if any analysis is planned.

1.1.2. Temporal variation

Consider an evaluation of new fish habitat, consisting of an evaluation of the results of electro-fishing surveys conducted in the rehabilitated reach once before and once after the works. What if you find more fish in the second survey? Does this mean that your work to create the fish habitat was successful? Not necessarily. The fish population might often vary from year to year by as much as you have measured. If you have no idea of the natural variation in fish numbers, you cannot make conclusions about the effectiveness of the rehabilitation (see Figure 28A). An exception would be a very long post-rehabilitation monitoring program where a general trend in fish populations can be established. However, natural variations may be greater than the subtle trends you may observe, so this type of evaluation design is poor. A similar mistake could lead you to conclude that your rehabilitation has not increased the number of fish when in fact it has (see Figure 28B).

This temporal variation should be taken into account when planning your sampling regime. Because of the complexity of natural systems, though you may rehabilitate with the summer fauna in mind, it is probable the project will also affect the winter fauna. You may 'stratify' your sampling into summer and winter (or spring and autumn), as you would spatially stratify sampling of pools and riffles. In this way you can measure the effect of the project on both groups, while minimising the overall variation. Similarly, some characteristics vary with flow. In this case, sampling may be required at a range of different flow levels, or may be triggered by a flow of specific size, such as the 5 or 10-year flood.

1.1.2.A. Accounting for temporal variation in your evaluation plan

There are two approaches to removing the mystery of temporal variation:

1. Replicate your sampling. Take replicate samples over time both before (ie. to measure background variation) and

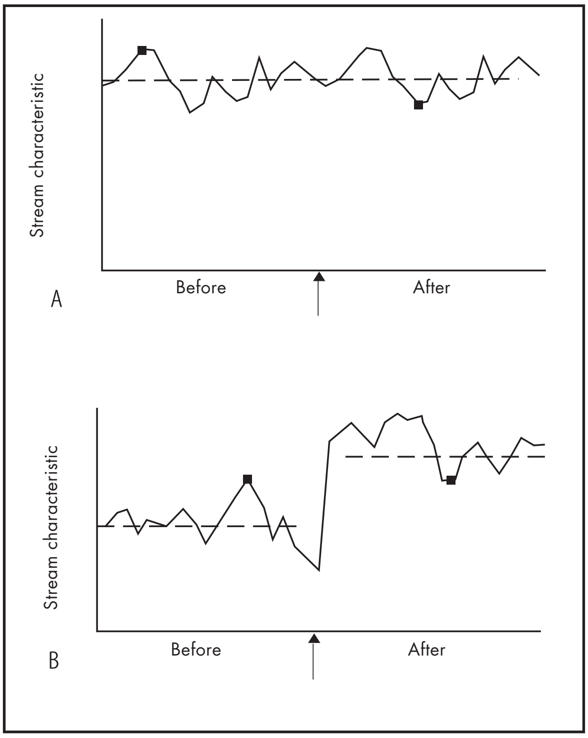


Figure 28. The two mistakes you could make by comparing only one sample before and one after rehabilitation (indicated by the arrow). In Figure 28A, the stream character (eg. number of fish species present) has not responded to treatment—the average number of species (the dashed line) does not change. However, by chance, the two samples (dots) would suggest that fish diversity has decreased. In Figure 28B, the opposite mistake occurs. The average fish diversity has increased, but the two samples suggest no change has occurred (modified from Underwood, 1996). Reproduced with permission from Blackwell Science.

after rehabilitation (ie. to measure the post-rehabilitation response plus background variation). By comparing the 'before' and 'after' monitoring, it is possible to separate the response to rehabilitation from the natural background variation, so long as the 'before' monitoring is conducted over a sufficiently long period (Figure 29).

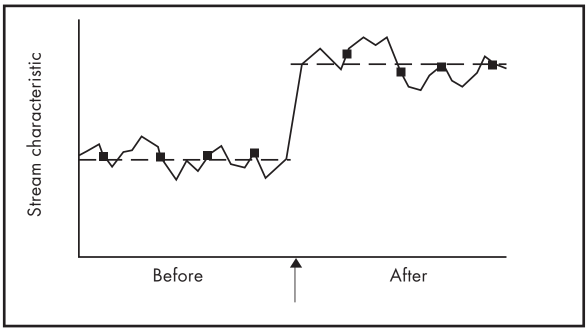


Figure 29. Taking replicate samples (dots) before and after rehabilitation (indicated by the arrow) will show the response to the rehabilitation with a much smaller chance of making the errors illustrated in Figure 28 (modified from Underwood, 1996). Reproduced with permission from Blackwell Science.

2. Use a control site. The control site is a reach, usually upstream, that is as similar as possible to the study or rehabilitated reach and subject to all the same influences except the rehabilitation (what you did to the stream). The control site is sampled in the same way and at the same time as the rehabilitation site. In this way, you can establish how the control site is related to the rehabilitation site before your rehabilitation takes place. Once your project is complete, if the control site has remained the same, but your rehabilitation site has changed, it suggests the changes were the result of the only difference between the sites—that is, your rehabilitation treatment (Figure 30). The control is an essential part of evaluation. Without one, no matter how simple your evaluation, you cannot be sure the changes you observe are because of your project. In reality a good evaluation plan will use before and after replicate sampling and a control site.

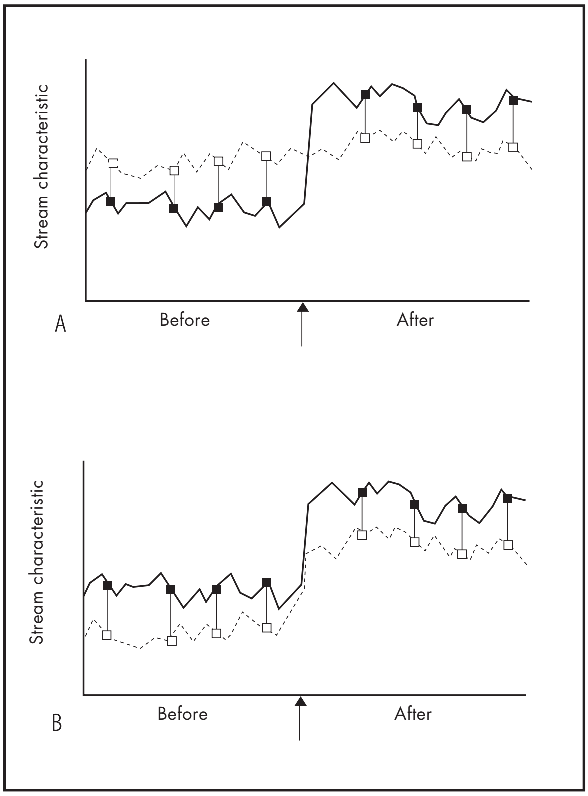


Figure 30. Including a control site in your evaluation gives you a way to check that any changes you observed were caused by the rehabilitation. In Figure 4A the stream characteristic (fish diversity in this example) increased at the rehabilitation site (solid line), but not at the control (dashed line). This suggests fish diversity increased because of the rehabilitation work. However, in Figure 4B the control site responds in the same way as the rehabilitation site. This suggests that the increase in fish diversity is the result of some stream-wide change, rather than the site-specific effect of the rehabilitation (modified from Underwood, 1996). Reproduced with permission from Blackwell Science.

1.2. Choosing the best sample size (power analysis, or how small a change do I want to detect?)

When deciding how many samples to take, time and money constraints suggest less is better. However, there is a problem with this. The fewer samples you take, the less chance you have of detecting any change your rehabilitation makes, particularly if there is a lot of variation between samples. Look again at Figures 28 and 29. When comparing only two samples, the differences in the true average were hidden, but the average of four samples was more representative of the real situation, and the differences were apparent. So, the power of your evaluation (chance of detecting a given change) depends upon how many samples you take, and how much variation exists between them. It is possible to calculate how much power you have (see Coehn, 1988). This can be very useful. You may find that in a very variable stream system, such as urban streams, for example, an evaluation including only a few samples would have the power to detect only huge changes to the stream that would be easily visible without a full scientific study. In this case, you may decide to find more money and increase the number of samples, or not to bother with this style of evaluation.

1.3. What makes a robust evaluation?

The need for a practical evaluation approach that will deal with natural and spatial variability has led to the development of BACI (Before–After/Control–Impact). This is an evaluation program with two sites (rehabilitation and control), with replicate samples taken through time, and replicate sub-samples taken each time you sample. This replicated BACI design is a quite robust evaluation technique. However, there is still the possibility that the difference between the control and rehabilitation sites was due to a chance event not connected to the experiment, and the conclusion that the rehabilitation project had made a difference would be wrong. In fact it is the rule, rather than the exception, that some extraneous circumstance will arise during the evaluation period (eg. a landholder downstream of the control site constructs a ford across the stream and blocks fish passage, or a gravel extraction plant starts up in the control site and raises the turbidity levels, or cattle are allowed to graze the control site because of a severe drought). The solution to this problem is to go 'beyond BACI', and have several control reaches (controls on your control). If possible, it is also advantageous to rehabilitate more than one reach. This results in the most robust design for your evaluation, as there is very little chance that the results could be caused by an unfortunate chance occurrence. It also provides baseline data for future projects which deal with the same sorts of problems.

Some rules of evaluation

Rule 1: Always have a control to check for natural fluctuations.

Rule 2: To account for spatial variation:

- stratify (take separate samples from different seasons or areas); and
- take sub-samples.

Rule 3: To account for temporal variation:

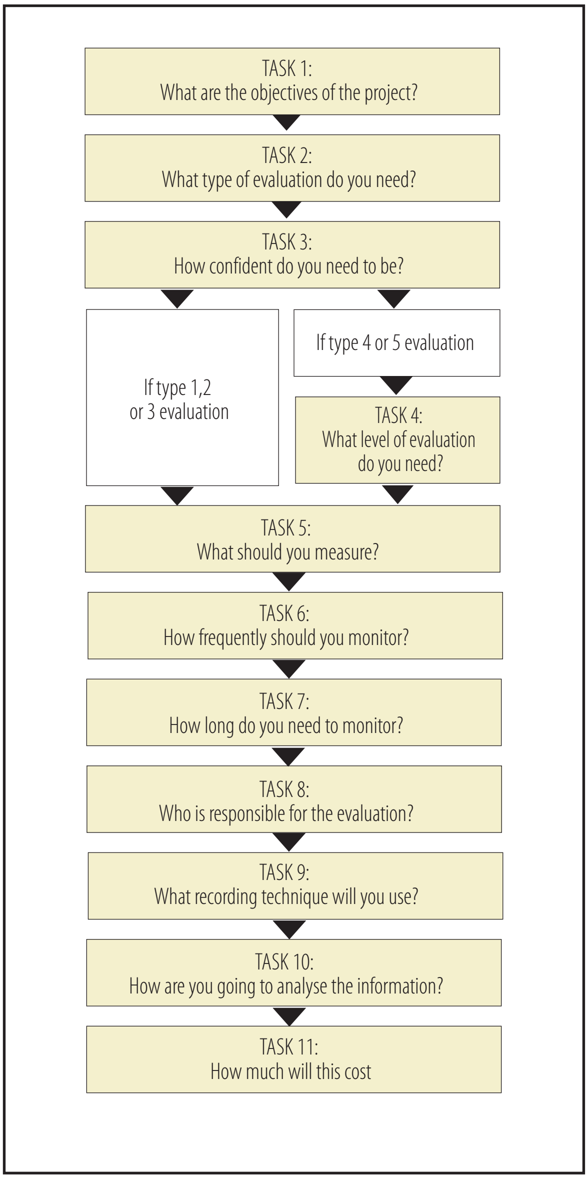
- replicate (take samples at more than one time); and
- include a control.

1.4. What can evaluation tell you?

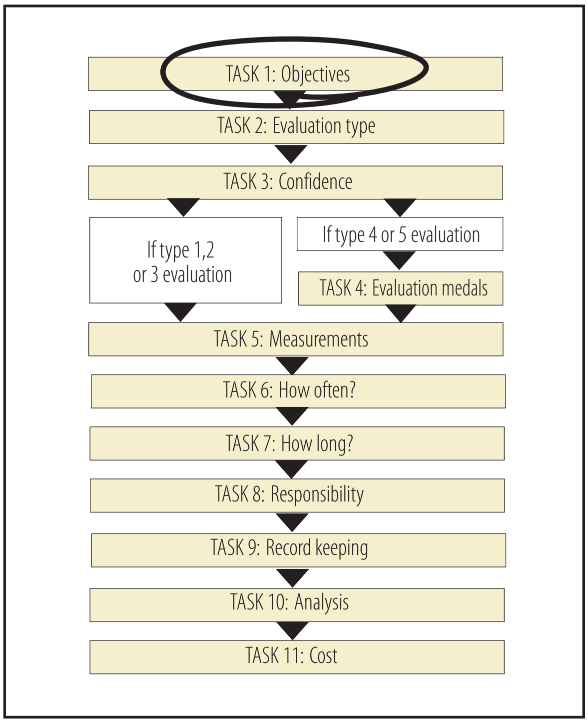
The most basic purpose of evaluation is to tell you if your rehabilitation project has succeeded or failed, according to your objectives. However, a well-designed evaluation will also give you something just as important —that is, the reasons for those results. This is the most informative part of evaluation, where you examine what aspects of the rehabilitation projects worked (fish did utilise the LWD habitat), and what aspects caused failure (the target species of fish were still rare in the reach, because they were out-competed by carp). It is this information that will help you improve and refine your rehabilitation techniques.

Bear in mind that distributing credit for success, or blame for failure, is much harder when the rehabilitation project consists of many different changes, all with their own effects. Unfortunately, most rehabilitation projects fall into this category. For example, consider a project that involved adding woody debris to the stream, constructing an artificial riffle to increase macroinvertebrate density (the favoured food of the target fish), removing the fish barrier downstream and an electro-fishing program to selectively remove carp from the reach. If the result was a success, it would be difficult to tell if this was because of the increased habitat, food supply, improved fish passage or less competition from carp. It may be that all aspects of the project contributed to the success. However, it would also be possible that the fish were responding to only one part of the project, such as the increased habitat. Meanwhile, the other aspects of the project might have had no effect, or might even have been disadvantageous to the fish, but this was masked by the success of the woody debris. It is not possible to separate these effects. This is not to say that projects involving multiple aspects should not be considered, rather that in these cases you should be aware of the limits to what your evaluation can tell you.

2. Planning the evaluation of a rehabilitation project



Planning an evaluation of a rehabilitation project is not necessarily hard, but it is important that you think about all of the issues involved. We present here 11 tasks you should work through to be sure you have considered all the important issues. Please note that these 11 tasks are an expansion of the 3 tasks shown in Step 10 of the stream rehabilitation procedure, Volume 1. Each of the 11 tasks is really a question you need to answer. The 11 tasks are shown in the preceding flow chart. Note that Task 4 applies only if you choose evaluation type 4 or 5 (evaluation of physical or biological outcomes).



2.1. Task 1: What are the objectives of the project?

The first rule of evaluation is that you be very clear what it is that you are evaluating. In *Step 7: What are you specific rehabilitation objectives*? of the Stream rehabilitation planning procedure, Volume 1, you should have developed clear objectives for your rehabilitation project. The success of the rehabilitation project is therefore measured by how closely the conditions of the rehabilitated stream meet those specified in the objectives.

Consider a project to increase fish populations by replacing LWD in a reach devoid of habitat. The objective should be as specific as possible. Rather than stating the objective as merely to increase fish numbers, you should consider if you are interested in all fish, or just certain species, perhaps popular angling fish, or maybe not just fish but macroinvertebrates as well. You should also consider by how much you wish to increase the population. Would you consider the project a success if there were only three more fish in the reach? The objectives you end up with may be something like "to increase the trout cod population in this reach by 50% in 5 years". Objectives must often be couched in terms of events of given probability. For example, this structure should survive a flood of 10-year average recurrence interval. If you expect a change in response to a particular flow regime, it is only reasonable to wait for that flow to occur before you can declare the project a success or failure (we will consider the importance of flow variability in Tasks 6 and 7: How frequently and How long should you monitor?).

Briefly, objectives should specify the following.

- How much change you want to see as a result of the rehabilitation.
- What length of stream you want to improve.
- How long you will wait before concluding the evaluation.

You should also have considered whether your objectives relate to outputs (tasks to be completed), or outcomes (the effect on the stream of those tasks), and what type of objective you have (Table 25). Table 26 provides some examples of how to turn general objectives into measurable objectives.

Table 25. Types of objectives for stream rehabilitation.

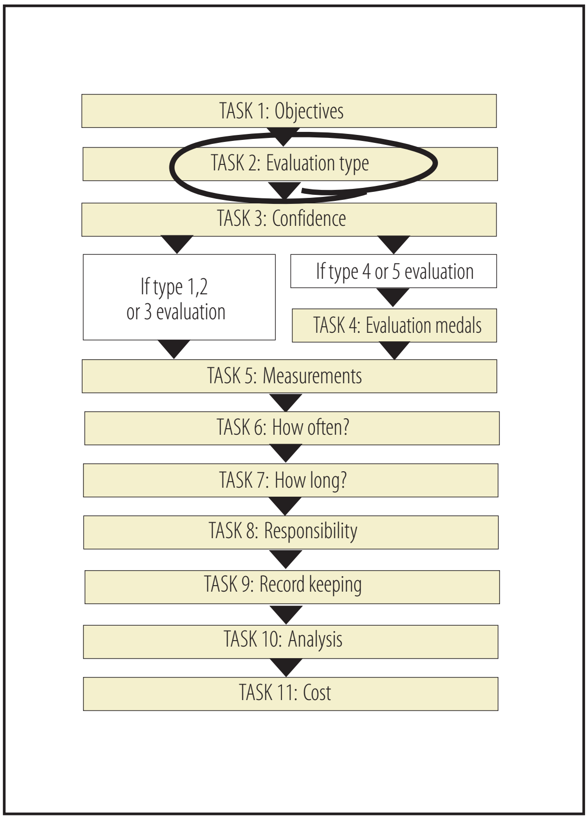
Output/ outcomes	Type of objective	Example of objectives
Output	Execution of the project.	• Fence 7–10 km of stream, and provide two off-stream watering points by next summer.
Output	Survival of the project.	• Flood gates in the fence survived a 5-year flood. • A core of people still attend Rivercare meetings after 3 years.
Outcome	Aesthetics of the stream.	• Revegetation inside the fence makes the stream look much more attractive after 5 years.
Outcome	Changes in the physical or chemical condition of the stream (may relate to the riparian zone, the physical form, the hydrology or the water quality).	• After five years, the pools would be between 20 and 50% deeper. • The riparian vegetation will provide between 1 and 10 fragments of woody debris per kilometre of stream per year, after 20 years.
Outcome	Improvement or maintenance of stream ecology.	• The range of species present (diversity) in the riparian zone will be between 50 and 100% of that found in the template reach after 5 years. • The numbers of a particular organism (eg. platypus, fish, macroinvertebrates, redgum) will increase to between 20 and 60% of populations found in the template reach after 4 years.

Table 26. Examples of measurable objectives for stream rehabilitation.

(Type of assessment: Y/N = either it has or it has not (presence or absence), Sample = measure something at regular intervals; Observe = regularly observe or inspect something.)

Area of interest	General objective	Measurable objective	Type of assessment
Physical form	Maintain present river course.	Over next 10 years, channel planform will not change by more that 5 m (assuming no floods larger then a 20-year return interval.	Y/N
	Protect upstream pool habitat.	Average depth in pool will not decrease over 10 years.	Sample (survey cross sections)
	Improve substrate for organisms.	Median particle size will double over 5 years.	Sample (particle size analysis)
	More hydraulic diversity.	Double the diversity of 'flow types' found in the stream in 5 years.	Sample (survey flow types)
	Preserve existing form.	Basic form of the river should not change up to a 20-year flood. (Set acceptable levels of natural change.)	Observe
Riparian zone	Restore the vegetation of the riparian corridor.	After 10 years, the planted vegetation should have similar diversity and density as that in a template reach.	Sample (survey vegetation)
	Willow removal.	By the end of next year, no living willow trees or regrowth should be found on either bank of stream for 2 km downstream of the bridge.	Y/N
		Replant with native vegetation tubestock by this time.	Y/N
	Restrict stock access.	Each year, fence no less that 2 km of stream between the road crossing and the town.	Y/N
	Maintain the vegetation in its present good condition.	No change in vegetation density or diversity in the defined reach on 6 monthly inspections over the next 2 years.	Sample (survey vegetation)
Aquatic life	Increase the population of fish species 'x'.	Over 5 years, a doubling in the population of species 'x' in the rehabilitation reach compared with the control reach.	Sample (survey fish population)
	Reintroduce a fish species to the stream.	In five years, the population of the species should grow in the target reach to the stage where 10 catches a year are reported by fishermen.	Observe
	Macroinvertebrates.	Doubling in invertebrate family richness in the reach over the next 5 years.	Sample (survey invertebrates)
	Aquatic mammals.	In 5 years, there should be a doubling in sightings in the target reach during surveys.	Sample (visual survey for platypus)
Terrestrial life	Birds.	After 5 years, the 8 target waterbird species should be breeding in the reach.	Sample (visual survey)
	Mammals.	Double the number of species 'x' trapped in 7 years.	Sample (trapping survey)
Hydrology	More-natural flood regime.	After 2 years, similar storm events in control and target catchments produce flood events of similar duration.	Y/N
Water quality	General water quality.	Reduced to same range as control reach for two consecutive years (or target range).	Sample
		Doubling in water quality rating according to the Index of Stream Condition after five years.	Sample
		Improvement in some water quality bio-indicator (eg. AusRivAS) in 5 years.	Sample
		Return of some indicator species (eg. stoneflies) to the reach after 3 years.	Observe

2.2. Task 2: What type of evaluation do you need?



You will develop your evaluation plan differently depending on the type of objective that you have. There are five types of evaluation that mirror the types of objective described in Table 25. These are described below, presented in order of complexity from the simplest type of evaluation to the most complex. Select the evaluation type that most suits the objectives for your project.

Note that the different types of evaluation are not mutually exclusive. Most projects have a series of objectives (like milestones), relating to different outputs and outcomes. In fact, it can be quite useful to incorporate all types of evaluation. This means you can keep track of the condition of your rehabilitation structures (and be ready with maintenance when required), as well as monitoring the effect they have on the physical or biological nature of the stream. Also, the different types of evaluation typically occur over different time frames, as discussed in Task 7 (How long do you need to monitor?). For example, evaluating execution can be done as soon as the works are completed, but you might have to wait 10 years to complete the evaluation of the biological outcomes of the work. Because of this, including different types of evaluation will mean regular reporting of progress, and help to keep the community interested in the project.

2.2.1. Type 1: Execution outputs

Funding bodies often define evaluation as being evidence that the works were executed according to plan. That is, the money was spent on the things it was supposed to be spent on. This is a simple accounting process, but should not be confused with other levels of evaluation. Execution means simply checking that the job was or was not done according to design: "the fences were built, the drop structure was put in on time, but we only put in six of the eight retards…". This type of evaluation is useful as an ongoing record of works, but is only the starting point for other levels of evaluation. It assumes that if the structures are there or the works are done then the project will be a success.

2.2.2. Type 2: Survival outputs

Has your project survived? This is the most common form of evaluation, and certainly the minimum that should be expected. It is an extension of execution type evaluation in that the existence of the structures implies your objectives have been achieved. For example, after the 1993 floods in north-eastern Victoria, the success of various structures was measured by whether they were still there after the flood. If they were, they were deemed to have succeeded (AVRMA, 1994). But this does not prove that the structures were successful; it can lead to no more than an assumption that they were.

Survival-type evaluation requires repeat surveys to see how the works are performing. It would usually start with a detailed 'execution'-type survey with follow-up reviews at either preset intervals or on the basis of flood events. For example, say we installed log sills to increase pool habitat. The first phase of the evaluation (execution) is to verify they have been installed as designed. This is then followed by an event-based survival evaluation which records if the sills have survived any flood greater than, for example, a 2-year return interval. This type of evaluation is very important for in-stream structures, as it helps us to identify the structures that are suitable for different stream types.

Sometimes it is also possible to identify why the rehabilitation has not succeeded (eg. "rabbits ate the plants", "seepage destroyed the structure because no geo-textile was used").

Evaluation of survival: V-log sills in northern New South Wales

From notes provided by David Outhet, John Bucinskas and Wal Hader (NSW, DLWC)

The Nambucca River, in the mid-north coast of New South Wales has suffered severe degradation since European settlement in the area. In an attempt to stabilise the gravel bed of the stream, 66 log sills were constructed. After some floods, 48 of the structures were inspected to assess if they had survived. Most had been outflanked, scoured from below, or covered in sediment.

These are some of the lessons learned from the structures that survived.

- Locate the structure on a straight reach or inflection point so that it does not get outflanked.
- V-logs should be used only on gravel-bed streams because downstream scour will undermine the structure in sand-bed streams.
- Straight log sills perform better than V-sills.

2.2.3. Type 3: Aesthetic outcomes

In many cases, the objectives of a stream rehabilitation project relate most strongly to aesthetics—that the stream should 'look' better or more natural. These objectives are the easiest to evaluate. Obviously, aesthetics is in the eye of the beholder, but it is pretty easy to come to a consensus. The same is true for most rehabilitation that involves replacing infestations of exotic vegetation with native vegetation eg. clearing blackberries, water weeds, or willows.

The key thing to remember about this type of evaluation by 'opinion' is that people have short memories. You must somehow record the original condition of the stream so that you do not have to rely on memory. Video recorders are good for this purpose, as are copious photographs. Remember the cost of a film is small compared with the cost of the project.

2.2.4. Type 4: Physical and chemical outcomes

Although the goal of rehabilitation is often to improve the ecological condition of the stream, this is usually done by improving the structural and chemical condition of the stream (eg. hydraulic habitat, LWD density, scour holes, substrate composition, water quality etc.). These physical changes are cheaper and easier to measure than the biological systems that they are meant to influence. As a result, most evaluation is targeted at these changes, and it is simply assumed that a biological response will follow. The key problem with this type of evaluation is to ensure that the change that you are measuring is related to your rehabilitation, and not to some other change in the stream. This problem is discussed below in Task 4: What level of evaluation design do you need?

2.2.5. Type 5: Ecological outcomes

Ecological improvement is the vision driving almost all stream rehabilitation projects. However, evaluating ecological outcomes is not as common as you might think. This is partly because we usually attempt to manipulate stream ecology by changing the physical or chemical nature of the stream, so evaluating success at that level often seems sufficient. Also, monitoring ecological change can be difficult, and take considerably longer than other types of evaluation. Ecological evaluations most commonly measure changes in the types, abundance and diversity of the species present (eg. are there fish present, how many fish are present, how many species of fish are present, what are the fish species present?).

As with evaluations measuring physical changes, it is very important to ensure that the change that you are measuring is related to your rehabilitation efforts, and not due to some unrelated change in the stream. This problem is discussed below in Task 4: What level of evaluation design do you need?

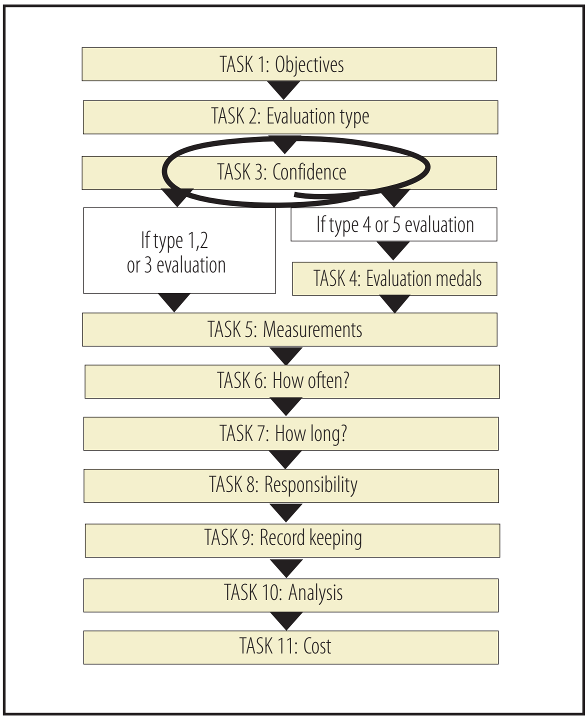
An example of a Type 4 evaluation

A rehabilitation project on Little Butte Creek, in south-western Oregon, USA, aimed to increase the number of trout present in the stream by increasing the habitat available (Maiyo,1996) . Table 27 shows the physical effects of the project by comparing the original condition with the post-project condition, as well as measuring some of the morphological changes produced by the project. As with execution and survival-type evaluations, this assumes that, if there is habitat available, then the trout population will increase. Thus, the results in Table 27 do not tell us if the project succeeded in increasing the number of trout, only that there was potential for fish to move into the new habitat. In this case, the relationship between habitat features and trout numbers is so well-established that this level of evaluation was considered sufficient to demonstrate the success of the project.

Table 27. Summary data table for Little Butte Creek restoration project, Oregon. Pre-project versus post-project comparison (Maiyo, 1996).

Stream attributes	**Pre-project**	**Post-project**
Total stream area (sq. ft.)	47,763	52,229
Pool area (sq. ft.)	4,039	20,529
Average maximum pool depth (ft.)	2.27	3.56
Wetted side channel habitat (sq. ft.)	0	3,820
Total number of habitat units	63	90
Wood Pieces		
Large (>36 in. x >50 ft.)	1	16
Medium (>24 in. x >50 ft.)	2	61
Small (<12 in. x <25 ft.)	2	15
Rootwads	2	9
Habitat – general (% by surface area)		
Pool/riffle/side channel ratio	8/92/0	39/53/8
Habitat – specific (% by surface area)		
Pools		
Alcove	0	1
Backwater	1	4
Dam	0	4
Lateral	4	9
Plunge	3	14
Straight scour	0	7
Riffles		
Low gradient	48	37
Rapid	44	16
Cascade	0	0
Side channels	0	8

2.3. Task 3: How confident do you need to be?



At this point potential evaluators should ask themselves two questions:

"How confident am I that what I am planning will work?"
"Who am I trying to convince with this evaluation?"

The level of detail of your evaluation project is a function of how confident you are that your objectives will be achieved, and how hard it will be to convince others by your results.

2.3.1. How confident are you?

Evaluation is really about confidence. How confident are you that your rehabilitation produced a change, and how confident can you be that somebody else will get the same result? The general rule is, the less confident you are, the more rigorous your evaluation needs to be in order to convince you that the project was definitely a success (or failure).

> There is no such thing as truth in evaluation, only levels of confidence. In science, these levels are expressed in statistical terms. The pertinent questions are: how much confidence do you need to convince somebody, and how much confidence can you afford to buy with the resources available?

2.3.2 Who are you trying to convince?

Different people are convinced by different evidence. The politician who funded the rehabilitation project may be more easily convinced of its success than a scientist currently researching in a similar field. We cannot afford to extensively evaluate every project but the level of rigour in your evaluation ultimately relates to the confidence you need to convince your audience that the results are correct. Your evaluation has to address the objectives to a level necessary to convince the appropriate people. More detailed evaluation than this could be a waste of resources.

> A very important question: "who am I trying to convince in this evaluation?"
>
> Yourself?
> The press?
> Politicians?
> The general public?
> Funding agencies?
> Local landholders?
> Other stream managers?
> The scientific community?
>
> Your evaluation has to address the objectives to the level necessary to convince the appropriate people. More detailed evaluation than this would be a waste of resources.

Consider the following examples.

1. You are planning to remove a concrete weir on a stream to allow fish passage. You are supremely confident that this will dramatically improve fish numbers upstream because you have read that the target fish species are migratory and you have seen fish of these species massing below the weir. Because you are so confident of a good result, you would like to remove other barriers upstream. To do this you need to provide the road authority with evidence of what their structures are doing. Therefore, you will do a detailed evaluation of fish numbers above and below the weir before and after the weir is removed.

2. You have a channelised stream devoid of riparian vegetation. Your project is initiated by a community group intent on beautifying the stream by fencing it off

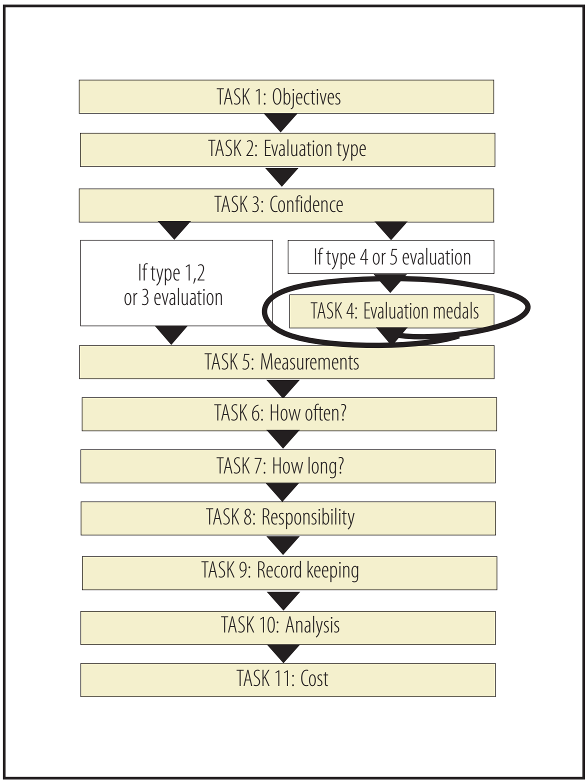
and revegetating. The objective of the work is entirely aesthetic. Your evaluation needs to convince the funding body and other Landcare groups of your success. This can be achieved with a simple series of before and after photographs.

3. Your boss has asked you to do something to the river that you think will not work. You do a detailed evaluation to convince yourself and your boss of the effectiveness of the project.

4. You are working on a Western Australian stream. You read an American article arguing that returning LWD to a sand-bed stream would increase macroinvertebrate populations as well as bird numbers. You would like to try this on your stream. You are not too confident that it will work in Western Australia, and your boss is sceptical but willing to let you give it a try as long as you evaluate the work. You would also like to publish the result in a scientific journal, thus you decide to do a full BACI evaluation design of the experiment (see Level 4 evaluation).

Select the target for your evaluation and keep that in mind during the following tasks.

2.4. Task 4: What level of evaluation design do you need?



There are five basic sampling designs used for detailed physical or ecological evaluation, with confidence in the result, effort and cost increasing substantially with each. These are shown in Table 28. Each design has been allocated a medal according to the level of confidence the scientific community would place in that type of evaluation. From the level of confidence you selected in Task 3 (How confident do you need to be?), select an appropriate evaluation type. The section on fundamentals of evaluation design, earlier in this chapter, discusses the terminology used here.

2.4.1. Level 1: Plastic medal

Unreplicated, uncontrolled, observation after rehabilitation (anecdotal)

Somebody intimately involved in the project, possibly with a vested interest in its success, makes observations of change, without measuring anything. This is the most common type of project assessment. For example, a project manager reports that fishermen have told one of his work-crew that they had noticed an increase in fish numbers soon after the works had been completed. Another common example is where the project manager says "you should have seen this reach before the project, it was terrible, now it looks great. Sorry, we don't have any photos, surveys or other evidence". Or again, "we haven't seen platypus in here for 20 years, and now they are back". This may be true, but in our experience it can equally be false. They may not have looked for platypus before the work was done. The best approach to anecdotal evidence of performance of a rehabilitation project is to use it to form a hypothesis that can be tested in other ways.

Good evaluation should not rely on memory.

From this point on we assume that the person doing the experiments is objective and does not have a vested interest in the outcome. To an extent, a carefully designed evaluation program can safeguard against subjectivity, by specifying how, where and when measurements must be taken. However, objectivity can best be achieved by getting your evaluation done by people who have no vested interest in the results. This can mean a group who were not involved in the planning or execution of the project (eg. a university team on contract).

Table 28. The five levels of evaluation, and the confidence you can have in their results.

Evaluation level	Description	Example	Level of scientific confidence
Level 1: **Plastic medal**	Unreplicated, uncontrolled, anecdotal observation after rehabilitation.	"I saw lots of platypus after we had done the work".	Very low
Level 2: **Tin medal**	Unreplicated, uncontrolled, sampling after rehabilitation.	"There was a gradual increase in the number of platypus in the two years after the work".	Low
Level 3: **Bronze medal**	Unreplicated, controlled, sampling after rehabilitation.	"After rehabilitation, there were more platypus in the control reach than in the treated reach".	Low–Moderate
	Unreplicated, uncontrolled, sampling before and after rehabilitation.	"There were more platypus after the work than before".	Moderate
Level 4: **Silver medal**	Unreplicated, controlled, sampling before and after rehabilitation.	"The number of platypus increased after rehabilitation in the treated reach, but not in the control reach".	High
Level 5: **Gold medal**	Replicated sampling, replicated controls, sampling before and after rehabilitation.	"The increase in the number of platypus in the treated reach was greater than any increase at either control reach".	Very high

Who will be convinced by Level 1 evaluation?

- Very effective for convincing people who want to be convinced that the project was successful.
- Can be effective on friendly politicians and funding agencies who are looking for good news.
- Can sometimes work at public meetings (ie. if your goal in the evaluation is to provide ammunition to persuade more community groups or other agencies to get involved, it may be safer and quicker to rely on anecdotal evidence than on measured evaluation, as this can be slow in coming and disappointing).

2.4.2. Level 2: Tin medal

Unreplicated, uncontrolled, sampling after rehabilitation

This is the most common type of sampling, and one of the weakest designs, producing a low confidence in the outcome (see Reedy Creek example below). The method is based on the hope that the effect of the rehabilitation can be identified by a trend in the stream over time. Unfortunately, it is difficult to be sure there was a change, because of the lack of sampling before the rehabilitation. Also, the lack of a control site means you cannot be sure that any change that is detected was caused by the rehabilitation and not by one of a thousand other things.

This approach can work, providing you sample long and frequently enough to identify the trend from the fluctuations. This type of design can produce results, particularly when there is a huge response to the rehabilitation, but will probably require longer sampling to achieve a reasonable level of confidence. However, the design is poor for systems characterised by high variability. For example, imagine that you have revegetated a reach and want to see if your work has decreased turbidity. Turbidity often varies by a hundredfold during flood peaks. This level of variation means it is almost impossible to detect a trend of improving turbidity levels after revegetation. You need some idea of the variation in turbidity before revegetation, in order to see if you have made an improvement.

In the simplest experimental case, your intervention may produce a new habitat that was not there before. If that habitat is then colonised by the target organisms, then you have been successful. Basic changes such as this are easy to identify and may not require sophisticated evaluation.

An example of tin medal evaluation: Reedy Creek, north-eastern Victoria

From Paul Brown, Marine and Freshwater Resources Institute, DNRE, Victoria

Reedy Creek is a large, incised stream (see Common stream problems, this Volume). Large rock chutes were constructed in the creek by the Broken River Management Board to stabilise the bed and banks. Large pools were formed behind the chutes, where before there was little permanent water (Figure 31). When these pools were sampled for fish (by electro-fishing), surprisingly large numbers of native fish were found in the pools. Although there was no sampling before and only one sample after the chutes were built, this evaluation is convincing because of the large numbers of fish present in the new habitat. Projects that create habitat are relatively easy to evaluate. It is important, however, to repeat the sampling a few more times. The initial explosion of fish in the new habitat could change considerably over time.

This type of post-rehabilitation monitoring can be greatly improved by sampling a control reach upstream of the rehabilitation reach at the same time. This allows the effect of the rehabilitation to be isolated from the background variation.

Who will be convinced by Level 2 evaluation

- This type of sampling can be perfectly adequate for funding agencies, less sympathetic politicians, and public persuasion—so long as the results look good. Results could easily suggest a slow response to the works.
- Could require a long time to get a convincing result (some people that you want to convince may have lost their seat in parliament by then).

Figure 31. These pools in Reedy Creek have been created by the construction of rock chutes.

2.4.3. Level 3: Bronze medal

Unreplicated, uncontrolled, sampling before/after rehabilitation, OR Unreplicated, controlled, sampling after rehabilitation

There are two designs that receive a bronze medal. Although they are not very robust techniques, statistical analysis of data is possible.

In the first design, the test reach is sampled one or more times before the rehabilitation, and again afterwards. This design provides much more rigour than the earlier designs, because it provides a baseline against which any change can be compared. This type of design is not common because it is rare for projects to be planned far enough in advance for people to do the pre-project sampling. Funding agencies tend to see a one or two-year delay for pre-project sampling as evidence of poor progress.

A more fundamental problem with this design is the absence of a control reach. This makes it impossible to tell if any changes observed are a result of the rehabilitation, or a change in some background condition such as rainfall.

The second bronze medal design has the opposite problem. In this evaluation design, there is a control site, but no sampling occurs at either site before the rehabilitation work. As a result, you can tell if the rehabilitated site and the rest of the stream (represented by the control) are acting differently, but you do not have any baseline data against which to compare the reach. This means you cannot be certain that the rehabilitated site has changed. It and the control reach may always have acted differently.

Who will be convinced by Level 3 evaluation

- Usually adequate for publication in trade journals like Landcare magazines etc.
- This is the level of confidence that would convince a sceptical senior manager, but would generate debate (but not necessarily complete rejection) amongst scientists about the 'validity of the experimental design'. (Will be better received if there is both replication and a control in the design.)

2.4.4. Level 4: Silver medal

Unreplicated, controlled, sampling before/after intervention

This is the standard BACI design (before–after–control–intervention) for experiments (Green, 1979). Both the target reach and an independent control reach are sampled before and after the rehabilitation. In this way the relationship between the control and the rehabilitation site is established before the rehabilitation begins. Any new differences between the control and the target sites after the rehabilitation can then be assumed to be caused by that intervention. There will usually be a statistical analysis of the data.

Who will be convinced by Level 4 evaluation ?

- Standard BACI design evaluation would easily convince a sceptical senior manager,
- A replicated BACI design (ie. several samples taken at each site) is considered the minimum standard for most journal publications.

2.4.5. Level 5: Gold medal

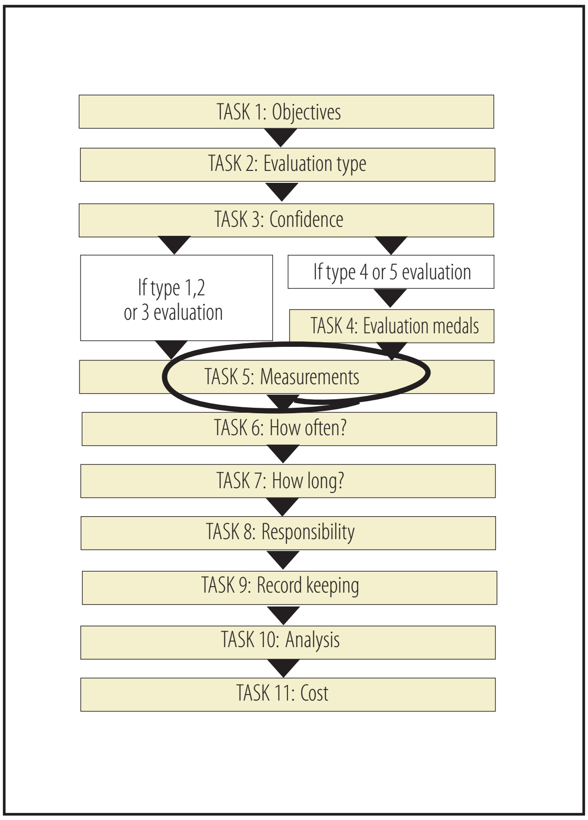
Replicated sampling, replicated controls, before–after intervention

This is the 'Beyond BACI' design (see Underwood, 1996), the most robust evaluation available for most stream rehabilitation. Statistical analysis of the data will almost always be a part of this design. The replicated sampling means differences before and after rehabilitation can be detected with more accuracy, and the use of multiple control reaches means the changes can be attributed to the rehabilitation with greater confidence. If your rehabilitation project involves treating several reaches of stream, incorporating all of these into the evaluation will also increase the confidence in the results. If the control and rehabilitation sites cover more than one stream, the results will be more widely applicable. Unfortunately, this design, while being the most robust against all criticism, tends to be so expensive that it is seldom used.

Who will be convinced by Level 5 evaluation ?

- The result would be difficult to argue with once the study is completed, and would provide strong grounds for management decisions.
- This is the level of confidence that is usually required for publication in an international scientific journal.

2.5. Task 5: What should you measure?



The primary job of evaluation is to tell you whether or not the project met your objectives. So obviously, the measurements you make should relate to those objectives. For example, if you set out to increase the fish population, then you should survey fish numbers. Some common measurement techniques for evaluating each of the five types of objective are summarised below. Bear in mind that this summary is only a list of possible measures—if you can think of some other way to monitor your progress, you should use it.

At this point it is worth considering what other information you could get from your evaluation. An assessment of success or failure by itself is not very informative. The most interesting part of evaluation comes from trying to work out why you got that result, and how you could improve your rehabilitation techniques for the next project. Finding the extra information will involve making some extra measurements of anything that is likely to influence you project. For example, droughts or floods can have detrimental effects on many different rehabilitation projects, so some measure of stream flow is often useful.

When considering what to sample and when and where to sample it, there seems an almost infinite array of information you could collect. There is no universally applicable standard of what to measure, so in each case you must tailor your design to the specific aims of your evaluation. Here are some general tips:

- You should minimise the number of things that have to be measured. Costs can get out of hand if the evaluation measures are not clearly focused.
- Existing routine measurements should be incorporated wherever possible (eg. routine turbidity, water quality, or gauging data by government departments).
- Information from the community, such as fish catch records from fishing clubs, can be incorporated to augment your own measurements.

Note that in this task, as well as in Tasks 6 and 7 (How frequently and how long should you measure?), you should bear in mind how you are likely to analyse the results of your measurements (Task 10). Higher forms of analysis will have certain requirements of the type of data they will accept. This restriction is most likely to be important for evaluations of physical and ecological outcomes.

2.5.1. Type 1: Execution outputs

This evaluation is based on whether you did what you said you would. If your objective was to build a certain number of structures, check they are all finished. If you used the template approach then you compare the template with the treated reach. For example, you might use this approach when reintroducing large woody debris, with the objective of adding enough wood for the treated reach to match the template reach. To evaluate, you measure and compare the debris density in the template and the treated reach.

2.5.2. Type 2: Survival outputs

Survival is really an extension of execution, where the rehabilitation site is visited a number of times to see how the works have survived. The type of measure for survival can be simply whether a structure is still present and functioning as designed.

2.5.3. Type 3: Aesthetics outcomes

A photographic record is an ideal way to document aesthetic changes to the stream, and should be the minimum evaluation for almost any project. Photo points marked with a monument are essential for this. The key is to be able to a photograph from exactly the same point each time the site is visited. This is accomplished simply using any of the following strategies.

- Several large nails hammered into a large log. You slide the camera into the space between the nails and it is held fast so that a consistent photo can be taken each time.

- Custom designed photo-point made from a wooden pole cemented into the ground.

- Three cement plugs (or similar) buried in the ground, on which to place a camera tripod.

2.5.4 Type 4: Physical and chemical outcomes

The long-term goal of stream rehabilitation is usually to increase the ecological diversity of the stream. However, physical habitat is easier to measure that stream ecology—it doesn't try to bite or run away, and it's not difficult to identify. You are then left with the assumption that if the physical change has occurred, then the desired ecological changes will follow. But what exactly do you measure?

- Channel morphology, bed sediments and large woody debris are structural features which influence the hydraulic environment.

- Flow types and patterns of depth, velocity and shear stress characterise the hydraulic environment.

- Water quality parameters, such as turbidity, temperature, salinity, and so on.

The Little Butte Creek evaluation, summarised in Table 27, is a good example of the sorts of physical measurements you can take.

When designing a project based on the physical habitat, you have to be careful to remember the animals and plants you are attempting to encourage. The objectives of your project should reflect the needs of those organisms (this can be tricky if the needs of the organisms are not well known). This section briefly outlines some methods for describing the structural character of stream channels.

Surveying

Many measures of physical changes in the stream are based on repeated surveys, usually either of cross-sections or long profiles. The key to useful surveying is to include a benchmark—something that is not going to move, like a tree or fencepost. This means that you can compare surveys from before and after rehabilitation. The benchmark helps you position later surveys in exactly the same spot, and also makes it easier to compare the results.

Channel morphology

Commonly measured features of channel morphology are:

- average depth;

- how depth varies (eg. an area of shallow, uniform flow, might change after rehabilitation into a sequence of deep pools and shallow riffles);

- the presence or absence of particular features of the channel, such as undercuts, or bars; and

- the shape of the channel (eg. bank height or slope, or channel width).

There are statistical techniques available to characterise the variation revealed by such surveys (eg. see Western *et al.,* in press).

Sediment characteristics

Particle size is the most commonly measured characteristic of the sediment.

Large woody debris

In streams with only small quantities of large woody debris, measurement is a simple matter of counting the pieces, and perhaps noting the size and type. In streams that are more densely laden with debris, the easiest method of measuring abundance is the line intercept method (Gippel *et al.,* 1996a).

Flow types

Flow types (ie. pools, riffles, runs and so on) can be characterised by simply counting the number and abundance of different types, or by measuring the area of each type. Rowntree and Wadeson (1996) present clear definitions of 11 different flow types, and a statistical technique to characterise the complexity of flow types in a reach.

On a far smaller scale, it is possible to measure hydraulic micro-habitat, characterised by velocity and depth, and thus calculate the hydraulic diversity for the reach (Stewardson *et al.,* 1999).

Habitat

Often when monitoring a stream you end up with a very large and complex collection of data. It is very useful to be able to reduce these to a single number, which means you have a chance of interpreting your results. The 'weighted useable area' model (developed in the USA) is a good method of assessing the availability of habitat for individual species or life stages (Nestler *et al.,* 1989).

Water quality

Some projects will have as their objective an improvement in water quality. Commonly used water quality parameters are discussed in Common stream problems, this Volume.

2.5.5. Type 5: Ecological outcomes

The core of ecological outcomes is the identification of plants or animals to an appropriate taxonomic level, whether that be family, genus or species. Depending on the level of identification, and the organisms involved, this can require considerable expertise. Obviously, plants are the easiest to survey (they're not too hard to catch!). The larger algae are also easy to sample, but identification requires a microscope and considerable expertise. Macroinvertebrates can be collected using fine nets (Tiller and Metzeling, 1998). Fact sheets such as those produced for Streamwatch (eg. Sydney Water and CSIRO) will help in identifying the more common orders of animal (eg. dragonfly, leech, beetle), but more detailed identification will require an expert. Fish can also be captured using nets (although this risks injuring or killing some individuals) or using electro-fishing. Note that identification of juvenile fish is very difficult. Platypus, birds and frogs can be surveyed by careful observations at appropriate times of day.

Having identified the relevant organisms, you can:

- measure the diversity and abundance of different taxonomic groups (eg. has the proportion of species that indicate a healthy stream increased?);
- look for the presence of different life stages (eg. now we have fenced stock out of the riparian zone, is there any natural regeneration of the riparian species?). Note that identification of juvenile organisms can be very difficult; or
- look for differences in the behaviour of animals (eg. are the fish found around the new habitat we constructed?).

There is a range of tools available to help you make sense from what can be a large and complex data set. These tools include measures of diversity, such as EPT scores, through to models based on empirical data, such as AusRivAS, and complex statistical analysis, such as multi-dimensional scaling. These techniques are discussed in Using Bio-indicators, in Catchment review, this volume.

2.5.6. Other information you may need to collect

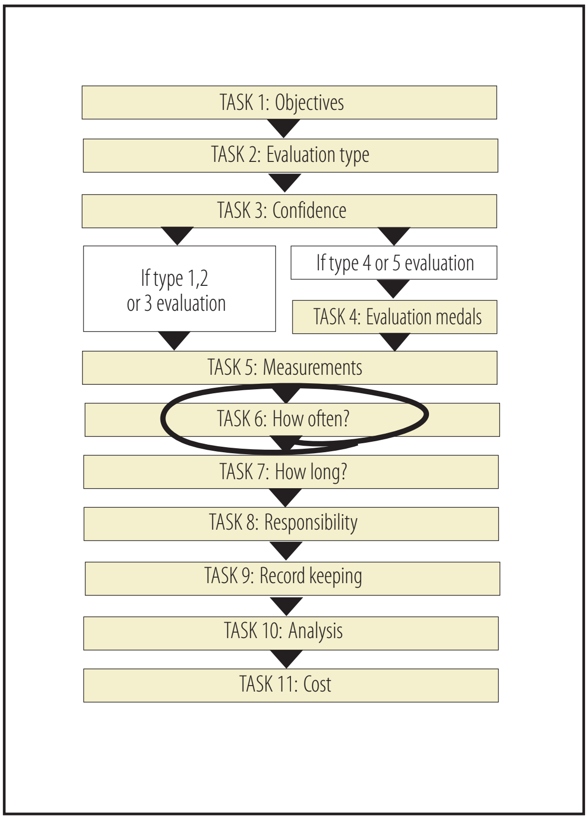
As suggested in the introduction to this task, a good evaluation will tell you not only if your project succeeded or failed, but also what factors contributed to that result, and how your techniques could be improved for your next project. In order to extract such fascinating tips from your evaluation, you will need to feed in some extra information about things that are likely to influence the outcome of the project.

It is often good to incorporate measurement techniques from lower evaluation types into your monitoring program. For example, a Type 5 ecological evaluation could also incorporate records of physical features, records of how structures have survived, whether they were executed properly and use photo-point surveys. These types of information will allow you to track the development of the project. It is unlikely that the ecological outcomes will occur if, for some reason, the works are not completed as planned, or they are damaged by a flood, or the physical outcomes sought do not develop.

You should also collect data relating to the general condition of the stream and catchment. For example, it is almost always useful to have some measure of discharge through the project reach. This may be provided by a nearby gauge, or it can be estimated from a gauge in a nearby catchment. Discharge data will tell you all sorts of things about what is driving the changes in your reach. You may get a general deepening of the channel in your reach, but this could be related to an unusually long period of winter flow rather than a result of any structures you have built. Such catchment-wide changes should be identified by comparing your site with a control, but having a discharge measurement will allow you to explain the change as well as observe it. Other things you may measure regularly could be aspects of water quality such as turbidity, nutrients, temperature, dissolved oxygen, or salinity.

Similarly, having a general feel for changes in the catchment could also help in interpretation. For example, the changes you observe could be explained by long sections of stream being cleared upstream, or a reduction in nutrient-rich wastewater from piggeries upstream. Perhaps the changes you find at your site could be explained by these catchment-scale changes, and not by the local changes that you are introducing.

2.6. Task 6: How frequently should you monitor?



There are two basic strategies for deciding on sampling frequency: event-based sampling, and sampling at a predetermined frequency. Event-based sampling is particularly relevant for structural works in a stream when we want to observe the effect of our intervention after floods greater than a set magnitude. Predetermined sampling frequency is where the sampling times are specified at the design stage and are not linked to flood events. Depending on what you are measuring, a combination of event and predetermined frequency will usually be the most effective strategy (Kondolf, 1995). Table 29 shows some common rehabilitation activities, the measurable objective and suggested frequencies and duration of sampling. Table 30 shows a summary of evaluation projects, their key measure and the frequency and duration of sampling.

2.6.1. Event-based sampling

Kondolf (1995) recommends a monitoring period of 10 years to successfully evaluate a project. Measurements need not be made every year, but there should be a series of at least 5 monitoring events over the 10-year period. Monitoring is conducted in, say, years 1, 2, 4, 7, and 10, or following each flow exceeding some threshold such as the annual peak flow, with return periods of 2 or 5 years (Kondolf, 1995). Therefore, if a flood occurred in year 6 the stream would be surveyed and not again until year 10 (unless the predetermined flow was again exceeded). This sampling program is good for projects concerned with stream stability, which are affected by flow size.

2.6.2. Sampling at a predetermined frequency

There are two questions to ask yourself about sampling at a predetermined frequency. First, what time of year are you interested in sampling, and second, do you need to sample every year?

The answer to the first question depends on what your interests are. For example, if you have decided to monitor how stream animals are responding to rehabilitation, you should consider whether you are interested in the summer or winter fauna, or both. Particularly for macroinvertebrates, you are likely to find quite different suites of species present in different seasons. If you want to survey the riparian vegetation, you may find spring is the best season, because plants are easier to identify when they are flowering. If you are monitoring water quality, you may find the summer base-flow differs markedly from winter flows, when some pollutants (such as salt) are diluted by extra flow, while the concentration of others (such as suspended sediment) will increase. Anything that varies seasonally should always be measured at the same time of year. If, for example, you surveyed invertebrates in winter, just before your rehabilitation work, and then in summer, after the work, you could not be sure which differences were caused by your actions, and which were natural seasonal variation.

The answer to the second question depends on how long you will continue monitoring, what you want to do with your data, and how variable your stream is. As discussed in *Choosing the best sample size*, in Fundamentals of evaluation design (above), the more variable your stream is, the more samples you will need. This will be more important for bronze, silver and gold medal evaluation designs that involve some statistical analysis of results.

Table 29. This shows some typical rehabilitation activities, the sorts of measures which may be used to evaluate the activity, and an adequate frequency and duration of sampling to determine the response. These would of course vary depending on the situation. For example, physical responses to rehabilitation are likely to be faster in small streams, because the catchments are smaller, volumes of sediment stored in the system will be smaller and so on. With biological systems, the response time will vary depending on the life cycle of the organisms involved.

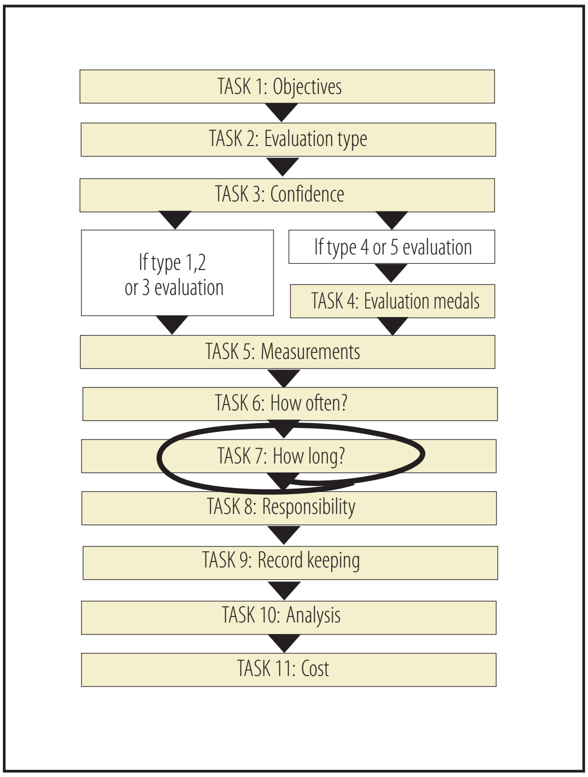
Rehabilitation activity	**Objective**	**Measure of response**	**How frequently do you sample?**	**How long do you sample for?** Before rehabilitation	After rehabilitation
Riparian vegetation	Closed canopy (tropics) Given density of surviving trees Given diversity of species Self-regenerating stand	Canopy cover Survival Species present Presence of seedlings	Once every two or three years	1 year	10 years
Re-snagging	More fish, more diverse macroinvertebrates	Surveys before and after, and control reach	Seasonal[1] (eg. spring and autumn)	2 years	3–5 years
Rock riffles	More diverse fish, more diverse macroinvertebrates	Surveys before and after, and control reach	Seasonal[1] (eg. spring and autumn)	2 years	3–5 years
Small weirs	Create pool riffle sequence; increase fish and macroinvertebrate diversity	Survey thalweg cross-sections, flow diversity, depth, bed material, fish and macroinvertebrates	Survey physical habitat before and after works, then after 2 year flood Survey biota seasonally	2 years	5 years
Bypass of fish barrier	Increase in fish population above barrier	Fish passing up fish barrier or Survey of population up and downstream	Seasonal* (when fish are migrating past the barrier)	Survey 2 years	3 years
Grade control structure	Stabilise bed so no further incision occurs	Survey thalweg and cross-sections	After 5 year flood and at 10 years	1 year	10 years
Erosion control works	Reduced erosion rate to that of a template reach	Works survive Erosion pin measurement	Floods greater than 1 year return interval	2 years	10 years
Reinstate cut-off bends	Reduced erosion and low velocity Reduced bank erosion	Flow velocity Erosion pin measurement	Floods greater than 1 year return interval	2 years	5 years
Sand extraction	Fall in bed Return of bed complexity	Cross-section surveys Longitudinal surveys Bed material composition	Annual or at five year flood		5–10 years (depends on extraction rate, size of stream and supply rate)

[1]It is important to sample at the same time of year.

Table 30. This table shows the duration and frequency of sampling from some evaluations made of rehabilitation projects (mostly from the USA).

Study	**Measure**	**Frequency**	**Duration**	
			Before rehabilitation	**After rehabilitation**
Koehn (1987)	Fish surveys	Once before, once after rehabilitation	2 months	3 years
Newbury and Gaboury (1993)	Trout eggs	Annual	None	6 years
Mallen-Cooper *et al.* (1995)	Fish numbers passing	Annual	2 years	2 years
Shields *et al.* (1995a)	Bed and bank stability Cover of vegetation	Variable	None	Variable. Up to 10 years monitoring, with up to 8 years casual observations after that
Shields *et al.* (1995c)	Fish species composition and abundance Physical habitat (pool area, heterogeneity, riparian vegetation, shade, woody debris)	Twice yearly	2 years	1 year
Frissell and Nawa (1992)	Condition of stream structures	After a 2–10 year flood	None	Once
House and Boehne (1985)	Stability of structures Channel morphology Fish utilisation of habitat Juvenile fish density and biomass	Annual	Shortly before rehabilitation	2 years
House (1996)	Habitat diversity Juvenile fish populations Spawning sites Gravel quality	Habitat was measured in year 1, 3 and 5 Other measures taken annually	1 year	11 years
Hunt (1976)	Number and size distribution of trout Trout biomass	Annually	3 years	7 years

2.7. Task 7: How long do you need to monitor?



For how long should we monitor? It is very important that, at the outset of a project, a time is set to complete the evaluation and final assessment of the project. Without such a deadline, interest may wane, and the evaluation could be left unfinished. So how long should that evaluation period be? The key question here is: how long will it be before I can expect a response in the variables that I am measuring? There are two issues here: is there a lag time between the intervention and the response, and will the response be sustained? Tables 29 and 30 give some ideas on duration of sampling.

2.7.1. What type of evaluation are you using?

Because of the different recovery processes involved, different types of evaluation will have different monitoring times (Tim Doeg, personal communication) (see Figure 32). Execution can be checked as soon as construction has finished. Survival must wait until the design flood has occurred. To evaluate aesthetics, you need to give the trees time to grow. Physical changes may also take time to eventuate, particularly if you have to wait for floods to occur. Biological outcomes may take longer still, because they are dependent on the physical changes. This means that, if you are doing a higher type of evaluation, you can stay involved with the progress of your rehabilitation by evaluating outputs, while waiting for the physical or biological outcomes to develop. This regular monitoring has the advantage of alerting you to any damage to your structures, so the project will be better maintained. Also, the regular updates on progress will help keep the community interested in the rehabilitation procedure.

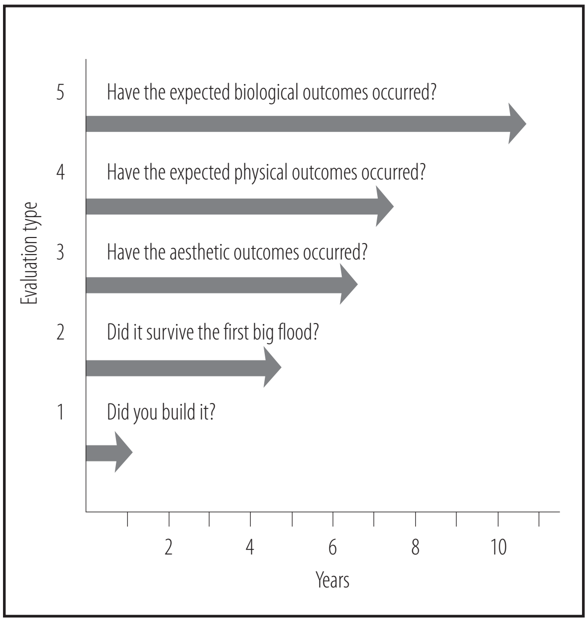


Figure 32. Some typical times taken for the various outputs and outcomes of a rehabilitation project to develop. You would evaluate each output or outcome at the end of its arrow (see Task 2 for description of evaluation types).

2.7.2. Is there a lag time between the intervention and the response?

The rate at which physical and biological systems respond to rehabilitation will depend partly on flow regime. This means physical recovery may be delayed until a flood of sufficient magnitude has occurred, and biological recovery may be slow until the minimum flow requirements of the species in question are met. In some cases, recovery will start slowly, and gradually gain momentum. For example, the population of a plant or animal will grow slowly while there are only a few individuals to reproduce, but as numbers increase, so will the growth rate. Hunt (1976) undertook a long-term evaluation of restoration of trout habitat in the USA. The evaluation began monitoring 3 years before the installation of restoration devices and continued for a further 7 years post-restoration. The results of this evaluation showed that the "the maximum number and biomass of legal trout did not occur until 5 years after the completion of development". Recognition of the success of this restoration project was realised only through effective long-term evaluation with sound baseline information.

The natural lags in a stream system may mean that it is decades before you see any response to your works. The classic example of this is establishing a link between catchment erosion control work and catchment sediment yield. Major catchment-wide erosion control works in the United States did not lead to any decrease in sediment yield even decades later (Trimble, 1982). The reason was that sediment seldom takes a simple path from catchment to outlet. Instead it is stored at various points along the way (eg. point-bars, fans, benches, channel floors). Movement of sediment from these existing stores maintained high sediment yields for decades, despite a decrease in catchment erosion. Many processes will have similar lags before they respond to intervention. Another example of natural systems with lags is the huge volume of nutrients already stored in deposited sediment in stream systems. Even if we stop nutrient output from agriculture and sewage plants, this great store of sediment-bound nutrients will be available for many decades. Salinity is another system with huge lags between action (eg. tree-planting) and results (lower watertables).

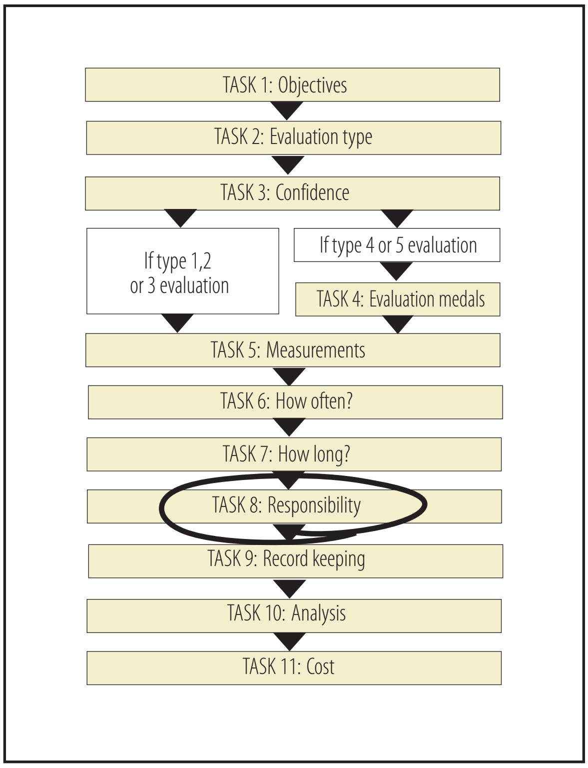
2.7.3. Will the response be sustained?

It is common to have marked fluctuations in response of systems. For example, we have seen several cases where, following construction of artificial habitat in a stream (say artificial riffles), there has been an initial burst of recovery, with good growth in populations of macroinvertebrates. However, this growth has been short-lived as some other variable gradually destroys the new colony—in these cases, usually gradual deposition of fine sediment.

As a result of these uncertainties, poor response after a year or two cannot be considered a failure. Equally, an initially encouraging result cannot be considered a success unless it has been sustained for several years. The length of the monitoring period will probably depend on the system being studied.

> **Set the endpoint of your study!**
>
> Make sure you have an endpoint in your study. It is important to decide on the endpoint of your evaluation when you are planning the project. Without this, monitoring can dribble along for a long time, and the data may never be analysed.

2.8. Task 8: Who is responsible?



There is mounting, and admirable, pressure to have monitoring done by community groups. The Waterwatch program is the key example of community monitoring.

In an ideal world, it should not matter who does the evaluation of a stream rehabilitation project. The experimental design should be so clear that anybody could come and do the work. Again in an ideal world, it would be the people who designed and constructed the project who would also do the evaluation. But in the real world there are several reasons why it does matter who does the evaluation. These relate to expertise, persistence and objectivity.

2.8.1. Expertise

Not everybody can do everything. For example, evaluating the number of fish larvae in a stream is a highly specialised job. Catching them is tricky, but amateurs can learn to use the equipment needed and to sample a range of habitat types. The problem is identifying the larvae, and making sense of the results. A recent meeting in Victoria considered approaches to monitoring biological health in streams using animal indicators and came to the general consensus that monitoring any biological community was a specialist task that was seldom an appropriate community activity (Monitoring River Health Workshop, River Basin Management Society, Latrobe University, 1997).

> "Whilst enthusiasm and energy are important assets to community involvement in environmental monitoring programs, in the long-run it will be data quality and reliability which will be the defining criteria of success" (Hodgkins and Bennison, 1997, p.9).

This, of course, has been the perennial argument with the Waterwatch program, in which members of the community monitor water quality. The consensus here is that the data provide useful descriptive information over a large area, and that the process is useful for raising awareness and for uncovering local problems missed by other monitoring, but the value of the data in scientific and management terms is limited (Hodgkins and Bennison, 1997). Again, it comes back to confidence. Gold medal monitoring produces data that are consistently accurate, and can be compared confidently with samples taken, say, 3 years ago by somebody else from another site 100 km away. It is important to consider whether your particular evaluation requires this level of confidence.

Even some of the most basic of monitoring techniques cannot readily be used by community groups because of the specialised equipment and expertise required. For example, electro-fishing, which is the most common method of field-sampling for fish, can be done only by highly qualified people.

2.8.2. Persistence

Detailed monitoring is often a boring, repetitive activity. Techniques have to be applied with ruthless consistency, and you have to go out whatever the weather, or however you feel. Monitoring has to continue even when nothing seems to be happening, or when the results are not what you wanted. And it often has to continue for years.

It is rare to find volunteers who have the stamina and persistence to face the rigours of a long-term monitoring program. However, if the monitoring involves simple protocols (eg. repeat photographs, counting something that is easy to count, identifying the presence or absence of something) then community members will be ideal for the job. Nevertheless, one person has to maintain responsibility for the quality of the data.

2.8.3. Objectivity

The foundation of evaluation is objectivity. Workers should measure and report bad news equally with good news. The ethic of scientists is to seek truth and to ensure that their own prejudices do not affect the 'outcome' of an experiment (this ethic is 'policed' by the critical review of scientific colleagues). Evaluation by people who are desperate for a particular outcome (ie. success) is less likely to be entirely objective. This is not even a question of honesty; rather it is the fact that people tend to see and measure what they want to see and measure, rather than what is true. If you don't believe that, consider how many people believe that their babies are the most beautiful babies ever born. Thus, for reasons of objectivity, it is best to have a project evaluated by people other than those who initiated it.

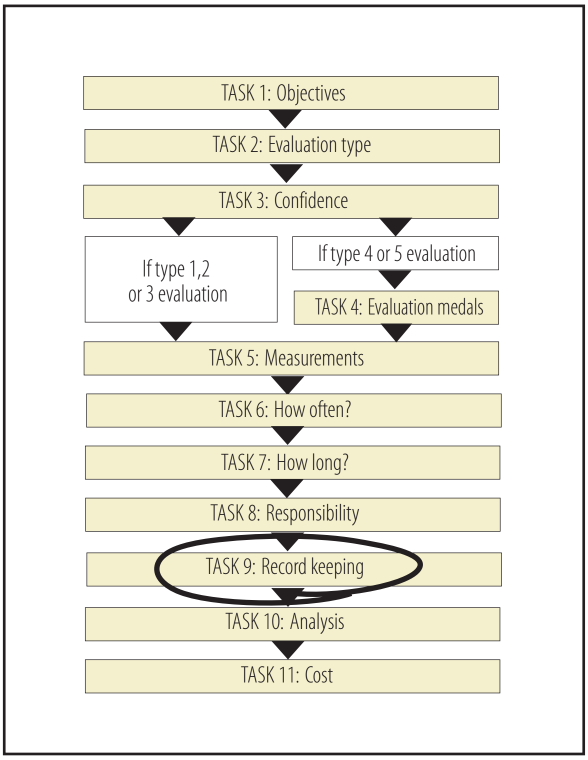
On the other hand, there are strong arguments for evaluation to be done by the same people who proposed, planned and executed the project. This has the best learning outcomes. Perhaps a middle ground is best, with monitoring done by the proponents of the project, while the methods and quality of the monitoring are evaluated by scientists.

2.8.4. Conclusions on responsibility

Most long-term monitoring will be carried out by professional scientists. There are many types of monitoring that can be done by non-professionals, but one person has to be responsible for the continuity and quality of the data.

Whoever does the evaluation, a critically important point is that the protocol and procedures for monitoring are so well documented that a new person can come in and reproduce the procedure. This is essential given the high turnover of personnel that is likely over a monitoring project that could last 5–10 years. For the same reason, the locations of all cross-sections and other measurement points should be clearly recorded and on-site 'monuments' installed. There are numerous examples of evaluation projects foundering because it was so difficult for new staff to work out what had been done, and where. Harrelson *et al.* (1994) give a detailed discussion of how to prepare and monument cross-sections, and generally plan rigorous field work.

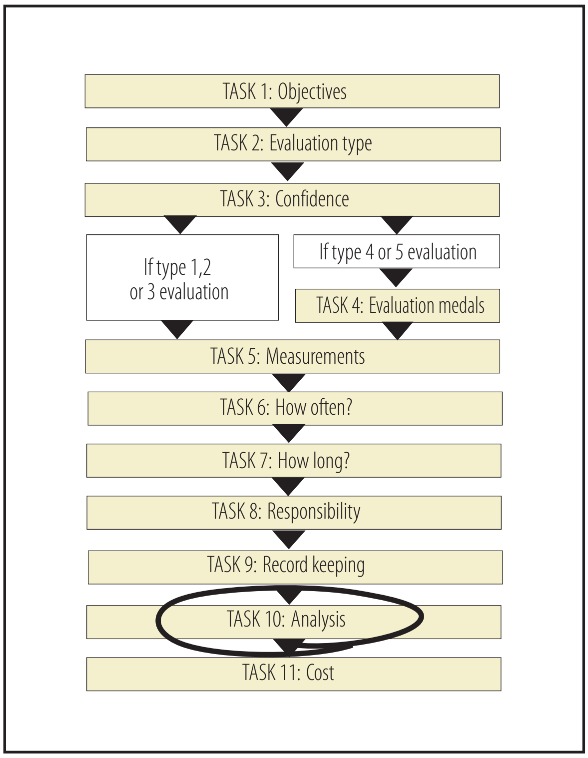
2.9. Task 9: What recording technique will you use?



Many evaluation programs are never completed because, at the end of the project, data collected are recorded in different ways, old records have been lost and the final job of collating a whole lot of data just doesn't seem very rewarding. There are a few key rules when it comes to data collection and reporting.

- Always prepare your own proforma recording sheet with a space for every piece of information you require (don't forget simple things like date and time).
- Every space in the recording sheet must be filled out even if it with N/A. A blank space implies 'I forgot', 'wasn't sure' or 'it's obvious'. The fact is, things are never obvious to someone who was not there, or even yourself in 12-months time when it comes to collating the information.
- Do not rely on your memory. Even the most obvious things must be documented because you might forget, or leave the project, and that information is then lost.

2.10. Task 10: How are you going to analyse the information?



When it comes to the analysis of your results, there are two basic options. Most simply, you can just 'eyeball' the data, and see if you think there was a big enough change after your rehabilitation to satisfy your objectives. With rather more difficulty, but considerably more accuracy, you can use some statistical test to process the data. As with the various levels of evaluation design, which of these analyses you choose depends on how much confidence you want to have in the final interpretation.

2.10.1. Eyeballing your results (simple comparison)

Examining your results by eye can be a fast and effective technique, particularly for small data sets. It often involves some simple manipulation of the data, such as calculating average values to compare. Eyeballing can look for changes or trends in the average value of your measurements. For example, you might compare the average number of macroinvertebrate families found in surveys before artificial riffles were constructed, with the average found after construction. It can be as simple as comparing two numbers. For example, you surveyed the fish population of the reach once before and once after constructing the riffles, and found five times more fish in the second survey. Alternatively, you can look for patterns of change. For example, you might compare the long profiles of the reach before the riffles were constructed, with the profile straight after construction, and after a one-in-three-year flood. You would be looking for the riffles to be shallower, and the pools between riffles to become deeper.

Eyeballing results is usually quick, easy and intuitive, and can be convincing when the rehabilitation caused a big change in the stream. However, it does not suit all data, or all purposes. It is difficult to be truly objective. You put a lot of effort into your rehabilitation project, and the stream looks so much better with those riffles and the pools below them. It is very difficult not to let your hopes and the belief you have improved conditions colour your judgment, however hard you try to prevent this. Also, large and complex data sets can be almost impossible to comprehend without mathematical help. How do you cope with lots of individual data points, all of which seem to vary in different ways? For example, if you survey macroinvertebrates in a relatively healthy stream, you could quite easily find over 50 different species. How do you make sense of your results when, after rehabilitation, some have increased abundance, others have decreased, there are some new species and others have disappeared. However, the greatest shortcoming of eyeballing data is its inability to take into account the variation in natural systems.

Eyeballing can be very useful, but because of the difficulty of taking variation into account, this sort of analysis is really convincing only when the change caused by the rehabilitation project is dramatically large. No-one is going to argue you made a difference if you catch 10 times more fish than before, but what if you only catch a few more, like Joe in the example that follows?

Eyeballing is:

- quick, easy and cheap;
- only trustworthy for detecting big changes;
- only good for small data sets;
- subjective; and
- will not convince sceptics.

A hypothetical example of analysing the results of an evaluation

Joe the stream manager had constructed some rather expensive artificial riffles in a reach that had several shallow headcuts. The channel had no deep pools and had a small fish population. Joe had wanted to do a first-class evaluation to show how well the riffles worked. He had fish survey data for four years before the riffles were constructed, and he surveyed for another four years after construction. At the end of the evaluation, Joe sat down and looked at the surveyed results (Table 31). Though they were not as dramatic as he'd hoped, he felt confident that there had been a moderate increase in the fish population. Pleased, Joe showed the results to his mate, Chris the ecologist, who he ran into on his way to apply for more money to build more riffles.

Table 31. The number of fish Joe found before and after the riffles were built.

Before	11	28	13	24	Average	19
After	17	24	19	36	Average	24

Chris looked at the results, and shook his head. "Well, we'll leave out the lack of a control site", he said. "These numbers may actually show the fish population hasn't changed at all. Remember that when you sample, you are not really measuring the population of fish, just how many you happen to catch in that survey. Some days you get lucky, and even though the fish population is the same, you catch more fish. See, before you even put in the riffles, your fish counts varied between 28 and 11. As well as that, natural populations are always changing a bit. If you look at how much variation there is in your results, I'd say there's a fair chance you didn't really change the total fish population at all, and you just got higher results in the second survey by chance." Chris did a few simple statistical tests called t-tests. These showed that in fact Joe couldn't be sure that the fish population has really increased, but there was a 78% chance that it had. "Well", said Chris, "it wouldn't convince everybody. Usually, scientists would only say fish numbers had changed if they could be 95% certain. I suppose you have to consider how certain of success you want to be, before you spend all that money building more riffles!"

2.10.2. Statistical tests

Using a statistical test is everything that eyeball analysis is not. It is tricky, time-consuming, requires a lot more care in collecting the data and often requires more data. However, it can cope with large data sets, is designed to take the subtleties of variation into account, is objective and is basically a lot more likely to be correct. The objectivity of statistics is its strongest point. Doing a statistical test involves asking the question, "How confident can I be that the work I did in the stream have really made a difference to the things I measured, over and above any natural variation?".

Statistical tests require you to decide how confident you want to be before you will accept that a project has succeeded. Scientists hate to be wrong, so they usually will want to be 95% certain that a change has really occurred. However, for management purposes, it may sometimes be acceptable to work with lower levels of confidence (Tim Doeg, personal communication). For example, when considering whether or not to use some rehabilitation tool, many stream managers would accept, say, a 75% chance that it will be a success. In this case, we should consider adopting such a confidence level in a statistical test of such management projects.

Statistics are really a form of complex mathematics, and there is no denying that it takes a lot of time and effort to come to grips with the discipline. In fact, we are not suggesting that you do. If you decide you want the ability to cope with complex data and confidence in the result that statistical analysis offers, then it is best to talk to an expert. It is essential that you do this in the planning stage of you evaluation, as it will influence the design of your monitoring program.

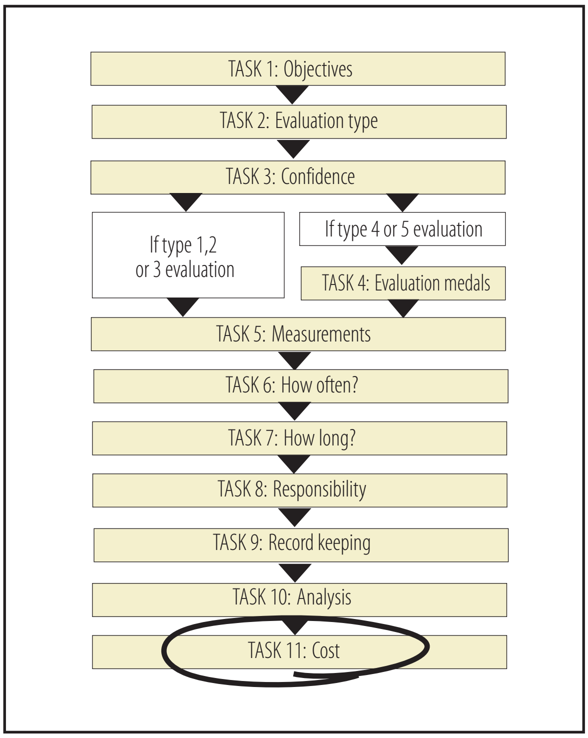
Statistical analysis can:

- be time-consuming, difficult and expensive;
- be trustworthy, providing you asked the right questions;
- handle large data sets;
- be objective; and
- convince hardened sceptics.

2.10.3. Conclusions on analysis

At the early stages of planing your evaluation, you should pause and think about what you want the results of your monitoring to look like. Are you expecting a huge response to your rehabilitation, one which will be easily detected without statistical analysis? Can your results be condensed into a few numbers that are easy to compare? Will you, and the people interested in your evaluation, be convinced if you do not use statistics? If so, then you could get by without a complex statistical test. However, if you would rather not risk being uncertain as to what your results mean, or wish to monitor something complex such as habitat diversity or macroinvertebrate populations, then it is wiser to choose a statistical analysis.

2.11. Task 11: How much will this cost?



The costs in evaluation come from buying or hiring equipment, and paying for labour (particularly expensive if you require expert assistance). This means that the simpler forms of evaluation (Execution, Survival and Aesthetics) can be quite cheap. However, any evaluation that requires people to regularly visit a site and measure something will be expensive. They may also require expensive equipment, eg. a basic electro-fishing back-pack unit costs about $6,000, while a full collection of nets and other gear for fish sampling would cost about $3,000 (Paul Humphries, CRCFE, personal communication). Hiring an electro-fishing boat and personnel to run it would cost about $1,000 per day.

Any project that requires samples to be taken and processed by professional staff (eg. grain-size analysis, macroinvertebrate identification) is likely to be very expensive. Has your project budgeted for this cost? Once you have decided on the level of evaluation, and the rigour of the design, the cost of monitoring tends to be reasonably similar whatever the size of the rehabilitation project. This means that, as a rehabilitation project becomes more expensive, the evaluation becomes relatively cheaper.

It is critically important that any evaluation component of a project is accurately costed at the outset, and that financial support is guaranteed for the duration of the project. You can imagine the scenario where a project is completed, evaluation continues for a year or two, a departmental head sees money sitting around in this evaluation fund-source "not doing anything". The challenge is to ensure that both money and personnel are committed to the evaluation for the planned duration of the project.

The cost of a gold medal evaluation: monitoring macroinvertebrate response to artificial riffles in Melbourne streams

Estimated by Dr Peter Breen, CRCFC

Cost of the six artificial riffles: $75,000

Cost of field sampling and laboratory analysis:
two person years + costs = minimum of $120,000

Ratio of construction/evaluation = 0.6

2.12. Summary of evaluation tasks

All projects should be evaluated in some way, even if it is only detailed photo records, and mapping of vegetation types. But it is foolish to consider evaluating all projects to a level of confidence that would satisfy scientists. The cost would be too high, but also, strict evaluation procedures could mean that altering (ie. improving) the project in mid-stream might confound the evaluation.

All stream rehabilitation projects should be seen as experiments. We will progress only when people openly admit that there is always room for improvement, and that some approaches have not proven successful in the past. Groups who widely publicise their 'failures' should be richly rewarded because they will save so many other people from making the same expensive mistakes.

The two key questions to ask in designing an evaluation approach are: how confident do I want to be that I have identified a response, and who am I trying to convince with the result? You should evaluate only to the level you need to. Much of the dissatisfaction and trouble with the 'evaluation' process comes from not specifying what the proponents will consider to be convincing evidence of success.

When developing an evaluation plan remember the following points.

- Select measurable characteristics that directly relate to the project objectives (carefully consider the selection of an appropriate spatial scale).
- Establish the desired level of these characteristics by taking measurements in an appropriate reference stream (or streams).
- Determine the timing and duration of measurements needed at the project and control sites both before and after works (this may need to include sampling at different flow levels).

A more sensible strategy than saying that all projects must be evaluated to gold medal standard is to select a range of projects of various sorts, and subject only these to rigorous, full BACI evaluation. These projects should be designed by scientists because, like accountants that can squeeze more out of your tax return, scientists can squeeze more knowledge out of an experiment.

3. Evaluation case studies

3.1. An evaluation of the effectiveness of artificial fish habitat in the Ovens River

This study by Koehn (1987) is an Australian example of a Type 5 evaluation (that is, investigating ecological change) using a silver medal (BACI) design. Examples of evaluations of this type are extremely rare. This case study takes you through each of the 11 steps described in the evaluation procedure.

3.1.1. Introduction

Between 1984 and 1987 a study of the effects of artificial habitat on fish numbers took place on a short stretch of the Ovens River near Porepunkah, in north-eastern Victoria. Before modification the stream was shallow and fast-flowing, consisting of a wide, flat bed and unstable shingle banks. The channel lacked in-stream cover and riparian vegetation. A low V-shaped weir was placed in the stream, and 24 m of river bed directly downstream seeded with large rocks. Below this, 100 m of channel was left unmodified as a control, while the following 30 m was unintentionally modified by willow debris. A 150 m section of river 2 km downstream was used as a second control site.

3.1.2. Task 1: What were the objectives of the original project?

This project aimed to increase fish stocks (two-spined blackfish, brown trout and rainbow trout were the species present) in a reach of the Ovens River in Victoria by introducing habitat in the form of rocks and a low log weir. Similar habitat enhancement has often been used in the northern hemisphere to increase trout and salmon stocks, and the habitat requirements of these fish are well known. However, there was no evaluated Australian version of this work, and little was known about the two-spined blackfish before this study, as the species had only recently been described. What information was available suggested the species prefers areas with plentiful stream cover. The closely related freshwater blackfish is also known to prefer reaches with slow-flowing water and plentiful cover, usually in the form of woody debris (Jackson, 1978a; Jackson, 1978b; Koehn, 1986). This led to the second aim of the project, to investigate the habitat preferences of two-spined blackfish through the evaluation of the first aim.

3.1.3. Task 2: What type of evaluation was needed?

The objectives of this project were to increase fish stocks by introducing habitat to the stream. Because the habitat requirements of two-spined blackfish were not well known, it was decided to directly evaluate the biological effects. If the link was well understood, just measuring the changes to the physical habitat might have been sufficient. This makes the evaluation Type 5 (biological effects). The physical effects were also investigated (evaluation Type 4), in order to begin amassing knowledge of the species' requirements.

3.1.4. Task 3: What level of confidence was needed?

The objective of this project was to increase the fish population of the treated reach. Because there was little known about the fish, it wasn't possible to be confident about what the result of the project would be. This, combined with the second objective—to enhance scientific knowledge of the habitat requirements of the two-spined blackfish—suggested that the study required a design with a high level of confidence.

3.1.5. Task 4: What level of design was appropriate?

A silver or gold medal level of design would provide confidence in the results of the evaluation. The researchers chose a silver medal design, incorporating sampling before and after the rehabilitation (so you can tell that a change occurred), and a control site (so you can be confident that the change was due to the artificial habitat).

3.1.6. Task 5: What was measured?

Because the objective of this project was to increase the fish population, the number of fish present had to be measured. Fish surveys were conducted at the study and control sites in February 1984 and February 1987 using a Smith Root MK VIA electrofisher. Fish were identified and their length measured. In the last survey, the location of captured fish was marked on a map, to differentiate between fish caught in modified and unmodified areas. What this evaluation actually measured was the increase in the summer population of fish that could be caught by electro-fishing.

The physical habitat was assessed in terms of water depth and velocity. Water depth was measured along representative transects (the report does not say if these were cross-sections or long-sections of the stream). Velocity measurements were taken 10 cm above the bed along the same transects, and the results placed in 20 cm/second categories. These measurements were taken in February 1984 (just before the modifications) and in July 1984, January 1985 and February 1987 after modifications.

The large rocks at the modified site were counted and general observations made in both 1984 and 1987. A photographic record was kept of the modifications and subsequent changes.

Other data collected included stream width, area of the pool above the weir and discharge. These were measured at the same time as other physical data were collected. There was no attempt made to get a measure of the peak flows during the study period.

3.1.7. Task 6: For how long did monitoring continue?

The fish population was surveyed once before the habitat modifications were made, in keeping with the silver medal BACI design. The post-modification survey took place three years later. From the literature (summarised in Table 30) this seems long enough to expect the new habitat to have had an effect. However, it may not be long enough for the fish population to have reached a new stable level. For example, Hunt (1976) found that it took 5 years for trout populations to reach a maximum after artificial habitat was added to a stream.

The physical habitat was surveyed soon before and after the works were completed, in 1984, and in 1985 and 1987. This gave an assessment of the state of the works at the times of the fish surveys. However, if the researchers had wanted to draw conclusions about the stability of the works, it may have been more appropriate to monitor after a flood of a five or ten year recurrence interval.

3.1.8. Task 7: How frequently were measurements made?

The researchers chose a silver medal design for this evaluation. This level of design incorporates one survey before and one after the rehabilitation. The fish population was surveyed once before and once after the structural works. This is the minimum required to conclude there was a change caused by the artificial habitat. However, it is not sufficient to give a measure of the variation in the fish population, or to show any trends in the population—the increase in fish numbers might be maintained, or it might be short-lived.

The physical habitat was surveyed more frequently—once before and three times after the habitat modifications. This repeated data collection allows the variation in the effectiveness of the habitat to be assessed. However, very little was done with the detailed information collected in those surveys which were taken between fish surveys. It may be that between 1984 and 1987, a very simple count of the rocks present (a Type 2 'evaluation of survival') would have been sufficient.

3.1.9. Task 8: Who was responsible for the evaluation?

The evaluation was carried out by a scientist from the Department of Conservation, Forests and Lands in conjunction with a local consultant. These people between them had the expertise required to complete the field work, as well as the persistence (it is relatively easy to maintain interest and complete the evaluation when it is your job). As professional scientists, they were likely to remain objective, despite being the initiators of the project.

3.1.10. Task 9: How was the information analysed?

No statistical techniques were used in the analysis of these results; indeed none were possible. Statistics rely on having some form of replication, so assessments of the variation can be made. Instead, the analysis relied on the differences being obvious to the eye with very little manipulation required. As can be seen below, this style of analysis is convincing in this case, because of the huge increase in the number of blackfish.

Fish

Fish numbers and density from before and after rehabilitation were compared.

Habitat

The depth and flow velocity data were converted into the percentage of the transect which fitted into each category (20 cm and 20 cm per second, respectively) and the number of times different categories were encountered during the transect (ie. the frequency distribution). These gave an indication of the dominant flow depth and velocity, and an indication of flow variability, respectively. These physical habitat measurements allowed a check that the rehabilitation had actually changed conditions in the stream, as well as helping in the interpretation of the biological data.

The number of rocks present just after the habitat was modified was compared with the number present at the end of the evaluation.

3.1.11. Task 10: How much did this evaluation cost?

There was no indication of cost in the report. However, it is likely the evaluation cost at least as much as the physical works.

3.1.12. Task 11: What recording techniques were used?

During electro-fishing, the positions in the reach where fish were caught were marked on a map. No other information is available on recording techniques.

3.1.13. Results and conclusions

Fish

Two-spined blackfish were the main species caught in the study. Some trout were caught, but their numbers were so low that they are disregarded in this summary. Table 32 shows the overwhelming result that there were nine times as many fish in the artificial rock habitat as expected, and five times as many in the willow debris habitat, while fish numbers in the unmodified stream did not increase. Similar results are found when the results are expressed as numbers of fish per 100 m^2 of habitat. From this it seems clear that the artificial habitat had a dramatic effect on fish numbers. With only one survey before and one after treatment, no statistical analyses of these results are possible. In this study it may not matter because the increase in fish numbers was so great. However, a more subtle response to the rehabilitation might have required some statistical analysis for a clear interpretation.

Table 32. The increase in blackfish numbers after the construction of artificial habitat in the Ovens River.

River section	Increase	Fish per 100 m^2
Rock area	x 9	9
Unmodified area (control)	x 1	1.1
Willow debris	x 5	6.7

Habitat

The velocity transects revealed a greater flow complexity after modification (9 velocity categories encountered before compared with between 13 and 19 after). They also showed an increase in both the slowest and fastest moving water in the rocky section. By comparison, flow complexity in the unmodified section had not changed, though the proportion of high velocity flow had increased.

The comparison of the number of rocks present just after the modifications and at the end of the study revealed that a large portion of rocks had been covered by sediment, and were therefore no longer providing fish habitat.

Conclusion

The researchers concluded that in-stream cover was important to "fish species, especially the two-spined blackfish", and "that the use of artificial cover can dramatically increase" fish stock. It is not stated, but we assume that the variation in flow velocity produced by the works contributed to the improved habitat. Importantly, there were few fish found in the deep pool formed upstream of the structure, suggesting that the cover and hydraulic habitat associated with the rocks, weir, and willows were more important than the pool depth. However, because the weir was not isolated from the rocks, it is not really possible to separate the effects of the two components of the rehabilitation.

The original objectives of this project were to increase the fish population of the modified reach, and to increase knowledge of the habitat preferences of the two-spined blackfish. These have plainly both been met. There was a nine-fold increase in two-spined blackfish numbers, and it is now known that the species, in this situation at least, prefers reaches with plentiful in-stream cover and diverse hydraulics, including areas of slow-flowing water.

3.2. An evaluation of the use of vegetation and structure to control stream bank erosion caused by bed degradation

An example from the Mississippi River, USA of a gold medal Type 4 (physical effects) evaluation (Shields *et al.,* 1995a).

3.2.1. Introduction

Stream bank erosion is a very widespread problem in the USA, and large amounts of money are spent on bank stabilisation. This study looked at three techniques for bank stabilisation that had been used in the north-west Mississippi at various times over the previous 18 years. The three techniques examined were:

1) revegetation only (five replicate sites);

2) combined revegetation and toe stabilisation (three replicate sites); and

3) combined revegetation, toe stabilisation and reshaping the banks (three replicate sites).

There were control plots at most rehabilitation sites.

3.2.2. Task 1: What were the objectives of the original projects?

The objective of each of the projects examined in this study was to create stable, vegetated banks where stream incision had caused major bank erosion. The process by which bed incision is followed by bank erosion is well known (Harvey and Watson, 1986; Simon and Hupp, 1987). As the stream bed deepens, bank height increases until the bank slumps into the stream. This slumped material is then eroded from the toe of the bank until the bank again reaches a critical slope and slumps again. This process can dramatically widen the stream. When the headcut has moved on, the banks are stabilised by deposition of sediment from erosion upstream, at least until the next wave of incision passes. The aim of this study was to compare the success of the three commonly used bank stabilisation techniques listed above, to "provide useful information for selecting combinations of plants and structures for stabilising and restoring banks of incised channels".

3.2.3. Task 2: What type of evaluation was needed?

The objective of these projects was to stabilise and vegetate eroding stream banks. As a simple measure, the survival of the vegetation and other works would indicate whether they were successful as continued erosion would have destroyed the works (Type 3 evaluation). You can also use channel morphology to assess the bank stability. Gently sloping banks are likely to be stable, unlike abrupt cliff-like banks. Revegetation was also an objective of the projects, so some assessment of the riparian vegetation was required. This study involved aspects of Types 4 (physical effects) and 5 (biological effects) evaluation.

3.2.4. Task 3: What level of confidence was needed?

The aim of this evaluation was to provide information for stream managers selecting techniques for bank stabilisation in incised streams. As bank stabilisation projects are usually rather expensive, particularly those that involve structural works, it is necessary to have confidence in the results. You would not appreciate having a useless technique recommended to you because a sloppy evaluation had not detected the faults. Also, the results were to be published in a scientific journal, which requires a very high level of confidence in their veracity.

3.2.5. Task 4: What design of evaluation was appropriate?

A silver, or preferably gold, medal level of evaluation design would give enough confidence in the results. The authors chose a gold medal design (a replicated BACI design), examining the stream before and after the intervention (to be sure a change had occurred), with replicate sites and replicate controls (to be sure the change was caused by the rehabilitation, and that a similar strategy would probably have a similar effect in other streams). This was possible largely because the original projects, which this evaluation covers, had included control sites.

3.2.6. Task 5: What was measured?

The objective of these projects was to create stable vegetated banks. Some method of assessing the success of the vegetation was required. The authors measured vitality by calculating the percentage survival of all the trees that were planted. This was done separately for each species present. At some sites, the success of the vegetation was measured by comparing the lengths of bank that were vegetated or bare.

The stability of the banks was assessed visually and by taking measurements of the channel morphology. On incising streams, unstable banks will be high and cliff-like, while banks which have stabilised will have gentle slopes. Channel morphology was assessed by measuring repeated cross-section and thalweg profiles at most sites.

Other information collected included stream stage, discharge and precipitation records for most sites, and the cost of the original bank stabilisation techniques.

3.2.7. Task 6: For how long did monitoring continue?

This was an opportunistic evaluation, incorporating suitable experimental plots of varying ages. As a result, the monitoring periods at different sites varied from only a single growing season to 18 years. A single growing season is really not long enough to assess the success of the stabilisation. The authors point out that, at some of the older sites, high early mortality in the planted vegetation was followed by successful bank stabilisation with natural regeneration of native species occurring within three years. As the longer periods of monitoring were sufficient to show this natural revegetation, this suggests that monitoring for slightly over three years would be sufficient to assess the success of the vegetation.

The success of bank stabilisation works also depends on whether they have been tested by high flows. This varied between sites, with some experiencing moderate floods, whilst two others had record floods. However, the construction of bank protection seems to have occurred in periods of below average flow at many sites. For those sites that have not yet experienced floods, it may be premature to conclude the works have stabilised the banks.

3.2.8. Task 7: How frequent were measurements made?

Because this evaluation was an overview of many individual projects, the frequency of monitoring varied from site to site. It is not clear from the published paper how frequently monitoring occurred. To assess the long-term stability of the stream banks, it might be possible to take measurements only once before and once after the modifications were complete. This would tell you if the project was successful. However, in those cases where the works failed, such a monitoring regime would miss any chance of telling you what caused the failure. Ideally, monitoring should occur more frequently than this, for example, once a year until the vegetation was established, or after every flood above a certain size.

3.2.9. Task 8: Who was responsible for the evaluation?

The evaluation was carried out by the authors (two hydraulic engineers and one ecologist) who were employed by the US Department of Agriculture. Between them they had the expertise to complete the monitoring, as well as the persistence. As professional scientists, they likely had the ability to remain objective.

3.2.10. Task 9: How was the information analysed?

This evaluation included many individual projects of different ages. As a result, information was not available in the same form for each site, and the length of monitoring period varied. This would have made statistical analysis very difficult. Instead, the results were examined in an 'eyeballing' style of analysis; in this case basically a qualitative comparison of descriptions of sites with each of the three rehabilitation strategies.

3.2.11. Task 10: How much did this evaluation cost?

The cost of the evaluation is not given in the published paper.

3.2.12. Task 11: What recording techniques were used?

Techniques for recording information in the field are not reported in the published paper.

3.2.13. Results and conclusions

The results showed that vegetation by itself was not sufficient to stabilise stream banks while the process of bed erosion went unchecked. However, if the bed was no longer eroding, natural recolonisation of unplanted control plots was generally as successful as manual revegetation (the proximity of a seed source is not commented on). Where toe protection was combined with revegetation, banks still failed but as the toe protection prevented scour from eroding the spoil, a stable angle of bank was formed and recolonised by local trees. This occurred even where the stream bed eroded slightly. Where banks were shaped along with the other treatments they "remained well vegetated and stable" at all sites.

3.3. Evaluating structural works on the Hunter River, New South Wales

This study by Nagel (1995) is an example of a Type 4 (physical effects) evaluation, using a Tin medal design.

3.3.1. Introduction

Large floods in the 1950s triggered catastrophic widening of streams in the Hunter River catchment (New South Wales). To stabilise the streams, many millions of dollars worth of structures (mesh embayments) were built to artificially narrow the stream along a stable alignment, incorporating willow plantations. New alignments and widths were determined by comparison with nearby stable sections of stream. The performance of 28 bank protection structures along 3.4 km of Baerami Creek (a tributary of the Hunter River) was evaluated in 1994 by Fiona Nagel (Nagel, 1995), then an honours student at Macquarie University, now Resource Officer, Riverine Management, Department of Land and Water Conservation North Coast Region, NSW.

3.3.2. Task 1: What were the objectives of the original project?

The original goals of the work were to "protect assets from abrupt channel changes during floods, and provide a stable unobstructed channel for the efficient conveyance of water and sediment". These objectives are not couched in terms that can be measured easily. It would have been better if they had included some indication of which assets should be protected, what size floods the channel should convey without significant erosion, and what the stable, unobstructed channel should look like in terms of, say, width, depth and roughness.

3.3.3. Task 2: What type of evaluation was needed?

The first objective of this project was to prevent abrupt channel changes during floods. This required a Type 4 (physical effects) evaluation to measure the channel morphology before and after major floods to quantify any erosion. The second objective was to provide a stable channel for the efficient conveyance of water and sediment. As this involved creating a new channel in the old over-widened bed, this objective could be measured in a Type 2 evaluation (survival), to see if the constructed channel is still present, or Type 4 (physical effects) to see if the new channel is capable of conveying water and sediment. The evaluation by Nagel (1995) was a combination of types 2 and 4.

3.3.4. Task 3: What level of confidence was needed?

The evaluation was aimed at assessing, for the benefit of stream managers, the value of stream stabilisation works, so that current stream stabilisation practices can be improved. A moderate level of confidence was sufficient.

3.3.5. Task 4: What design of evaluation was appropriate?

A bronze or silver medal design was appropriate for a moderate level of confidence. However, this evaluation was handicapped by being designed 27 years after the completion of the structural works, rather than during the project planning. There was little precise information available on the pre-works channel. No control sites were included in the original project; they would have allowed a comparison of the natural recovery of the river with the effects of the structural works. Instead, the evaluation was limited to comparing the original design of structures with their condition in 1995, and studying the river's geomorphic condition. However, 28 replicate site were incorporated. This would be classified as a tin medal design with replication.

3.3.6. Task 5: What was measured?

Collecting measurements for an evaluation designed after a project is completed is usually difficult. Relevant information is often not collected before work commences, and evaluation must rely on inferring the original condition of the stream from sources such as old surveys or air photos.

Evaluating the survival of structural works usually involves comparing the present condition of a structure with its 'as-built' condition. In this case, this involved detailed examination of historical records including old surveys and field ganger reports detailing the construction. Where these were missing, construction dates for the works had to be inferred by willow tree core dating or extrapolation from old photos. The channel morphology was measured to detect changes in channel alignment, sinuosity and width, and bed level changes. Interpretation of aerial photographs yielded information on channel changes. Additional information of stream gauge and rainfall records was obtained where possible, but these records were incomplete.

3.3.7. Task 6: For how long did monitoring continue?

The measurements of the channel and channel training structures took place between 1 and 27 years after construction, depending on the age of the works. Twenty-seven years seems a very long monitoring period, but nevertheless it did not include any floods of the magnitude which caused the original channel widening. As the project objectives didn't specify what size floods the structures should withstand, it is unclear if this monitoring period is sufficient.

3.3.8. Task 7: How frequently were measurements made?

The structures were examined once in the 27 years since construction. This is sufficient to measure gross changes since construction, but not to provide information on the trends in channel development, or suggest what events may have caused failure, where it occurred. Monitoring after every flood of a given size is ideal.

3.3.9. Task 8: Who was responsible for the evaluation?

No evaluation appears to have been built into the original project design. Fiona Nagel, an honours student from the School of Earth Sciences at Macquarie University was responsible for the post hoc evaluation. Such a person would have access to the expertise required to complete the monitoring.

3.3.10. Task 9: How was the information analysed?

Changes in the channel alignment at each field site were put into discrete categories, including upstream or downstream meander translation, bend rotation or extension, or movement of the channel away from the works. The channel-training structures were ranked in terms of effectiveness. An example of a 'least effective' site may have erosion into the bank the structure was designed to protect, as well as upstream and downstream erosion, and few surviving planted trees.

3.3.11. Task 10: How much did this evaluation cost?

This evaluation was part of a student project, and costs were therefore low, around $3,000. However, this included unpaid labour of almost 6 weeks in the field, and much of two years' part-time study.

3.3.12. Task 11: What recording technique was used?

Data were recorded in the field, on pre-printed forms.

3.3.13. Results and conclusions

The stabilisation works examined here were not really designed with evaluation in mind. It is possible to evaluate the **outputs** of the project—the stabilisation structures and vegetation. These generally seem to have survived, although the willows used at the older sites are now reaching the end of their lives. However, it is harder to say anything concrete about the outcomes of the project. The structures have controlled erosion of the bends that they were designed to protect. However, the stream has narrowed and developed a new meander wavelength. Because of this, the banks are now eroding up and downstream of the works. Nagel (1995) suggested that such adjustments were an inevitable result of the flow regime. Because there was no control site, it is difficult to say if the current situation is preferable to one where no stabilising work was done. Given the lower flow regime since the installation of the structures, it is possible that the observed contraction of the channel would have occurred without any intervention. This lack of high flows also means the structures have never been tested by floods as large as those of the 1950s. Thus, it is difficult to decide whether or not to call the works a success, or just a case of serendipity.

MISCELLANEOUS PLANNING TOOLS

- Why stakeholders may not support your plan
- Setting priorities for stream rehabilitation
- Legislative and administrative constraints
- Benefit–cost analysis of stream rehabiliation projects
- The geographic information system (GIS) as a stream rehabilitation tool
- Some costs of stream rehabilitation activities
- Bibliography of some technical information available in Australia

WHY STAKEHOLDERS MAY NOT SUPPORT YOUR PLAN

*Compiled with the assistance of Neville Oddie**

The support of other people is critical for the long-term success of all stream rehabilitation projects. This will mean not only getting support from landowners, but also from any other stakeholders in the stream, including anyone with an interest in the general community, government departments, and industry. In *Step 2: Who shares your goals for the stream*? in the Stream rehabilitation procedure, Volume 1, we discussed how to go about getting people's support. In this section, we expand on this, describing seven reasons why other stakeholders in the stream might not support a rehabilitation plan, and how you might go about finding a compromise that everyone can agree on. The following applies particularly to rural landholders.

1.1. Landholders do not recognise that there is a problem

In many situations, landholders will have a different vision of their stream than do stream managers. Farmers may see streams in terms of the drainage and water supply functions, or as a nuisance (a source of pests or weeds, or floods). Alternatively, landowners may have a vision of the stream based on, for example, aesthetics, flood conveyance, stability or trout fishing, rather than the broader environmental goals of the stream manager. Landholders may well see no problem with a stream that has very little ecological value in its present state.

> ## Possible solutions
>
> Change the landholder's vision of the stream.
>
> Set up demonstration sites that show what can be achieved.
>
> Involve the landholders in the problem identification process.

1.2. They can see that there is a problem, but it's not *their* problem

Stream rehabilitation benefits the community and future generations as well as landholders. In this situation, landholders may feel that the responsibility for rehabilitation (and its costs) lies with the community rather than with them.

> ## Possible solutions
>
> Know the cost and any other consequences of the project from the outset (see Natural channel design, this Volume, for methods of estimating flooding and erosion consequences of the works). Knowing the cost of the project makes it easier to negotiate compromises.
>
> Know the value of benefits to the farm that may result from the project (see, for example, the end of this chapter).

1.3. Stakeholders disagree with the stream manager about the cause of the problem

Often, people will agree with the stream manager that there is a problem, but vehemently disagree about its cause. Years of observation of stream behaviour, including short and long-term changes, often means that people have formed ideas about the causes of stream problems. However, they may not have an understanding of the geomorphic or biological processes underlying changes to the stream. People may mistake association with causation, as in the following example. This is not to say that stakeholders can't be right and stream managers wrong, rather, just because somebody has observed something for a long time does not automatically mean that they understand the cause, or know the best solution.

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Confusing association with causation: Nambucca River, north coast of New South Wales

The banks of the Nambucca River have been eroding dramatically. River oaks growing on the bank face are toppling into the stream. The local view is that the trees are weighing down the banks and causing them to collapse, so the best management is to remove the trees. The stream manager's view is that the bed is deepening, causing the banks to collapse, and the trees are not involved. The appropriate management would be to stabilise the bed.

Possible solutions

Involve local people in the investigation of the problems, so that they can uncover the reality of the situation for themselves.

1.4. They do not believe that the plan will work

Where people feel that managers have not identified the correct stream problem, or where they do not understand the underlying processes, they may feel that your proposed solution does not make sense.

Possible solutions

Make sure people understand the problems.

Flesh out the methods to explain how they will work, perhaps using a small-scale model, a computer simulation, or pictures of the method successfully used elsewhere.

Organise a trip to a demonstration site where the method has worked well (it can be worth cultivating pioneering landholders).

Don't be unrealistic about the possible outcome of a project. People will lose interest when promised improvements fail to appear, and will often be harder to motivate for the next project.

1.5. They believe the impacts of the plan will be too great, or are unclear

People may understand why a stream rehabilitation project is proposed, and agree with the problems and solutions suggested, but remain unwilling to accept the costs, in terms of the increased risk of flooding or erosion, loss of land to the riparian zone, the need for alternate watering points, and so on.

Possible solutions

Acknowledge the impact of stream works, and budget for work that will reduce the impact of the project (eg. alternative watering points).

Determine the likely increases in flood depth and duration or erosion (see *Natural channel design*, this Volume), so that landowners can judge for themselves if the risks are significant. Quantifying the risks helps keep them in proportion.

1.6. They are unwilling to commit time, resources and personal energy to the project

Sometimes, people agree with the need for a project, and approve of the problem identification and proposed solution, but do not have enough spare time or money to help at that time.

Possible solutions

Landowners are more likely to make the effort to donate their labour if they can see that their time is used efficiently.

Explain that streams cannot be taken for granted, and that they really need the same care and attention as a crop.

1.7. Stakeholders do not 'own' the plan

Community 'ownership' of a stream rehabilitation plan is generally seen as a prerequisite for success. It matters little how technically good the plan is, if it is not 'owned' and embraced by the local community it has a much higher chance of failure. Similarly, if you hold the strings too tightly, regarding the plan as 'your baby', you will probably lose support and be left 'holding the baby'. Ownership means that, as well as being involved in the development of the project, local people take at least some responsibility, so that the success or failure is, in part, up to them.

Possible solutions

People should be involved in the entire process of planning and rehabilitating the stream.

People should be given some power over the project. This may be possible by defining basic boundaries the plan must stay within (eg. it must lead to a long-term increase in biodiversity), but within those bounds the community plays a major role in deciding what form the project will take.

1.8. Some economic benefits of vegetation on farms

*Provided by Mike Askey-Doran**

NOTE: Most of these figures come from studies of patches of remnant bush on properties, not specifically from riparian zones.

Vegetation acts as a windbreak, sheltering stock from extremes of cold, wind and rain, and reducing death rates in new-born lambs or newly shorn sheep. In a trial in south-western Victoria, a 5-day period of cold, wet and windy weather led to the deaths of 40% of lambs in exposed areas compared with 12% in sheltered areas (Reid and Bird, 1990). On one bitterly cold night in 1987, up to 30,000 sheep died in western Victoria, while 1,600 sheep (worth $80,000) that were moved into remnant bush survived.

Trees provide shade, which reduces heat stress. Heat stress has been shown to reduce the fertility of both cattle and sheep (Bird *et al.,* 1984). Pregnant cows are more prone to abort when heat stressed, and new-born calves are more likely to be undersized (Reid and Bird, 1990). Heat stress affects appetite which leads to reductions in weight gain and wool production. Research has demonstrated that cows and calves grazing with adequate shade have weight gains up to 0.6 kg daily compared with 0.3 kg for stock without shade. Work in Armidale has demonstrated that shelter leads to both increased wool production (up to 31%) and higher live-weights (up to 6 kg). Shade is especially important for dairy cattle, as milk production drops off as temperatures rise above 20°C (Reid and Bird, 1990).

Fencing riparian land can prevent the loss of valuable stock, such as dairy cattle, which may drown if they fall into a stream.

Riparian vegetation acts as a windbreak, reducing wind velocities and consequently reducing water losses from both soil and crops. Pasture and crop yields can be as much as 20–30% higher on the downwind side of a shelterbelt compared with unprotected crops. The windbreak can be effective for a distance up to ten times the height of the windbreak (Sturrock, 1981).

Anecdotal evidence suggests that retaining remnant vegetation can add up to 10% to the sale price of rural properties. Agricultural and cattle properties in Western Australia that have retained remnant vegetation have been favoured over over-developed properties. People purchasing land are valuing remnant bushland as a real asset and are adding this value into their purchase price (O'Brien, 1996).

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SETTING PRIORITIES FOR STREAM REHABILITATION

Almost every reach of every stream has suffered from some human impact since European settlement. Some streams are still in fairly good condition, while others would be unrecognisable to those who knew them 200 years ago, because of major changes to the riparian zone, channel, and water quality. Many streams or reaches are presently deteriorating, or are threatened by future degradation as land uses develop and change. Other streams are recovering from past disturbances. In any one reach, there are often many different problems, from habitat simplification caused by erosion or deposition, to bad water quality or the presence of exotic plants or animals such as willow or carp. Because of this complexity of stream condition, and the shear magnitude of the damage to our streams, deciding what to work on first is possibly one of the most important tasks in stream rehabilitation.

This chapter is a companion to *Step 5*: *Setting priorities* in the Stream rehabilitation procedure in Volume 1. *Step 5* includes an introduction to the concepts behind our prioritisation, while here we present a more-detailed technique for assigning reaches to the priority categories, and prioritising problems for treatment. The flow chart below shows the relationship between the 14 tasks in this chapter and the 7 tasks in *Step 5*.

Tasks described in Step 5	Corresponding tasks in this section
TASK 1: Assign reaches to categories	TASKS 1- 6: The reach priority shuffle
TASK 2: Rank multiple reaches in the same category	The reach priority categories
TASK 3: See if there are reasons to alter the rankings	TASK 7: Are there reasons to change the rankings?
TASK 4 & 5: Set problem priorities	TASK 8-11: Setting problem priorities
TASK 6: Exceptions to the problem priorities	TASK 14: Exceptions to the problem priorities
TASK 7: Check if some reaches should have more then one rank	TASK 12-13: The reach priority reshuffle

1. Where do I start?—the reach priority shuffle

In *Step 5* of the Stream rehabilitation procedure, Volume 1, we presented nine priority categories to guide your rehabilitation planning. Here we present the 14 tasks of the reach priority shuffle that you can use to help you decide which reach fits into which category (note that this shuffle will work just as well for prioritising at the regional scale, where, instead of reaches, you consider entire catchments).

Reaches will be ranked according to **rarity** (rare–common), **condition** (good–bad), **trajectory** (deteriorating–improving), **proximity to good reaches**, and **ease** of rehabilitation (easy–hard). The reach priority shuffle is presented in Figure 33. Detailed descriptions of the nine priority categories can be found in *Step 5* of the rehabilitation procedure, Volume 1.

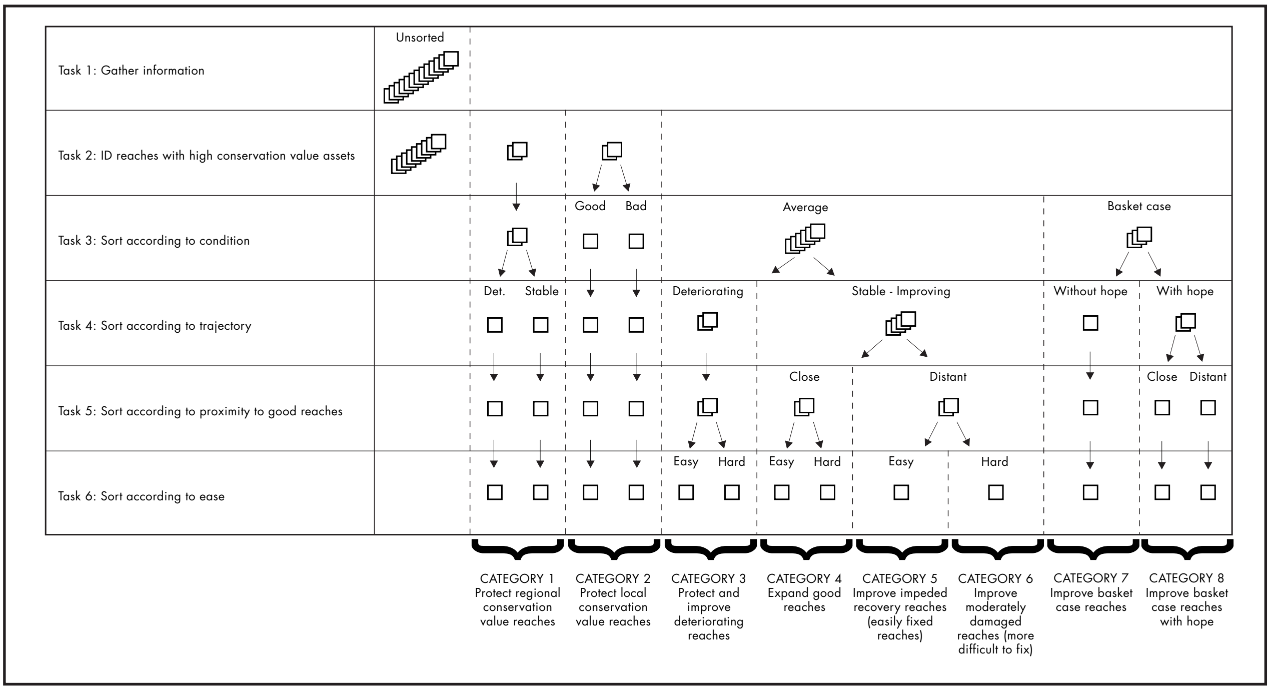

Figure 33. A diagram of the reach priority shuffle. To do the shuffle, you need to write the name of each reach onto a card, then shuffle the cards into the reach categories using the six tasks described below. Here we shuffle reaches from a hypothetical stream. This diagram shows only some of the possible paths into each category. Note that there are 13 reaches in this example, so 13 cards can be seen in each task.

1.1. Task 1: Gather information

In order to do this prioritisation, you will need to be familiar with each reach or catchment you are considering. You should have a list of high-quality assets (including any special conservation values that are of regional or national significance), a list of degraded assets, some notes on the trajectory of assets (is it stable or getting better or worse?), and a list of problems (that threaten quality assets or damage degraded assets). *Steps 3 and 4* of the Stream rehabilitation procedure, Volume 1 describe how to identify these features of your stream.

> One way to get through the following process is to write the name of each stream reach on a card (if you have several reaches), along with a list of its assets and problems. Then you play the 'reach priority shuffle' as you work through the next five tasks. An example of the first shuffle is shown in Figure 33.

1.2. Task 2: Identify reaches containing assets with high conservation significance

Sort out those reaches with conservation value. These may be reaches whose condition is so good that they can be considered to be surviving remnants of the original stream condition. Such reaches may have been chosen as templates in *Step 3* of the Stream rehabilitation procedure, Volume 1. Alternatively, the reaches may contain a particular asset, such as an endangered plant or animal (or an endangered river type), that it is important to conserve. *Identifying valuable reaches*, in Common stream problems, this Volume, discusses how to go about identifying known populations of vulnerable, rare and endangered species. Often there are no, or only very few, reaches in this category. Alternatively, you may have more than one reach containing the same asset (eg. a rare fish that is found through half a river system). If you have a few reaches that are in similar condition, simply rank them all together. There are two levels of conservation significance: regional conservation value and local conservation value.

Regional conservation value reaches contain assets that are rare in the region, State, or nation. These reaches are at the top of the priority list.

Local conservation value reaches do not have high conservation value regionally, but they can be defined as having high conservation value relative to the rest of the catchment. An example would be a forested headwater reach in an otherwise cleared catchment. This reach would get high priority within the catchment, but if most of the regional headwaters were forested, it would have a lower regional value.

1.3. Task 3: Sort the reaches according to condition

Preserving reaches in good condition should be a major aim of stream rehabilitation, so the next task is to rank the reaches according to their condition. All the reaches in very good condition should already be in the regional and local conservation categories. If you have more than one reach in either of these groups, then you can use their relative condition to decide which is a higher priority. The reaches you have not yet assigned to a category you should split into two groups: an average group, and a basket-case group.

The **average** group contains all the reaches in average condition—not specially good or bad. You will probably have many reaches in this group—they will be divided into smaller categories in the following tasks. At this stage, they are the second-lowest priority.

The **basket-case** reaches are in extremely bad condition. They would require enormous effort to rehabilitate, with small chances of success. These reaches will be your lowest priority.

1.4. Task 4: Sort the reaches according to trajectory

How the condition of the reach will change over time can be important when deciding on priorities. It is usually more efficient to stabilise deteriorating reaches now, rather than having to fix them later. So reaches that are deteriorating are a higher priority than reaches that are stable. Reaches that are presently improving by themselves are the lowest priority. Thus, where you have more than one reach in a category, rank them according to their trajectory. You should break up the average group into a **deteriorating** category, and a **stable–improving** group. The basket-case group should be broken into **basket case without hope** (the deteriorating and stable reaches, that will not recover without help, such as the saline streams of Western Australia), and **basket case with hope** (improving reaches, that might eventually recover naturally, such as the incised lowland streams of coastal New South Wales).

1.5. Task 5: Sort the reaches according to their proximity to a reach in good condition

It is easiest to improve the condition of the stream by expanding an area in good condition, rather than trying to create a new island of improved stream amongst the degraded reaches. There are two reasons for this. First, although quality assets can be isolated within an otherwise degraded setting (a healthy riparian zone beside a stream with a sand slug, for example), their value is greatest when combined with other assets to form a complete stream community. Secondly, the recovery of plant and animal communities is generally fastest when there is a healthy community close by. This is because colonising individuals will find the new habitat faster if there is no barrier of inhospitable degraded reach (see *Recovery of disturbed stream systems in Australia*, in Stream rehabilitation concepts, Volume 1, for a discussion of this). In order of priority, you should work on:

- reaches with a mix of high-quality assets and some degraded assets (eg. a reach with a good riparian zone, and good in-stream habitat, but poor water quality);
- poor quality reaches that link two reaches in good condition;
- poor quality reaches connected by one end to a reach in good condition; and
- poor quality reaches that are distant from good quality reaches.

Thus, if two or more reaches still have the same priority, rank them according to how close they are to a reach in good condition. Split the stable–improving group into a category of reaches that are close to good reaches, and a group of distant reaches.

1.6. Task 6: Sort the reaches according to how easy they are to rehabilitate

If you have a choice between two similar tasks, it is sensible to do the easier task first. Thus, this final ranking of reaches is done according to how easy it would be to fix each reach. For example, you may have a reach that has bad condition, and is stable because the natural recovery is impeded. Its condition could be dramatically improved by a small intervention. So, if any two reaches still have the same priority, you can rank them according to how easy they would be to rehabilitate. Split the **distant** group into a category of easily fixed **impeded recovery** reaches, and a category of more difficult **moderately damaged** reaches.

1.7. The reach priority categories

You have now finished the first stage of the reach priority shuffle, and should have eight categories of priorities. Where you have more than one reach in a category, you should have separated them on the grounds of condition, trajectory, proximity, and ease of rehabilitation. The full shuffle is shown in Figure 1. The eight categories, with a brief description, are listed below, and can be read about in more detail in *Step 5: Setting priorities*, in the Stream rehabilitation procedure, Volume 1. Note that there is one extra category—reaches in good condition that are protected from threats fit into Category 0. How a reach arrives in this category is revealed in the next section.

Category Zero: ***Reaches in good condition throughout, that are already protected.*** Reaches in this category need nothing done to them. There are no active threats, and they have been protected against any potential threats. All the assets in the reach are in good condition. All this reach needs is a watchful eye, to check for the development of new threats in the future.

Category One: ***Protecting regional conservation value reaches.*** The highest priority is to preserve those reaches that are important nationally or regionally. These could contain endangered species or communities, or be a good quality fragment of a once common stream type.

Category Two: ***Protecting local conservation value reaches.*** These reaches are surviving remnants of the original stream condition. They do not fit into Category 1, because they are common in the region, but they are still important assets.

Category Three: ***Protecting and improving deteriorating reaches.*** Some reaches will already be damaged, but their condition is continuing to deteriorate. It is usually more efficient to stop further deterioration than to wait for the damage to reach a plateau, and then try to fix it.

Category Four: ***Expand good reaches.*** Expand good areas of the stream, by:

- improving reaches with some good-quality assets and some degraded assets;
- improving poor-quality reaches that link two good quality reaches; and
- improving poor-quality reaches that are linked at one end to a good-quality reach.

Category Five: ***Improve impeded recovery reaches (easily fixed reaches).*** These are the reaches that are in poor condition but have stabilised (ie. their condition is not deteriorating). A natural recovery process ought to be occurring, but some stream problems prevent this. If you identify and fix that problem, you can allow the natural recovery to do the hard work of improving the stream condition.

Category Six: ***Improve moderately damaged reaches (more difficult to fix)***. These are reaches that are damaged by human impact, but have good potential to recover at reasonable cost. They differ from Category 5 reaches in that they require several interventions, rather than just one.

Category Seven: ***Improve basket-case reaches.*** These are reaches in very poor condition, and which have little chance of recovering by themselves over time. Such reaches will usually need very expensive and difficult intervention if they are to recover.

Category Eight: ***Improve basket-case reaches with hope.*** These are the reaches that are in very poor condition, but which do have some chance of recovering themselves with time. Such streams are also expensive and difficult to artificially rehabilitate, but they have a pretty good chance of recovering themselves over time.

1.8. Task 7: Are there reasons to change the reach priority rankings (getting more bang for your buck)?

Having sorted your reaches into the categories, you may decide to rearrange the order of priority in order to get the most value for your rehabilitation dollar. This is discussed in *Step 5* of the Stream rehabilitation procedure in Volume 1. Briefly, you might decide to give a low priority reach higher priority because:

- it will help muster community support;
- it will create a reach with regional conservation value;
- it is sometimes easier to start rehabilitation in the small upstream reaches; or
- outputs from the reach will have a detrimental effect on the lake, estuary or wetland that will ultimately receive the water.

2. Which problem do I fix first?

Unfortunately, the task of prioritisation is not yet over. You have now decided the order in which you will work on your reaches. But in each reach, where do you start? If you are lucky, there will be only a few problems that need fixing, but it is more common for a single reach to have lots of problems, all of different magnitude. How do you work out where to start? Should you fix all the problems in this reach before moving on to the next? The key is to consider the importance of the assets that are threatened by the different problems, and to remember that you should protect all the valuable assets in all reaches before you begin to improve the condition of the steam. Then the problems are ranked by how fatal or limiting each problem is for each asset. In order to work this out, it might be necessary to 'reshuffle' the reaches. These tasks are described below.

2.1. Task 8: Identify the most important assets in your top-priority reach

In rehabilitation terms, a stream problem is only a problem because it damages the natural assets of the stream. For the top-priority reach, identify the most important asset. Use the same principles as the reach priority shuffle—rare before common, good condition before bad, deteriorating before improving, close to other assets before distant, and easy before hard. In a Category 1 reach, for example, the most important asset will be the one with regional conservation value (eg. the rare species, or pristine morphology).

2.2. Task 9: Identify the problems that threaten or damage the asset

Which problems get priority depends whether you are in the protection or improvement stage of your rehabilitation. Does the asset that you are looking at need protecting (ie. is it from a reach in Categories 1, 2 or 3)? In this case, list all the problems that might cause the condition of that asset to deteriorate. If you have already protected any regional and local conservation assets, and stabilised any deteriorating reaches, then you are ready to improve the condition of the asset. In this case, you should list all of the problems that prevent your asset from improving. Note that this means you can look at the same asset twice, once to protect it from future deterioration, and again to improve its condition.

> Note that although these problems might come from within the reach, they could also come from upstream (such as bad water quality, or sediment), or from downstream (such as a feral animal population, or an erosion head migrating upstream). You might often find that protecting one reach means treating problems elsewhere in the stream.

2.3. Task 10: Are there any fatal problems that threaten or damage the asset?

Fatal problems are so severe that they exclude assets from the stream. They must be fixed first—there is no point doing anything else in the stream until the fatal problem is fixed. Extremely bad water quality, or a major barrier to fish passage, are examples of fatal problems, as are sand slugs, huge deposits of sand in the bed of the stream, travelling slowly downstream. Sand slugs can fill a stream, swamping all the in-stream habitat, and leaving very shallow water flowing over a smooth sheet of mobile sand. Not surprisingly, such a stream will support few aquatic plants or animals. Until the sediment has moved through the reach (this can take many decades) or has been stabilised in some way, it will continue to swamp any habitat, including any added to the stream artificially. Any work on the stream must first tackle the sand slug to be successful. Thus, fatal problems are the highest priority.

> **A fatal problem**
>
> Dartmouth Dam releases cold water to the Mitta Mitta River (Figure 34). The cold water has dramatically reduced the number and diversity of native fish in the reach below the dam (Koehn *et al.*, 1997a). If your goal is to return native fish populations to their original size and diversity, then there is less point planting riparian vegetation (presently dominated by willows), and improving in-stream habitat, when the water will still be too cold for fish. You either fix the fatal problem of water temperature, or you consider working elsewhere.

Figure 34. The Mitta Mitta River below Dartmouth Dam, Victoria. Cold water released from the dam is the limiting problem for the native fish in this river (Koehn *et al.,* 1997a).

2.4. Task 11: Are there any other limiting problems that affect the asset?

A limiting problem is the one that most severely affects an asset (*An introduction to stream ecosystems in Stream rehabilitation* concepts, Volume 1, contains a discussion of limiting variables and this is expanded upon in *Determining the key problems in the reach*, Natural channel design, this Volume). If you don't fix the limiting problem, but work on other problems, then the recovery of the asset will still be limited. Fatal problems are really just a very extreme example of this. Limiting problems are the next highest priority after fatal problems.

Take the example of river blackfish. These fish love woody debris—they shelter under it, and spawn amongst it. Consider a reach with a very small blackfish population, and three problems with a bearing on that—there is some nutrient enrichment, only moderate density of macroinvertebrate (the main food), and only one piece of LWD. The lack of debris is probably the limiting problem; that is, all the available debris is used by fish, and no more fish can live in the reach, because there is no room under the debris. If a rehabilitation project focused on increasing food supply to this reach, or improving the water quality, it would have no effect on the fish, because there are already as many fish as there is habitat to support. So, after the fatal problem, the most limiting problem threatening or degrading an asset has highest priority.

2.5. Task 12: Reshuffle the reach

At this stage, you know what problems you need to tackle, in what order, to protect (or to improve, if the valuable assets are already protected) the condition of the top asset in the top-priority reach. Should you now continue working on the top-priority reach until it is protected from all threats, and all in good condition? While this is sometimes the best strategy, in many cases it would allow other valuable reaches to deteriorate for want of attention, while you aim for perfection at the first site. But how do you decide when to turn to the next reach? The answer to this is to 'reshuffle' your top reach into the reach priority categories, before you identify the problems affecting the next most important asset. This means you will protect all the valuable assets in all the reaches, before you begin to improve the condition of the stream. We do this in the following way.

1. Identify the most important asset in the top-priority reach, and prioritise the problems that threaten (or damage) that asset (Tasks 8 to 11).

2. Ask yourself, if you fixed all the problems you have identified that threaten (or damage) that asset, what would be the condition of the rest of the reach? Would all the assets be in good condition? Would they all be protected against future threats?

   - If you answer yes, then congratulations, the reach is now upgraded to Category 0!

   - If you answer no, then there is still work to be done in the reach. You need to consider what priority this work would have, compared with all the other reaches in your stream.

3. Run the reach through the reach priority shuffle again, but this time pretending that the most important asset is already protected (you have already prioritised that), and so ignoring it. The reach might now come out in a different category, and thus appear twice in the priority list. See Figure 35 for an example of the first reshuffle .

2.6. Task 13: Repeat the problem prioritisation process as many times as necessary

Run through Tasks 8 to 12 again, this time working in the new top-priority reach, on the most important asset. When you have prioritised what needs to be done to protect (or improve) this asset, once again you pretend that you have already fixed the asset and repeat the process of reshuffling the reach. Repeat the process, until you have mapped out enough work to be going on with, or have prioritised all the problems in your stream.

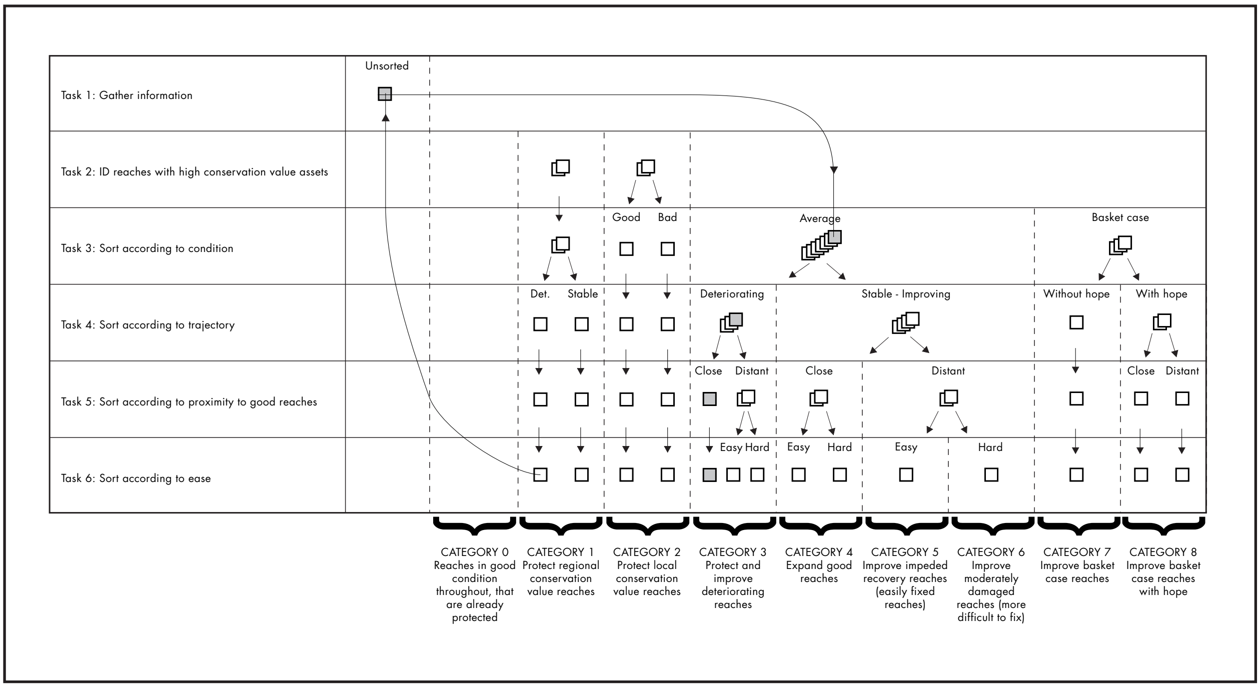

Figure 35. An example of the first reshuffle of the reach categories. The reach being reshuffled here is in average condition but deteriorating, as (for example) willows are invading the riparian zone. The reach also has a regional conservation value asset, such as an undisturbed natural loading of woody debris. Originally, the reach was in Category 1 (Regional conservation value). Once the protection of the woody debris is prioritised, the reach is reshuffled, and comes out in Category 3 (Deteriorating reaches), because of the willow invasion. The other regional and local conservation reaches will be protected from any threats, before the willows are dealt with.

2.7. Task 14: Exceptions to the problem priorities—getting more bang for your buck

Just as there are reasons to sometimes change the reach priority rankings (Task 7), there are sometimes reasons to take a problem that is neither fatal nor most limiting and work on it anyway. This is discussed in more detail in Task 6 of the Stream rehabilitation procedure in Volume 1. Briefly, you may decide to work on a problem because:

- it affects a large area of stream, so one action could result in a large improvement in condition;
- the stream will take a long time to recover, so you need to start the process as soon as possible; or
- treating a certain problem will help muster community support for rehabilitation.

3. Prioritisation case studies

3.1. Doing the reach priority shuffle and problem prioritisation on Mythic Creek

Remember the five reaches of Mythic Creek that we followed through the Stream rehabilitation procedure in Volume 1? We will now apply the reach priority shuffle to this example. A detailed description of the stream can be found at the end of *Step 3*, and a description of the assets and problems in each reach is at the end of *Step 4* in Volume 1.

Task 1. Gather information

A very brief description of the five reaches is given in Table 33.

Task 2. Identify reaches containing assets with high conservation significance

Reaches 1a and 3 both have local conservation significance. That is, they are in relatively good condition, and although

Table 33. A brief description of the five reaches of Mythic Creek.

Reach (in order of priority)	Description (condition, trajectory, relation to other reaches)	Problems
Reach 1a	In pretty good condition, with respect to the water quality, the channel stability and morphology, and the riparian zone.	There is a proposal to build a dam in this reach, the riparian zone is grazed, as is the rest of the catchment, and there are a few weeds in the riparian zone. The condition is stable, apart from the threat of the dam and the increasing weed population.
Reach 1b	In bad condition. Erosion, poor habitat complexity, considerable nutrient enrichment from a piggery, poor riparian condition. May slowly recover habitat complexity. The riparian zone is partly cleared and weedy.	The reach has low habitat diversity because of incision, and sedimentation from gully erosion as well as desnagging and cattle trampling in the stream. The cattle contribute to the weedy, degraded condition of the riparian zone. The water quality is low because of nutrients from the piggery and the cattle, turbidity from the erosion, and high temperatures because of lack of shade and shallow water. Overall, the condition is stable.
Reach 2	In poor condition—simplified habitat, sediment aggradation, poor riparian zone, and erosion.	There is low habitat diversity because of sediment deposition from upstream, some bank erosion in the reach, desnagging and cattle trampling. The water quality is similar to Reach 1b. There are weeds in the riparian zone. The proposed dam in Reach 1a would impact this reach. Overall, the condition is fairly stable.
Reach 3	A gorge stream, in good condition with respect to morphology and habitat complexity.	This reach has moderate habitat diversity, although some sediment has deposited in the pools, some desnagging has occurred, and cattle have access to the stream. The water is still turbid with a high nutrient load. The riparian zone is weedy and grazed by cattle, and is deteriorating. The proposed dam in Reach 1a would impact this reach.
Reach 4	In bad condition—fish barrier, poor riparian condition (infested with weeds), lack of habitat complexity, poor water quality. Is unlikely to recover without intervention.	Again, there is low habitat diversity in this reach, because of channelisation, cattle trampling, bank erosion and desnagging. Levees prevent the floodplain from being flooded. The water has a high nutrient load, temperature and turbidity. The riparian zone is open, weedy and grazed. The proposed dam in Reach 1a would affect this reach. The condition is stable.

there are examples of similar reaches in similar condition in the region, there are none in the catchment.

Task 3. Sort the reaches according to condition

In the local conservation value category, Reach 1a, with its good water quality, morphology and riparian zone, is in better overall condition than Reach 3. Of the other three reaches, 1b and 2 are in average condition, and 4 is a basket case.

Task 4. Sort the reaches according to trajectory

Only Reaches 1a and 3 are threatened by significant deterioration. Seeing they are already prioritised on the grounds of conservation value and condition, their trajectory makes no difference to their ranking. Reach 4 is stable, with no hope of improvement without intervention, and thus fits into Category 7, Basket case without hope. Reaches 1b and 2 move into the stable/improving group.

Task 5. Sort the reaches according to their proximity to a reach in good condition

Reaches 1b and 2 are not yet assigned to a category. Of these, Reach 2 is just downstream of Reach 1, which is in good condition, and thus fits into Category 4, Expanding good reaches. Reach 1b is not upstream or downstream of a good reach, and so fits into the distant group.

Task 6. Sort the reaches according to how easy they are to rehabilitate

The only reach not yet assigned to a category is Reach 1b. In order to protect the higher priority Reaches 3 and 4 from the sediment and nutrient problems from upstream, most of the major problems in this reach will already be fixed by the time it becomes a top priority. Thus, by that time, it will fit into Category 5, Easily fixed reaches. The steps taken in the reach priority shuffle are shown in Figure 36.

Task 7. Are there reasons to change the reach priority rankings (getting more bang for your buck)?

None of the reasons to alter the reach priorities are relevant to Mythic Creek.

Task 8. Identify the most important asset in your top-priority reach

Reach 1a is the top-priority reach. It has local conservation value because it is in generally good condition. The in-stream morphology is its most important asset.

Task 9. Identify the problems that threaten or damage the asset

The morphology of Reach 1a is threatened by the construction of the proposed dam, the effects of the dam on the flow regime, and the cattle that are free to walk through the stream.

Task 10. Are there any fatal problems?

The effects of the dam construction, and the effect of the altered flow regime will probably cause serious long-term damage to the reach.

Task 11. Are there any limiting problems?

The cattle trampling prevents the in-stream morphology from being as close as possible to the pre-European state.

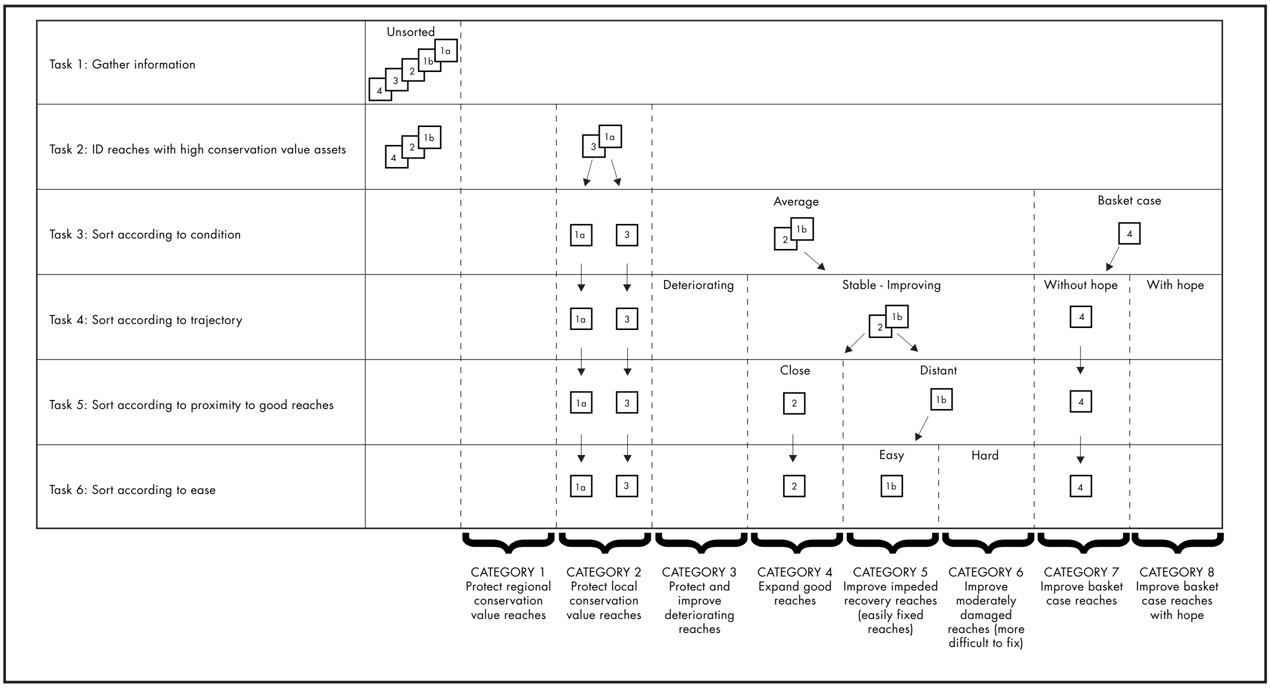

Figure 36. The result of the reach priority shuffle on Mythic Creek.

Task 12. Reshuffle the reach

The priorities so far are:

1. Stop the construction of the dam.

2. Exclude stock from the stream.

If we pretend these have been done, and reshuffle Reach 1a, where would it end up? It would return to Category 2, Local conservation value, because of the relatively untouched riparian vegetation. Once this was protected, the reach would be reshuffled into the average condition group, then into the stable to improving group, and finally into Category 4, Expanding good assets. Reach 3 would follow a similar path (Figure 37). The final list of problem priorities for Mythic Creek can be found in *Step 5* of the Stream rehabilitation procedure, in Volume 1.

3.2. An example of the reshuffle in Simple Creek

Imagine Simple Creek, a small rural stream that can be divided into two reaches.

1. The upstream reach is typical of many small streams in the area. The riparian zone is in good condition. However, for some years, the landowners have been desnagging the reach, a process that is still continuing, and erosion has caused a further loss of in-stream habitat. The land use is changing from cropping to grazing, and the riparian zone, bank structure and water quality are all under threat from the impacts of grazing. This reach is a Category 3, Deteriorating reach.

2. The downstream reach is stable, but generally in worse condition. The riparian zone has been cleared and the banks grazed for some time, and the damage has already been done. However, a rare species of fish persists in the pools. Because of this fish, the downstream reach is a Category 1, Regional conservation value reach.

We will now run through Tasks 8 to 13 twice.

Task 8. The most important asset in the top-priority downstream reach is the rare fish.

Task 9. The fish population is threatened by a lack of habitat for juvenile fish, because of the cattle trampling and polluting the shallow areas. High water temperatures in summer because of the lack of shade are another problem.

Task 10. Neither problem is fatal.

Task 11. The lack of juvenile habitat is most limiting, because it means only a few young fish survive each year. The high summer temperatures are a stress on all the fish but usually few die, so this is next most limiting.

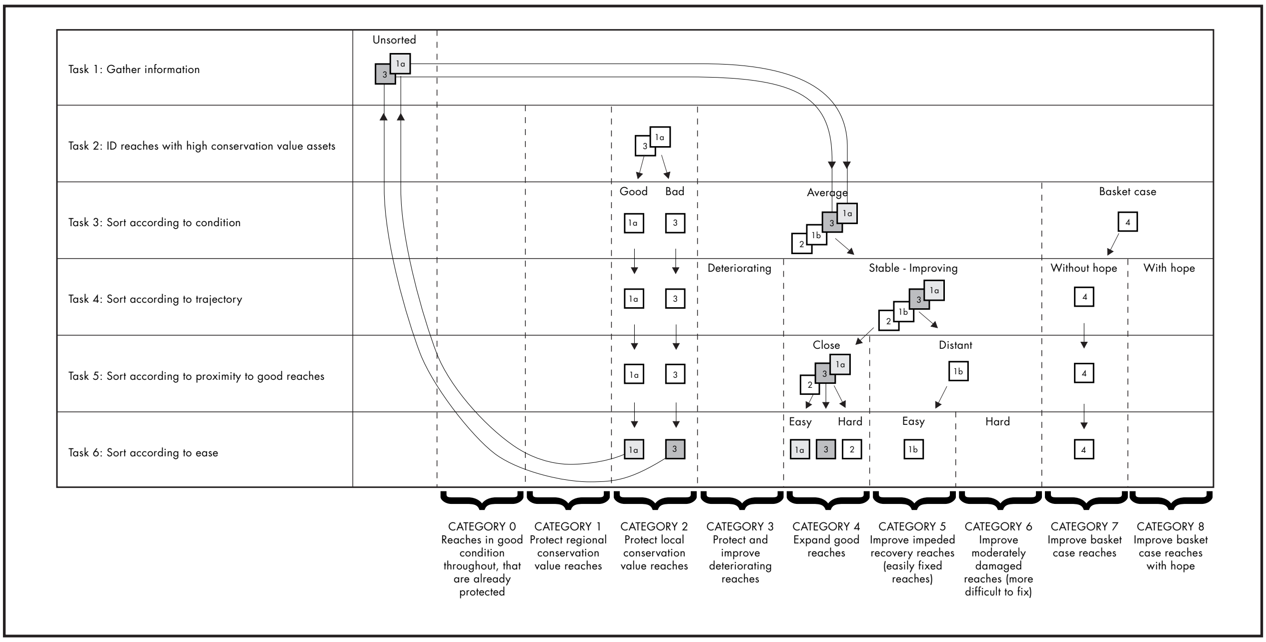

Figure 37. The result of reshuffling Reaches 1a and 3 in Mythic Creek.

Task 12. We now consider what category the downstream reach would fit into if the rare fish were protected. The reach has no other regional or local conservation assets, and is not deteriorating, but it does have a good asset in the rare fish. Thus, it would come out as Category 4, a reach with good assets to be expanded on.

Task 13. We now repeat Tasks 8 to 13. However, now the top priority is the upstream reach, because this is Category 3, and the downstream reach is Category 4.

Task 8. The most important asset in the upstream reach is the riparian zone.

Task 9. The riparian zone is threatened by the impacts of clearing and grazing.

Task 10. Clearing would be fatal to the riparian zone.

Task 11. Grazing in the riparian zone would be limiting.

Task 12. What category would this reach reshuffle into if the riparian zone was protected from clearing and grazing? Because of the desnagging that is continuing in this reach, it would remain in Category 3, Deteriorating reaches. The next iteration of tasks 8–13 would work out how to protect the woody debris load from further deterioration.

Task 13. To finish working out the order in which problems should be fixed, we would continue to repeat this process, but this is enough to show you how the process works. Below is a summary of the priorities for Simple Creek that have come from the above prioritisation.

1. Protect the rare fish population in the downstream reach by providing more juvenile habitat.

2. Protect the fish in the downstream reach by providing shade to lower summer water temperatures.

3. Protect the riparian zone in the upstream reach by preventing any clearing.

4. Protect the riparian zone in the upstream reach by preventing grazing.

5. Protect the woody debris in the upstream reach (individual problems not yet prioritised).

6. Improve the condition of the downstream reach (individual problems not yet prioritised).

7. Improve the condition of the upstream reach (individual problems not yet prioritised).

LEGISLATIVE AND ADMINISTRATIVE CONSTRAINTS

The following tables summarise legislation relevant to stream rehabilitation State by State. Unfortunately, tables have not yet been developed for the ACT or the Northern Territory. The table is designed to be used in *Step 8: Are your objectives feasible?* in the Stream rehabilitation procedure, Volume 1. The tables are set out as follows.

Column 1	Gives the issue: usually relating to ownership, administration or specific management activities.
Column 2	Identifies the government agencies responsible for administration of the issue.
Column 3	Lists the legislation and other documentation relevant to the issue.
Column 4	Briefly discusses the issue.

If you have any specific questions please contact the person or department noted at the top of each table. The information provided in these tables was distilled from information provided by State government officers as shown, and is considered a good guide as of 1998.

Because legislation changes rapidly, and because your situation may be unusual, we recommend that you verify your legal position with the appropriate government department. The following tables are provided as a guide only.

1. Queensland stream management

*By John Amprimo and Geoff Guinea**

The primary contact for all stream rehabilitation work in Queensland is the Department of Natural Resources (QDNR). Details of relevant legislation are given in Table 34.

Table 34. Legislation relevant to stream rehabilitation in Queensland.

Issue	Agency	Documentation	Discussion
Administration:			
Boundaries	QDNR[1]	*Water Resources Act 1989*	Currently being reviewed by the Natural Resource Management Working Party (NRMWP). At present the Crown maintains ownership of the bed up to the top of the low bank of the watercourse. From a management perspective, a watercourse is interpreted as being land between the high banks of any river, creek or stream which flows permanently or intermittently through two or more properties. This is, however, applicable only to freshwater streams (down to the tidal limit). The tidal limit is defined as the upstream extent of the 'spring tide'.
Estuarine systems	QDE[2]	*Coastal Protection and Management Act 1995* *Nature Conservation Act 1992*	For streams below the tidal limit, the *Water Resources Act* is no longer applicable, and responsibility for most matters falls to the QDE, through the *Coastal Protection Act* and *Nature Conservation Act*. However, QDNR still has some jurisdiction by way of implementing the Fisheries Act which applies to both fresh and saltwater systems.

[1] QDNR: Queensland Department of Natural Resources

[2] QDE: Queensland Department of Environment

[3] LGAQ: Local Government Association of Queensland

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Table 34 (cont'd). Legislation relevant to stream rehabilitation in Queensland.

Issue	Agency	Documentation	Discussion
Licences vs permits	QDNR	*Water Resources Act 1989*	Activities in streams are regulated through permits and licences issued under the Water *Resources Act*. Licences are issued for activities that will occur repeatedly (such as water extraction), or have a long-term impact (eg. a large dam). Permits are issued for impacts that occur once only, or have a minor impact (eg. clearing of native vegetation or removal of in-stream material). Licences are advertised for public objection and can be challenged in court, permits can not.
Leasehold vs freehold	QDNR	*Land Act 1994*	The *Land Act* is relevant to streams only where the stream forms a boundary between leasehold land and any other parcel of land. Under the *Land Act*, specific provisions such as clearing controls can be applied to the leasehold land. In the past, a general provision has been that native vegetation should not be cleared from within 40 m of a non-tidal watercourse, and 400 m of a tidal estuary.
Management activities			
Modifying fish habitat	QDNR	*Fisheries Act 1994*	In-stream structures must not impede fish passage. Fish habitat areas can also be declared under this Act. Disturbance of the stream and riparian zone can be banned in declared fish habitat areas.
Modifying bed and banks	QDNR	*Water Resources Act*	Minor in-stream works that are not likely to modify the downstream flow regime, such as filling an eroding bend, require a permit from QDNR. Note that any action that encourages deposition of sediment (such as planting reeds or other vegetation) could be defined as 'placing of fill' under the *Water Resources Act* and may require a permit.
Water abstraction and impoundment structures	QDNR	*Water Resources Act*	For the abstraction of water, or construction of major in-stream structures such as weirs, a licence is required from QDNR. The licensing procedure requires a notification period during which objections from 8 km upstream and 24 km downstream of the site of the proposed activity can be made.
Removal of native vegetation	QDNR	*Water Resources Act 1989*	Removing native vegetation from a watercourse requires a permit under the *Water Resources Act*. Further protection of riparian vegetation may be required under lease conditions (boundary streams of leasehold land) or through application of tree-clearing guidelines currently being developed.
	Local govern-ment	*Land Act 1989* Tree clearing guidelines, tree protection orders	Removing vegetation on freehold land can also be controlled by local government, by implementing vegetation protection orders.
	QDNR	*Fisheries Act 1994*	The destruction of mangroves in estuarine reaches is controlled by the QDNR under the *Fisheries Act.*
Removal of exotic vegetation	QDNR	*Rural Lands Protection Act 1985* Fact Sheets	No permission is needed to remove exotic vegetation. QDNR has a series of fact sheets on how to most effectively control/remove exotic vegetation, particularly those species declared weeds under the *Rural Lands Protection Act.*
Revegetation	QDNR	Fact Sheets	No permit is needed to revegetate a stream with native vegetation. QDNR has a series of fact sheets on revegetation techniques and lists of species suitable for Queensland.
Riparian zone management	QDNR	*Water Resources Act 1989* *Land Act 1994* Tree clearing guidelines	Restrictions on riparian zone clearing and disturbance can be enforced as leasehold conditions for boundary streams *(Land Act)*. The tree clearing guidelines currently being developed may also include powers to restrict clearing and disturbance.
Catchment management groups	QDNR LGAQ[3]	No statutory authority Incorporation into planning schemes	Integrated catchment management groups have no statutory power, although the catchment management strategies (CMSs) which they prepare may be endorsed by the Minister. The LGAQ is helping to provide these CMSs with statutory power by encouraging their adoption into local government planning schemes.

2. New South Wales stream management

*by Peter Wem**

The primary contact for all stream rehabilitation work in New South Wales is the Department of Land and Water Conservation (DLWC). Additional advice, specifically on environmental issues (eg. habitat requirements, environmental monitoring), can be gained from the New South Wales Environmental Protection Authority (EPA) or the Fisheries Department. Details of the relevent legislation are given in Table 35.

Table 35. Legislation relevant to stream rehabilitation in New South Wales.

Issue	Agency	Documentation	Discussion
Administration:			
Ownership	DLWC[1]	*Water Act 1912*	All land below tidal high water mark is Crown Land. Above tidal high water mark, stream bed and banks are usually freehold land. Where a stream forms the boundary, ownership is to the centre thread of the stream. Leasehold land: ownership responsibilities as per freehold land. National parks: National Parks and Wildlife Service is responsible. There will be many complicated scenarios that will require title searches: stream management groups are advised to search titles before starting any works.
Local government responsibility	Local authority	Local Environmental Plan	Urban areas owned by local government and covered by a Local Environment Plan are generally administered by local government. However, activities on private lands within urban areas still require State agency approval.
Estuarine systems	DLWC	*Coastal Protection Act*	The DLWC also has management responsibility for streams below the tidal limit.
Access	DLWC	*Rivers and Foreshores Improvement Act 1948* *Water Act 1912*	Any State government officer has the automatic right to access streams in relation to any matter concerning an Act, although in practice access is generally by agreement with the landholder.
Catchment management groups	DLWC	No statutory authority Incorporation into planning schemes	Catchment management and planning groups have no statutory power but their planning decisions may be adopted by local authorities to provide statutory authority.
Management activities:			
Removal of native vegetation	DLWC	*Soil Conservation Act 1938*	The removal of vegetation within 20 m of the high bank requires DLWC approval for gazetted rivers. Since most major rivers are gazetted, the DLWC should be contacted before any vegetation is removed.
Removal of exotic vegetation	DLWC	*Soil Conservation Act 1938*	All vegetation including willows and other exotic vegetation (eg. camphor laurels) is covered by the *Soil Conservation Act* and approval must therefore be granted for their removal unless they are declared noxious weeds.

[1] DLWC: New South Wales Department of Land and Water Conservation

* Manager, Riverine Corridor, NSW Department of Land and Water Conservation, 2-24 Rawson Place, Sydney, NSW 2000. Ph: (02) 9372 7724, Fax: (02) 9372 7799, Email: pwem@dlwc.nsw.gov.au

Table 35 (cont'd). Legislation relevant to stream rehabilitation in New South Wales.

Issue	Agency	Documentation	Discussion
Revegetation	DLWC[1]		You do not need authority to revegetate a stream with native vegetation, unless it can be shown that such an activity will affect the integrity of the stream or another person's interests.
Water abstraction and impoundment structures	DLWC	*Water Act 1912* *Water Administration Act 1986*	For the abstraction of water, or construction of major in-stream structures such as weirs, approval is required from DLWC.
Modifying bed and banks	DLWC	*NSW Rivers and Foreshores Improvement Act 1948*	Any action which interferes with the bed and banks but does not modify the channel alignment or location requires approval by DLWC (such activities may include placing rip rap and other erosion control measures). All government agencies that are constructing authorities are excluded from this formal requirement, but DLWC is usually consulted before works are implemented.
Channel re-alignment	DLWC	*NSW Rivers and Foreshores Improvement Act 1948* *Water Act 1912*	All channel re-alignment activities must be approved by the DLWC under the *Rivers and Foreshores Improvement Act* and the *Water Act.* Government agencies must also seek approval.
Sand, gravel or soil extraction	DLWC	*NSW Rivers and Foreshores Improvement Act 1948; Water Act 1912*	All sand, gravel or soil extraction in NSW requires a permit. The DLWC is responsible for issuing permits for extraction in or near streams. Extraction within the stream channel or within 40 m of the top of the bank, or which is likely to impact on land which is within 40 m of the top of the bank, must be approved by the DLWC.

[1] DLWC: New South Wales Department of Land and Water Conservation

3. Western Australian stream management

*by Luke Pen**

The Water and Rivers Commission (WRC) is the key river management authority in Western Australia, and should be the first point of contact for river management queries. There are six 'management authorities' that administer proclaimed waterways, and need to be contacted for proposed work within a proclaimed area. Details of the relevent legislation are given in Table 36.

Table 36. Legislation relevant to stream rehabilitation in Western Australia.

Issue	Agency	Documentation	Discussion
Administration:			
Ownership	WRC[1] Department of Land Administration	*Rights in Water and Irrigation Act*	The ownership of the stream bed and banks usually reverts to the ownership of land surrounding the stream; that is to say the bed and banks of a stream that passes through private property are also part of that property, ie. privately owned. There are exceptions to this; in proclaimed areas under the *Rights in Water and Irrigation Act*, the bed of a stream that forms the boundary of a private property remains in Crown ownership. There are corridors of Crown Land gazetted along some streams; these streams and others within larger tracks of Crown Land remain in Crown ownership.

* Water and Rivers Commision, PO Box 6740 Hay St, East Perth, WA 6892. Ph: (08) 9278 0374, Fax: (08) 9278 0585

Table 36 (cont'd). Legislation relevant to stream rehabilitation in Western Australia.

Issue	Agency	Documentation	Discussion
Management	WRC[1]	*Swan River Trust Act 1988* *Waterways Conservation Act* *Country Areas Water Supply Act* *Water Boards Act* *Metropolitan Water Supply Sewerage and Drainage Act* *Metropolitan Water Authority Act)*	There are six 'declared management areas'. One of these—the Swan River Trust management area—is declared under the *Swan River Trust Act*, and lies more or less along the waterways of the Swan, Canning, and southern rivers on the Swan Coastal Plain, and for short distances into the Darling Range. The other five declared management areas exist under the *Waterways Conservation Act*. Maps of the declared areas are kept by the management authority for each area. The five areas are: – Peel Inlet—mostly tidal sections of the Serpentine and Murray Rivers; – Leschenault Inlet—about to be extended to catchment-wide area, excluding portions of the city of Bunbury, and the catchment upstream of Wellington on the Collie River; – Avon River—catchment-wide management area; – Wilson Inlet—catchment-wide management area; and – Albany waterways—catchment-wide management area. Each declared management area has a community-based management authority supported by the WRC. Any works in these streams require the permission of the management authority. Further permission must be sought from the WRC for any works in proclaimed water supply catchments, and in reserves proclaimed under the *Country Areas Water Supply Act, Water Boards Act, Metropolitan Water Supply Sewerage and Drainage Act*, and *Metropolitan Water Authority Act*. Local government authorities should always be contacted before stream rehabilitation work to ensure the works comply with the Town Planning Scheme.
Estuarine systems	DoT[2]		Tidal watercourses remain in Crown ownership for the purposes of navigation, and are managed by the Department of Transport.
Leasehold vs freehold			Leasehold land may be more tightly controlled by way of lease conditions such as restrictions on vegetation removal, but this is the exception rather than the rule and leasehold land is generally managed as for freehold land in an unproclaimed area.
Administrative Agencies	Local government WRC DoT	Various Acts	Local government administers foreshore reserves for recreation, parks and gardens. The Department of Conservation and Land Management and the Ministry for Planning (in a custodial sense) administers regional parks, one of which lies on the Canning River. The Water and Rivers Commission administer foreshore reserves and water reserves. The Department of Land Administration deal with vacant Crown Land. The Water Corporation administers gazetted drainage reserves, some of which occur along natural streams. It also manages drainage in declared drainage districts. Department of Transport permission is required for work on navigable watercourses and for streams gazetted for boating (ie. water skiing).

Table 36 (cont'd). Legislation relevant to stream rehabilitation in Western Australia.

Issue	Agency	Documentation	Discussion
Management activities:			
Removal of exotic or native vegetation	WRC[1]	*Waterways Conservation Act* *Swan River Trust Act 1988*	Permission is not needed for the removal of exotic or native vegetation on waterways in freehold areas. In non-freehold areas permission for vegetation removal is required from the relevant administrative agency or leaseholder. The WRC will advise on the control of waterway weeds.
Revegetation	WRC Water Corporation Local government	*Waterways Conservation Act* *Swan River Trust Act 1988*	Permission is not required to revegetate a stream on freehold land. In non-freehold areas permission is required from the relevant administrative agency or leaseholder. For gazetted drains vested in local government, permission is required from the Water Corporation or relevant local government authority. The WRC provides advice on species selection for revegetation.
Modifying bed and banks	WRC	*Waterways Conservation Act* *Swan River Trust Act 1988*	In-stream modifications are restricted only in declared management areas and proclaimed water supply catchments, gazetted drains and navigable waterways. Permission is required from the WRC, Water Corporation or DoT[2] as appropriate. In declared management areas, permission is required from the relevant authority or trust.
Water abstraction and impoundment structures	WRC	*Waterways Conservation Act* *Swan River Trust Act 1988*	Riparian rights (ie. domestic, limited irrigation, livestock watering) are maintained for properties in both proclaimed and unproclaimed areas. Other uses must not significantly diminish the flow in unproclaimed areas, and must be licensed in proclaimed areas. The construction of dams/impoundment structures in proclaimed areas requires permission.
Sand and gravel extraction			Permission required as per 'modifying bed and banks'

[1]WRC: Western Australia Waters and Rivers Commission
[2]DoT: Western Australia Department of Transport

4. Victorian stream management

*by Peter Vollebergh**

The first point of contact for stream rehabilitation in Victoria should be either the relevant catchment management authority (CMA) or the Victorian Department of Natural Resources and Environment (NRE). CMAs have responsibility for the day-to-day management of Victorian waterways, although some in-stream works such as gravel extraction still require NRE permits. Details of the relevant legislation are given in Table 37.

* Waterways Unit, Victorian Department of Natural Resources and Environment, PO Box 41, East Melbourne, Victoria 3002. Ph: (03) 9412 4011, Fax: (03) 9412 4803

Table 37. Legislation relevant to stream rehabilitation in Victoria.

Issue	Agency	Documentation	Discussion
Administration:			
Ownership	NRE[1], CMAs[2]	*Land Act 1958*	Bed and banks in Victorian streams are usually the property of the Crown (some that were alienated early are privately owned, eg. part of the western district). On larger streams there is usually Crown Land frontage. This comprises a Crown reserve extending back 20 m from the top of each bank, plus a variable width of 'unreserved' Crown Land between the reserve and the surveyed boundary. There are 25,000 km of frontage reserves. Frontage reserves are static, so if the stream course changes, the public reserve can become landlocked in private farmland. Stock grazing on public water frontages has been permitted via agricultural licences issued by NRE. The power to issue these licences will be transferred to CMAs in early to mid 1999. The first point of contact on administrative matters should be either the relevant CMA or the NRE. CMAs have responsibility for the day-to-day management of Victorian waterways, although some in-stream works such as gravel extraction still require NRE permits.
Administration of bed and banks	NRE, CMAs, local governments	*Water Act 1989* *Planning and Environment Act 1987*	Crown frontage is administered by NRE or CMAs via licence conditions covering its use. Private frontage may be controlled by local government planning scheme requirements.
Estuarine systems	CMA, port authorities	*Water Act 1989* *Marine Act 1988* *Port of Melbourne Authority Act 1958*	A waterway includes intermittently and permanently flowing creeks, rivers, streams and watercourses. (This presumably includes estuarine reaches.) The lower reaches of the Gippsland Lakes Rivers, Snowy River, Lower Genoa River , Corner Inlet etc. are designated as ports under the *Marine Act 1988* and *Port of Melbourne Authority Act 1958.* The appropriate port authority must be contacted for any works in these areas.
Heritage rivers	CMA and PV[3] within National Parks	*Heritage Rivers Act 1992*	Eighteen rivers are declared as heritage rivers because of their natural, cultural, heritage, recreational and scenic values. Works around these rivers must be in accord with the management plans and other heritage river recommendations.
Access		*Land Act 1958*	Public access is permitted to Crown frontages for recreation (not including camping), but access to Crown frontages cannot be obtained through private land without the landowner's consent.
CMA	NRE	*Water Act 1989*	CMAs have statutory power under the *Water Act*. The responsibility for day-to-day stream management issues is delegated from NRE to the CMAs. CMAs have the capacity to make by-laws to control activities on waterways.
Management activities:			
Removal of native vegetation	CMA	State section of the planning scheme	Remnant vegetation cannot be removed within 30 m of a waterway. Also, native vegetation on any landholding of 0.4 ha or greater cannot be destroyed or lopped. Complete details are in 'Planning guidelines for native vegetation retention controls', available through NRE.

Table 37 (cont'd). Legislation relevant to stream rehabilitation in Victoria.

Issue	Agency	Documentation	Discussion
Removal of exotic vegetation	CMA	*Water Act 1989*	The removal of exotic vegetation (excluding those classified as noxious weeds under *Catchment and Land Protection Act 1994*) from a waterway requires a 'works on waterway' permit from the relevant CMA.
Revegetation	CMA		You do not need authority to revegetate a stream using native vegetation. CMA offices can provide advice on revegetation.
Modifying the riparian zone habitat	NRE	*Flora and Fauna Guarantee Act 1988*	A permit from NRE is required for undertaking any works where taxa listed under the *Flora and Fauna Guarantee Act* are likely to be killed, injured, disturbed or collected. Management actions also have to be compatible with action plans currently being prepared (under the *Flora and Fauna Act 1988*) to counter the following potentially threatening processes: – removal of woody debris from Victorian streams; – increase in sediment input to rivers and streams due to human activities; – the prevention of passage of aquatic biota as a result of the presence of in-stream structures; – degradation of native riparian vegetation along Victoria's rivers and streams; – deliberate or accidental introduction of live fish into public or private waters within a Victorian river catchment, when the taxon to which the fish belongs cannot reliably be inferred to have been present before 1770; and – alteration to the natural temperature regimes of rivers and streams.
Water abstraction and impoundment structures	NRE, rural water authorities	*Conservation, Forests and Lands Act 1987* *Water Act 1989*	The construction of dams, weirs, or other structures, in or across waterways which potentially interfere with the passage of fish or the quality of aquatic habitat must be submitted to NRE for comment. Approvals are required from the relevant rural water authority (Goulburn Murray Water, Southern Rural Water, Wimmera Mallee Water, Sunraysia Rural Water).
Modifying bed and banks or channel re-alignment	NRE	*Water Act 1989*	Any modification of the waterway, including stream stabilisation works, requires a 'works on waterways' permit from NRE.
Sand, gravel or soil extraction	NRE	*Extractive Industries Development Act 1995* *Land Act 1958* *Catchment and Land Protection Act 1994* *Water Act 1989*	Large-scale extraction operations >2,000 m^2 and >2 m depth need a licence under the *Extractive Industries Development Act*. Most river sand and gravel extraction operations are smaller than this. Small-scale extraction operations on Crown Land require a licence issued by NRE under the *Land Act* (or occasionally the *Forests Act*). Small-scale extraction on private land requires authorisation by NRE under part 7 of the *Catchment and Land Protection Act*. All sand and gravel extractions on waterways also require a 'works on waterways' permit from NRE. Further information can be found in 'Extractive Industries on Crown Land. Owners Consent. Guidelines on Issues and Processes', available from NRE.

[1]NRE: Victoria Department of Natural Resources and Environment
[2]CMA: Catchment Management Authority
[3]PV: Parks Victoria

5. South Australian stream management

*by Jim Burston**

Stream management in South Australia is delegated to catchment water management boards and local government. The Department of Environment and Natural Resources (DENR) can provide advice on whether there is a management board for your particular stream.Details of the relevant legislation are given in Table 38.

Table 38. Legislation relevant to stream rehabilitation in South Australia.

Issue	Agency	Documentation	Discussion
Administration:			
Ownership		*Land Act 1958*	The ownership of the bed and banks of a stream usually reverts to the ownership of the surrounding land. This means that river frontage reserves are not usually specified except in urban areas where watercourses have the status of 'reserve' and are managed by local government.
Administration	CWMB[1] WRPC[2] Local government DENR[3]	*Water Resources Act 1997*	Watercourses are termed 'prescribed' or 'non-prescribed'. A prescribed watercourse is one where water extraction must be authorised. The management of streams is delegated to four authorities based on the preparation of water plans: • State Water Management Plans are administered by WRPC; • Catchment Water Management Plans are administered by the CWMB; • Local Water Management Plans are administered by local government. Streams within local government boundaries are administered by the local government; and • Watercourses outside local government boundaries that are not covered by any of the above water plans are administered by DENR. There are water plans for the River Torrens and Patawalonga catchments. Plans are expected to be adopted for the Onkaparinga River, Murray River and North Adelaide–Barossa catchments by June 1999.
Access	CWMB	*Water Resources Act 1997*	Where the watercourse is on private land, permission to enter a property should be obtained from the landholder, although authorised officers under the *Water Resources Act* may enter any land.
General duty of care		*Environmental Protection Act 1993* *Water Resources Act 1997*	All management activities need to take account of Section 25 of the *Environmental Protection Act*, which relates to general environmental duty. Under the *Water Resources Act*, • landholders are obliged to maintain their watercourse(s) in good condition; and • landholders have a duty to take reasonable steps to prevent damage to the bed and banks of a watercourse.

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Table 38 (cont'd). Legislation relevant to stream rehabilitation in South Australia.

Issue	Agency	Documentation	Discussion
Management activities:			
Removal of native vegetation	Native Vegetation Council	*Native Vegetation Act 1991*	Permission is required for the removal or clearance of all native riparian vegetation, both aquatic and terrestrial.
Removal of exotic vegetation	DENR, CWMB or local council	*Local Government Act 1934*	Exotic vegetation removal must comply with any water plan covering the site.
		Animal and Plant Control (Agricultural Protection and Other Purposes) Act 1986	Local government may remove obstructions, so if willows are obstructing the channel, local government can give approval for their removal.
			Landholders have an obligation to destroy vegetation defined under S.57 of the *Animal and Plant Control Act.*
Revegetation		*Local Government Act 1997,* S.636 & 641	No permission is required to fence and revegetate along a channel. However, if the revegetation causes any 'obstruction' or may cause flooding that will be a danger to life or property, the local government may remove the obstruction.
Water abstraction and impoundment structures	CWMB[1] or DENR[3], Local government	*Water Resources Act 1997* S.9(3)(e) & S.9(4)(a) *Local Government Act 1934* S.635 *Development Act 1993*	For prescribed watercourses under the *Water Resources Act,* permission is required to abstract water. Advice on prescribed watercourses can be obtained from the relevant contact agency for your stream, ie. WRPC[2], CWMB, local government, DENR. For non-prescribed watercourses, abstraction is acceptable as long as it does not contravene a water plan. For impoundment structures, a permit to undertake a 'water affecting activity' must be obtained from DENR, unless that activity constitutes a 'development' for the purposes of the *Development Act*. However, such development activities are referred to the DENR as part of the planning process.
Modifying bed and banks	DENR; CWMB or local government; EPA[4]	*Water Resources Act 1997*, S9 *Local Government Act,* S.635 Environmental Protection Act 1993 S.25	Where a water plan exists, permission is required from the relevant contact agency, ie. CWMB, local government , DENR. Additional permission may be required from the local council as well as from the CWMB or DENR. If the works may contribute to the release of sediment such that the sediment load exceeds 25 mg per litre suspended load, then a licence is required from the EPA. All works should confirm to the EPA's Stormwater Pollution Control Code of Practice.
Sand, gravel or soil extraction	CWMB, DENR, and local government	*Water Resources Act 1997*, S.9 *Local Government Act 1934*, S.635	Where a water plan exists, permission is required from the relevant contact agency, ie. CWMB, local government , DENR. Additional permission is also required from the local government authority.

[1]CWMB: Catchment Water Management Board

[2]WRPC: Water Resources Planning Committee

[3]DENR: South Australia Department of Environment and Natural Resources

[4]EPA: Environmental Protection Authority

6. Tasmanian stream management

*by Max Giblin**

The management of streams in Tasmania is delegated to a range of government bodies depending on the aspect of stream management. As a first point of contact the Rivers and Water Supply Commission (RWSC) should be able to advise you on the relevant contact organisations or provide advice themselves. Details of the relevant legislation are given in Table 39.

The primary piece of legislation for Tasmanian river management—the *Water Act 1957*—is currently being reviewed, with updated legislation expected by early 1999.

Table 39. Legislation relevant to stream rehabilitation in Tasmania.

Issue	Agency	Documentation	Discussion
Administration:			
Agency responsibilities	RWSC[1]		RWSC is the main administrator of day-to-day river management activities.
	IFC[2]		IFC is responsible for reviewing impacts on freshwater fisheries, down to tidal limit.
	DELM[3]		DELM reviews environmental impact assessments; management of Crown frontages, Aboriginal heritage and threatened species.
	DPIF[4]		DPIF is responsible for the review of impacts on marine resources, ie. estuaries.
	FPB[5]		FPB controls clearing along frontages in commercial timber-harvesting operations.
	PWS[6]		Local government is responsible for control of water pollution. PWS is a section within DELM that manages rivers in parks and reserves.

Note: RWSC can enforce all necessary precautions and any necessary corrective action.

[1]RWSC: Rivers and Water Supply Commission

[2]IFC: Inland Fisheries Commission

[3]DELM: Tasmanian Department of Environment and Land Management

[4]DPIF: Department of Primary Industry and Fisheries

[5]FPB: Forest Practices Board

[6]PWS: Parks and Wildlife Services

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Table 39 (cont'd). Legislation relevant to stream rehabilitation in Tasmania.

Issue	Agency	Documentation	Discussion
Ownership	DELM		Most non-tidal (inland) frontages are in private ownership. Numerous riparian reserves have been acquired by the Crown through rural subdivision procedures during the past 15 years, but this now only happens where development densities and recreational requirements indicate a need. Most tidal frontages are owned by the Crown.
Access to a stream			Individuals will normally require landowner's permission; statutory authorities have statutory powers of entry for undertaking formal schemes.
Private easements		*Conveyancing & Law of Property Act 1978*	Adjoining or other landowners may acquire an easement over private land if necessary and if in the public interest.
Management activities:			
Clearing willows	RWSC	*Water Act 1957*	Formal permission is not required for clearing willows unless the clearing is part of a joint, formal scheme, which will normally be the case where works grants are involved. RWSC can regulate individual river activities, but has a statutory responsibility to consult with relevant agencies such as IFC and PWS on conservation issues. Rivercare planning guidelines recently published to assist Landcare groups with accessing specialist advice and preparing Rivercare plans
Grade control structures	RWSC IFC	*Water Act 1957* *Inland Fisheries Act 1995*	The same conditions as for willow clearing apply; but if any structure creates a water storage in the river it will require prior written permission from the RWSC, mainly for dam safety reasons. IFC can regulate any adverse impact on freshwater fisheries.
Fencing and revegetation	RWSC	*Water Act 1957*	As for willow clearing; but again RWSC can regulate if necessary, eg. to control flood effects.
Interfering with flow	RWSC IFC	*Water Act 1957* *Inland Fisheries Act 1995*	Same as for willow clearing; RWSC can regulate activities to prevent any adverse effects. IFC can regulate any adverse impacts on freshwater fisheries
Bank revetment	RWSC IFC	*Water Act 1957* *Inland Fisheries Act 1995*	Same as for structures and flow interference.
General	DELM RWSC	*Environmental Management and Pollution Control Act 1994* *Water Act 1957*	Activities likely to have a significant environmental impact may require an environmental impact assessment under this Act.

Note: RWSC can enforce all necessary precautions and any necessary corrective action.

[1]RWSC: Rivers and Water Supply Commission

[2]IFC: Inland Fisheries Commission

[3]DELM: Tasmanian Department of Environment and Land Management

[4]DPIF: Department of Primary Industry and Fisheries

[5]FPB: Forest Practices Board

[6]PWS: Parks and Wildlife Services

BENEFIT–COST ANALYSIS OF STREAM REHABILITATION PROJECTS

*Produced from material provided by Mike Read and Neil Sturgess**

Benefit–cost analysis (BCA) is used to help make government and community decisions about whether to spend scarce public funds on, say, river management rather than on other investments, or the decision about which river management programs represent the best use of scarce funds (Read Sturgess & Associates, 1992). The assumption is that the best value project will return the highest benefit for a given cost. BCA is a method that applies a strict procedure to produce this ratio of benefits to costs.

BCA is simply a process of comparing all the cost and benefits of a particular project in current dollar terms. For example, a rehabilitation strategy might be to remove willows from a stream in year one, fence the stream in year two, and revegetate the stream in year four. The benefit of this project may be a pick up in the recreational fishing industry in the stream from year 10 onward. So how do we compare the costs which are expended in the first few years with benefits which don't start for 10 years? The solution is to convert all costs and benefits to current dollar terms (present value) and simply sum the present value of the costs and benefits to get the net present value (NPV) of the project.

A difficulty of BCA is that, in trying to convert future dollars to a current value, we often need to predict what the future value will be (eg. what if land has been lost to erosion in 10 years time; what will be the cost of land ten years from now?) then discount the future value to give it a present value. Economics textbooks such as that of Hanley and Splash (1993) explain how to select the appropriate discount rate and calculate present values.

This section describes BCA for stream rehabilitation projects, and concludes that it is difficult to apply traditional BCA to stream rehabilitation because of the many non-market benefits involved, although the rapid appraisal method (RAM) provides some techniques for valuing such benefits. For details of the methods summarised here see Read Sturgess & Associates (1992).

Two case studies of BCA are included at the end of the section. One, from north-east Victoria, using the RAM approach, and one from Queensland, using standard BCA.

1. The difficulty of applying BCA

BCA is excellent for assessing the value of projects with a financial return and involving commodities that can be given a price based on market values. For example, consider a proposal to build a dam that will supply irrigation water. The cost of the dam, reticulation and land lost due to inundation can all be given market values, as can the expected increase in returns (benefits) through the use of water for irrigation. Thus, a BCA of the market goods (those goods which are tradeable and hence have a market value) is relatively easy to make. BCA of projects dominated by non-market goods is not so easy. The non-market goods are those which are not traded. They include items such as the value of pristine wilderness, and the value of being able to use the river or dam for recreation.

All stream rehabilitation projects will have a large proportion of non-market values driving them.

Unfortunately, it is generally much easier to justify the environmental destruction of a stream with a BCA than it is to justify the stream's rehabilitation. There are three reasons for this.

1. As we have emphasised many times, it costs much more to fix a stream than to destroy it. This is largely because the human impact on stream systems often induces an increase of energy. That is, channelisation, gullying, levees etc. all lead to an increase in the 'power' of a stream system (increased slope or increased

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discharge). Rehabilitation efforts have to overcome this energy and so are expensive.

2. Estimating the benefits and costs requires an assessment of the probability of particular changes occurring in the stream if the works are not done. For example, what will be the cost of increased suspended loads to streams if work is not done? 'What if' questions of this type are inherently difficult to answer.

3. The benefits of the stream rehabilitation are usually non-market benefits and therefore difficult to cost.

The difficulty in conducting BCA for 'environmental' stream projects is that of establishing the costs and benefits of the non-market values they are concerned with, such as people's desire to enjoy spending time in natural surroundings, or the value of a slightly degraded environment as compared with a pristine one?

A recent alternative to BCA for assessing the value of projects with many non-market values is multi-criteria analysis (MCA). This compares projects dominated by non-market goods by 'scoring' the non-market goods. Some people see MCA as an acceptable alternative to BCA and a panacea for decision analysis. Reed and Sturgess strongly disagree, saying that MCA merely shifts the hard part of the analysis from the question of valuing unpriced goods and services to deciding on what weights to give the criteria that are used to score those goods and services. Those weights had better be proportional to the community's willingness to pay for the goods and services (what is assessed for BCA) or MCA will give the wrong answer. Furthermore, as well as the river engineer, MCA needs a team of technical experts if it is to be done properly, BCA needs a single, determined economist. In the end, both provide information to the decision-makers but decision-makers must still exercise their interpretive skills and their judgment.

BCA remains the standard procedure for valuing projects, is widely accepted by government treasuries and program administrators, and is the standard adopted by the OECD and the Commonwealth Government and the Murray–Darling Basin Commission.

Information that is useful for BCA

At first it might appear remarkable how little information is available on the benefits that accrue from stream rehabilitation activities. The surprise may diminish when one tries to measure the subtle effects of various treatments. The following evaluation of a gully control project shows clearly that rehabilitation work can be cost effective.

Sharpley *et al.* (1996) reported on a 13-year study of the effects of treating a 5.7 ha gullied catchment by bulldozing the gullies (gully shaping) and seeding with Bermuda grass. The gullied catchment lost 27,500 kg of soil, 7.1 kg N, and 4.1 kg of P/ha/year, compared with the ungullied control catchment that lost 4,900 kg of sediment, 3.1 kg N, and 1.6 kg of P/ha/year. The cost of the treatment was $US1,100/ha, which means that *210 kg of sediment, 5 g N and 3 g P were retained for every dollar spent on treatment.*

These results provide a strong case for use of BCA in planning stream rehabilitation work.

2. How to value non-market goods

There are three basic methods of valuing non-market goods. BCA textbooks, such as that of Hanley and Splash (1993), can be consulted for further details of their application and limitations.

1. The *hedonic pricing method* (HP) links the value of the non-market good to that of a market good (Hanley and Spash, 1993). For example, a farm containing a 'natural' stream may have a higher value than a farm with a degraded stream (other factors being equal). Thus, by improving the degraded stream to a 'natural' state will increase the market value of a farm.

2. The *contingent valuation method* (CVM) estimates market values through willingness to pay (WTP) and willingness to receive. For example, improved stream

habitat brought about by stream rehabilitation could be valued by asking stream users how much they are willing to pay for improved habitat. How much, for instance, would visitors be willing to pay for the improved fishing following stream rehabilitation?

3. The *travel cost method*: is based on the expense users actually incur to use a non-market good, through travel expenses, national park entry fees, on-site expenditures, and so forth. For example, the value of a good reach of stream could be indirectly gauged by calculating how much it has cost fishermen to spend the weekend fishing there.

Unfortunately, these methods of valuing non-market goods are time-consuming if surveys of land values or stream users are required (particularly if data from a similar BCA project are not available). The best approach is to look first at market goods, which are relatively easy to value, and to try valuing non-market goods only if the difference between the costs and benefits is too large and the value of the non-market goods becomes critical.

The rapid appraisal method (RAM) approach relies on this approach. It first compares the benefits and costs of market values then, if the result is not positive, looks at whether the non-market values are sufficient to cover the 'gap'. That is, if the project is not viable on economic grounds, then you consider non-economic values to see if the project then becomes viable. The attraction of this method is that time need not be spent guesstimating values for non-market goods which may not be critical to decision-making. There are two possible outcomes using this method.

1. Market benefits outweigh market costs (for example, the cost of rock beaching is less than the replacement cost of a road that it will protect), hence the project provides a net benefit without considering the non-market values.

2. Market benefits are similar to, or less than market cost (for example, the cost of rock beaching is *more* than the replacement cost of a road that it will protect). Since the project has a net cost (market goods), the manager must make the judgment as to whether the non-market goods are 'worth' the discrepancy between market cost and market benefit. There are methods of applying scoring, and willingness to pay values to estimate non-market goods, but the level of detail required is a function of the discrepancy between market cost and benefit and the magnitude of the rehabilitation project. There is no point spending half the rehabilitation budget of a small community project deciding whether or not the project is worthwhile.

The RAM approach to BCA can be summarised as four basic steps.

1. Summarise the potential benefits and costs of proposed management options relative to the do-nothing scenario.

2. Summarise level of detail and known information for initial analysis (ie. compile all the easy to calculate costs and benefits).

3. Undertake initial analysis of benefits and costs, including 'what if' scenarios and threshold values.

4. Decide whether this initial, rapid, analysis has provided sufficient information to be conclusive. If not, proceed to a more detailed analysis.

It is our experience that it is often not necessary to proceed beyond Step 4.

Using 'threshold' values

When the monetary valuation of some non-market benefits is regarded as impossible, other mechanisms of drawing the decision-makers' attention to the importance of those benefits must be used. Some of these mechanisms, including photographs and scoring methods, have been discussed elsewhere (Read Sturgess & Associates, 1992). We believe a valid approach is to present the unpriced benefits of rehabilitation and focus on their threshold values: that is, the values which would at least bring the benefits and costs of the rehabilitation option being considered closer together.

Suppose, for example, that Option X for rehabilitation is found to have a ratio of dollar benefits to costs of 0.7. Option X would also improve in-stream habitat and increase the chances of survival of an endangered species of native fish. It is possible to provide scores for the improvement in habitat (Mitchell, 1990) or the Index of Stream Condition (DNRE, 1997b), and an assessment in the improved probability of species survival. These pieces of evidence should be presented to the decision-maker together with, if available and appropriate, evidence such as photographs from sites which provide a benchmark for the expected improvement in environmental conditions.

Then ask: 'What would the value of these unpriced benefits have to be for the total benefits of Option X to equal its costs?" Clearly, the answer is \$Y, where \$Y = \$Cost – \$(valued) Benefit . The question for the decision-maker becomes: 'is the community's valuation of improved habitat and increased probability of survival likely to be greater than this threshold value?'.

When applying the RAM, the analyst is encouraged to use case studies; to seek consensus views to approximate damages to, say, recreational assets, rather than use rigorous survey methods; to argue from known past events; and to use the results of past studies. The last of these is particularly important for the valuation of unpriced benefits. The process of transferring values from other studies can supply indicative values to aid the analysis by formulating 'what if' scenarios. For example, the priced benefits of a program are less than the costs but 'what if' the value of recreational fishing on this stream were similar to that found by valid research methods on stream X in another State? Or what if the value were half or twice that on Stream X? Such 'what ifs' reveal possibilities and help decision-makers do their job more effectively.

The continued use of BCA as the primary tool of decision analysis, and the use of threshold analysis in the manner described above, has been endorsed by the Commonwealth Department of Finance (1991) and by the LWMP Economic Committee (1996).

Finding a 'robust' solution

After having used RAM for the evaluation of the benefits of a number of management options, one can extrapolate the costs and benefits to similar projects. This approach is founded on our belief that the gains from painstaking research and evaluation for the purposes of a policy decision are unlikely to warrant the extra cost. Therefore, the analysis is shortened and made appropriate to the task by:

- considering only those benefits and costs for which there is reliable information or reasonable assumptions can be made;
- minimising the level of detail with which they are estimated; and
- proceeding in an iterative fashion only as far as necessary to capture and analyse the minimum amount of information which is required to allow a robust solution.

> A robust solution is defined as one in which further detail would not alter the decision about the best option. Further detailed analysis beyond that point would improve only the estimate of the margin by which the chosen alternative was the more efficient, not the decision itself.

This position is adopted because there are always some values for which a preliminary estimate can be made rapidly with wide confidence limits, but for which it would be extremely time-consuming to improve the detail of that estimate. It cannot be overemphasised that orders of magnitude of effects derived from initial and less-complex analysis, coupled with sensitivity analysis of key parameters, can give rise to useful and timely results.

Reed and Sturgess list the following 'lessons learned' from their experience in applying BCA to stream management problems.

- Don't be put off by the problems and apparent complexity of analysing the benefits and costs of stream rehabilitation (or, ask us to have a go for you).
- Don't be side-tracked by bewitching, analytical 'methods' such as multicriteria analysis.
- When assessing benefits, use the rapid appraisal method (RAM) and be imaginative in applying it—ask 'what if' questions about hard-to-value items. Remember that your time frames for analysis are short and the RAM is easy on the budget.
- Be 'practical' in your application—don't seek unnecessary detail about how good the better alternative is, just show it's the best.

Case study 1: An example from north-east Victoria using the rapid assessment method

While being a comparatively quick way to conduct BCA, RAM still requires the investment of time and energy, the amounts depending, of course, on your rehabilitation program and the relative importance of being accurate in your estimates. Read Sturgess & Associates (1992) include five detailed case studies which illustrate the application of the RAM method. The following example is a subsection of one of those case studies. The case study considers four common stream problems in the catchments of the Ovens and King rivers (north-east Victoria):

- incised streams;
- actively eroding streams;
- unstable alignment; and
- siltation.

The example to follow is for the rehabilitation of an incised reach on Boggy Creek. Boggy Creek has experienced major widening and deepening. The reach of concern is 4 km in length and is crossed at one point by a road bridge.

The rehabilitation plan would be the use of a series of grade-reducing barriers in the stream bed (eg. rock chutes/riffles) for bed control; occasional structural bank protection using rock beaching or brushing; fencing off the reach of stream 5 m from the top of the bank; and revegetating the banks to provide added stability. Without work, it is predicted that the stream would stabilise in 30 years; with the project, the stream is assumed to stabilise from year 1.

Step 1) Benefits and costs summary

Potential benefits of a stream rehabilitation program to stop headcutting:

- agricultural land will no longer be eroded;
- road bridge will need to be replaced in 15 years instead of 10;
- reduced siltation of downstream reaches; and
- improved in-stream habitat.

Potential costs of rehabilitation program:

- land loss through fencing;
- cost of structures; and
- cost of maintenance.

Step 2) Summarised details for initial analysis

Benefits

Stop loss of agricultural land:

- The estimated rate of widening is 0.5 m per year (total for both sides of the stream) for 10% of the reach length (0.4 km) for the period of the program, which relates to 0.02 ha per year for 30 years. If the land is valued at $2,000/ha, land loss without the project is $40 per year or a total present value of $690.

Road bridge replacement:

- It is estimated the works would increase the life of the road bridge from 10 to 15 years. The bridge has an estimated replacement value of $168,000. The benefit is discounted to a present value of the benefit of $20,000.

Reduce siltation:

- Off-site impacts are important to consider when summarising costs and benefits. In the case of downstream siltation, benefits could be both non-market such as improved habitat, and market, such as less maintenance required. The benefits from reduced siltation are hard to predict let alone cost, so this 'hard-to price' item goes into the group of items that would be used if the BCA ratio came out less than 1.

Improved stream habitat:

- The stream habitat value is a clear non-market variable and cannot be directly estimated. Surrogate measures could be adopted, such as willingness for persons to pay to use an area of such and such habitat value etc. The value of improved stream habitat could also go into the group of hard-to-price items.

Costs of project

Land lost through fencing:

- Assuming that the river frontage is mostly Crown land, the cost of fencing is not related to the cost of the land (Crown owns this land) but to the loss of production from the land (land used for stock production). Based on a 5 m strip (very narrow!) along each side of the stream, and the fencing would take place over two years, the fenced-off area would be 1.5 ha in year one and 1.5 ha in year two of the project. Assuming a gross margin of $13 per dse (dry sheep equivalent) and a stocking rate of 10 dse per ha the cost of fencing has a present value of $245 ($195 for year one and $195 discounted to present value in year 2).

Cost of rehabilitation program:

- Rehabilitation program costs include costings for plant, materials and labour for the initial work, and the cost of follow up maintenance work and any evaluation carried out.

The Read and Sturgess example goes on to include the streams in a catchment-wide RAM. Additional stream problems addressed in the strategy are problems of active erosion, unstable alignment and siltation. The conclusion of step 2 provides an estimated market benefit of protecting Boggy Creek in terms of incision, active erosion, unstable alignments and siltation at $227,800 (90% is a result of protection of nine bridges throughout the catchment). The estimated cost of a rehabilitation program over 30 years is $399,000. Thus, the net present value represents a deficiency of $171,000, or having a benefit–cost ratio of 0.57, such that 57 cents out of every dollar spent will be returned through some market benefit.

Step 3) Consider 'what if' scenarios

Consider 'what if' scenarios and the sensitivity of the analysis to different inputs: for example, the market benefits are very sensitive to the conservation of infrastructure. In this example there are nine bridges contributing to the market benefit. The method by which the replacement cost and life of the bridges are estimated will have a dramatic effect on the market benefits.

Alternatively, consider the cost overrun ($399,000 – $227,800 = $172,000) in terms of the non-market benefits. In order to make a decision on this project, the question would be posed: Is improved habitat through reduced siltation and preserved riparian zone (from stabilised alignment) for the stream length worth $172,000?

Step 4) Decide whether more information is needed

Based on the RAM results, the decision-maker decides whether to go ahead, seek information on alternatives, seek more detailed information or simply reject the option.

Case study 2: Evaluating stream stabilisation works using traditional benefit–cost analysis

Brizga *et al.* (1996a) describe a BCA undertaken on bank stabilisation works on Cattle Creek, a tributary of the Pioneer River in north-east Queensland. The stream has a history of severe erosion associated with tropical cyclones, and the surrounding land is used for sugarcane farming and has a high value. This example considers the benefit–cost of revetting the stream solely for the protection of sugarcane farmland. This is not meant to justify the use of riprap but to illustrate the sensitivity of BCA to the discount rates adopted and the problems with predicting future farmland value. Three different discount rates are used: 3, 6 and 10% (for a discussion on the appropriate selection of discount rates see Commonwealth Department of Finance, 1991). Land is valued on the basis of sugar price. The case study considers three possible sugar prices: 1) the peak price in 1980 $630/t (current Australian dollars); 2) the average sugar price from 1980–1992, $403/t; and 3) the average expected international price of raw sugar, $300/t. The value of farmland is based on the yield of sugar per ha, the cost of growing the cane, and the breakdown of gross value of sugar between the mill sector and farms. The key data for this study are summarised in Table 40, and the costs and benefits in Table 41.

Table 40. Key project data for the Cattle Creek BCA.

Length of reach:	3.3 km
Length of works:	2.85 lineal km of bank
Unit cost of works:	$120/m
Total cost of works:	$342,000
Annual maintenance provision (%):	5% of capital cost
Project life:	20 years
Annual maintenance provision:	$17,100
Total area protected:	17 ha

Table 41. Cost and benefit summary of Cattle Creek revetment.

Discount rate (%)	3	6	10
Cost			
Average annual cost/ha of land protected	$630	$590	$551
Benefits			
Scenario 1: sugar price = A$630/t			
Average annual benefit /ha of land protected	$3,827	$2,413	$1,575
Scenario 2: sugar price = A$403/t			
Average annual benefit/ha of land protected	$1,167	$736	$480
Scenario 3: sugar price = A$300/t			
Average annual benefit/ha of land protected	$515	$325	$212

Revetting the stream can be justified on the basis of protecting sugarcane farmland alone when the BCA ratios in Table 42 are greater than or equal to 1. For all discount rates it is cost-effective to revet the stream if sugar prices stayed at the peak 1980 level, but if we look at the more realistic value of an average of the 1980s sugar prices, the revetment work becomes marginal for a discount rate of 6% and is uneconomical if the real discount rate is 10%. Using the predicted long-term sugar price which is appropriate for this long-term (50 year) project, revetment is uneconomical for all discount rates.

Table 42. Benefit–cost ratios for the alternative scenarios (ratio >1 is economic).

Discount rate (%)	3	6	10
Scenario 1	4.18	3.36	2.62
Scenario 2	1.28	1.02	0.80
Scenario 3	0.56	0.45	0.35

This example illustrates two key points: the first is the importance of estimating future produce values 'correctly', and the second is that by judicious selection of discount rates and valuation techniques, the BCA outcome can easily be skewed.

Care must be exercised in the way future values are predicted: are they long-term averages or the extension of a trend? The different scenarios used to estimate price either show the revetment plan as a tremendous economic boost, or an uneconomic blunder. If the methods of estimating a clearly defined, tradeable commodity such as sugar are so easy to skew, imagine how easy it is to get the numbers wrong for non-market goods such as environmental quality.

The second point relating to the selection of discount rates and valuing techniques should serve as a warning to rigorously review BCA work to make sure the values adopted are a fair and balanced assessment and that alternative scenarios are investigated.

Finally, this case study illustrates that expensive bank revetment designed to protect farming land alone is difficult to justify even in a very high value land use like sugarcane growing. Adding environmental benefits may help justify such works!

THE GEOGRAPHIC INFORMATION SYSTEM (GIS) AS A STREAM REHABILITATION TOOL

By Jim Burston and Karla Billington†*

1. What is a GIS and how much does it cost to set up?

Geographic information systems (GIS) are computer-based systems that are used to store and manipulate geographic information such as maps. It is a simple, relatively low-cost mapping tool that allows easy presentation of information and is useful for managing information. The South Australian Department of Environment and Natural Resources set up an extensive GIS system when developing catchment management plans for the Inman and Torrens rivers. The following is an assessment of the usefulness of GIS for stream rehabilitation. As an example of cost, a 'PC' based GIS system should cost around $7,000 to set up. This figure includes software (eg. ARCVIEW/MapInfo) and a suitable PC but *it does not include any data*. The cost of data is potentially very expensive, especially if it does not exist and needs to be 'captured' (ie. you have to do some field work or spend time to crunch numbers to create the data).

The cost of data will also be expensive where it has to be bought from government agencies or other commercial sources. The collection and input of 'original' data is expensive (in terms of collecting the data, software requirements, and the use of highly skilled personnel) and requires the use of the more complex and costly ARC/INFO (as compared to ARCVIEW). However, once the data set has been created, it is extremely cheap and easy to convert to a PC-based GIS.

There is great potential where the data exists and can be used on a PC GIS system (eg. ARCVIEW3). The training time to create a competent ARCVIEW3 user is relatively low. Bear in mind that competency in ARC/INFO is considered to take about 3 years of full-time exposure, thus it is an expensive system in terms of time cost in training personnel.

2. Are the analysis tools of a full-blown GIS really helpful in planning a rehabilitation project?

The answer to this question depends upon how you intend to use the GIS.

Serious consideration must be given to the cost of the information. There is a bit of an 'industry' pushing local decision-makers to utilise state-of-the-art models that require substantial quantities of data. According to Lovejoy (1997), if the budget is limited and managers are concerned about short-run objectives and efficiency, then the dollars are better spent doing on-ground works rather than data gathering. If the data are to be used for 'one-off' planning decisions, then GIS is of questionable value. However, if the data are to be distributed and widely used by other parties, then GIS is useful. Managers should carefully evaluate their short and long-term objectives to determine whether low-tech or high-tech solutions are warranted. Don't be fooled, GIS technology does not improve the accuracy of map data.

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For South Australian conditions, most of the rehabilitation options revolve around 'fencing and revegetation'—we suspect that this might be the case for many other areas in Australia. Consequently, most of the design of the rehabilitation options is fairly crude, 'back of the envelope' sort of stuff, where the answers are generally worked out in the field.

A GIS has the advantage of being able to integrate different types of spatial information (ie. land use, soils, cadastral, stream coverage, roads etc.) and non-spatial data (eg. photos, MS Word or Excel files). However, many of the data required to develop an action plan for rehabilitation are either unavailable (that's why the Riparian Project did all the survey work in the first place) or exist at a scale that is inappropriate. Many of the data that are bought 'off-the-shelf' require some degree of ground-truthing to validate their accuracy.

Once the data exist, the PC-based GIS can be very useful in developing a rehabilitation program. It can help determine the length of watercourse affected, the cost of repairs, on whose property the works are to be undertaken, production of summary tables for issues/sub-catchments/local council areas or what ever else is required. This can all be done in a very short time. Furthermore, it has a great capacity for monitoring and auditing (ie. what/where/when/cost) a rehabilitation program (as we have set up for the work being done in the River Torrens).

GIS is now widely accepted as the standard format for data storage. The advent of PC GIS enables ease of access for all resource managers.

The standard GIS model employs co-ordinates (ie. latitudes and longitudes) to define segments or points along a watercourse (the arc-node model). We have experienced difficulties with the analysis of data, particularly when measurements are required between different features along a watercourse. Other problems included inefficient storage of data (especially for segmented linear data) and difficulties in overlaying and analysing linear and point data.

3. Analysis of GIS information

If there is a strong requirement for analysis, then the ARC/INFO package 'Dynamic Segmentation' (DS) has great potential. To the best of our knowledge, we are the only people using this package for stream rehabilitation work in Australia.

DS is a system for measuring changes along a linear network (eg. roads, sewers, electricity grid, stream network). The strength of this package is in its ability to analyse data that may change along a stream network (eg. water quality). It is also useful for analysing between various data sets (eg. location of knick points, type of bed material, bank stability). DS enables the development of more complex and flexible models. Its real value may be best exploited by those who want to understand the underlying processes and mechanisms of stream processes and the water quality of those streams.

If you just want to 'fix up' the river, then don't worry about Dynamic Segmentation.

4. Data transfer

The integration of spatial and non-spatial information makes this an extremely valuable resource for managers. It enables users to view the current condition of the watercourse and then use the ARCVIEW format as a tool for monitoring, auditing and displaying the results achieved in implementing on-ground works. Furthermore, all this information can be written to a CD-ROM, with accompanying documentation, to greatly increase the accessibility of the data.

If you're going to use GIS, you must ensure that at least one member of the project team is a GIS expert, who can 'trouble-shoot' as required and train other staff.

5. Is the effort and cost of GIS worth it? What are the benefits and costs?

For whole of catchment rehabilitation project – YES.

For the treatment of isolated reaches of watercourse – generally NO.

Benefits: ease of access to data; monitoring/costing of rehabilitation options; GIS is recognised as a standard data storage format; there is a lot of undeveloped potential in the ARC/INFO package, 'Dynamic Segmentation', for the analysis of river processes.

SOME COSTS OF STREAM REHABILITATION ACTIVITIES

Please note that this manual does not provide detailed financial advice and the following tables are a general guide only.

1. The costs of stream management works

It is useful for stream rehabilitators to have an idea of the potential cost of rehabilitation works. The following tables and notes are the beginnings of what we hope will be a more comprehensive inventory of the costs of rehabilitating streams in Australia. Most of the following data were taken from White *et al.* (1999), whose paper also includes other interesting statistics on the money being spent on stream rehabilitation in Australia at present. Note that the DLWC River Management Unit (NSW) has published excellent tables for estimating the cost of works in streams (published in 1994).

All values are in 1997–98 Australian dollars. These values can be corrected in the future for inflation by using the consumer price index.

Traditional stream management of degraded streams (including stabilisation of the bed and banks) can be very expensive (often in the order of tens to hundreds of thousands of dollars per stream kilometre), but rehabilitation of degraded streams is likely to cost even more. In part, this is because of the extra assessment and evaluation costs that are often associated with rehabilitation work.

Indicative unit rates for some stream rehabilitation projects, techniques and resources are provided in Tables 43 and 44. It should be noted that the rates will be highly variable and will depend on factors including: the size of the stream, establishment costs for equipment at a site, distance from work centres to work sites, and climatic and other environmental conditions.

Table 43. The scale of stream rehabilitation project costs.

Item	Indicative unit rate	Source
Full revegetation (from tube-stock), and fencing, of a riparian strip on both banks of a stream (direct seeding of vegetation may be considerably cheaper).	$12,000 per km	R. Hardie, pers. comm.
Typical rock chute in a small creek (say streams up to 15 m wide, 1 m drop, length 10 m, apron length 4 m, plus abutment protection).	$5,000–$20,000 per chute	R. Hardie, pers. comm.
Fishways: • rock ramp (up to 2 m vertical) • vertical slot (3–6 m vertical)	 $10,000–$30,000 per vertical metre $60,000–$100,000 per vertical metre (Total cost of 1 m rock ramp fishway = $10,000, using 24 m^3 of rock).	 T. O'Brien, pers. comm.

Table 43 (cont'd). The scale of stream rehabilitation project costs.

Item	Indicative unit rate	Source
Stabilisation and revegetation of degraded urban streams (eg. Melbourne streams).	\$0.5–\$0.8 million per kilometre (\$500–\$800 per linear metre)	Melbourne Water
Flow alignment works (eg. retards).	\$20,000–\$50,000 per bend on medium-sized rivers Using 'Jacks' on a NSW stream = \$10,000 for a single bend	R. Hardie pers. comm. John Gardiner, DLWC, NSW
Twentymile Creek, Mississippi, USA. Stream rehabilitation involving grade control, alignment training, revegetation of an incised stream.	\$0.5 million per km	(Danley *et al.*, 1995)

Table 44. Costs of stream rehabilitation resources (most values come from ID&A Pty Ltd).

Item	Indicative unit rate
Seed from native species (commercial collection) .	\$170/kg (Burston and Brown, 1996)
Tree seedlings:	
• 10 cm to 20 cm	\$0.50 to \$1.00 each
• seedlings (which are small)	\$0.20 to \$0.40 each
Tree planting (including preparation, planting, excluding maintenance)	\$3.00/tree
Willow control—lopping (including safeguards to stop willow spread) followed up by herbicide treatment:	
• Moderate infestation	\$3,500/km of bank
• Severe infestation	\$6,000/km of bank
• Intensive infestation	\$12,000/km of bank
Fencing materials	\$2.50 per metre of fence
Excavator hire:	
• 12 tonne	\$65 per hour
• 20 tonne	\$85 to \$100 per hour
• 30 tonne	\$100 to \$130 per hour
Broken rock (delivered)	\$15 to \$25 per cubic metre delivered (\$9.40–\$15.60 per tonne)
Railway line (which can be used as piles)	\$20 per metre
Timber that can be used in rails of flow retards:	
• Red box, 150 to 300 mm diameter, 4 m length	\$10–\$15 each
• Red box, 150 to 300 mm diameter, 6 m length	\$12 to \$20 each
Labour:	
• Project works supervisor	\$15–\$25/hour
• Works crew member	\$15/hour
Survey team (surveyor, assistant, basic equipment)	\$100/hour
Engineering design and supervision	10–15% of project cost
Administration	5–10% of project cost

2. Additional costs of stream rehabilitation works

Stream rehabilitation often involves works that enhance stream health, or modifications to works that would otherwise damage the health of the stream. Stream rehabilitation involves some new costs to stream managers (such as the cost of adding large woody debris to streams), as well as the extra costs of doing works so that they do not damage stream health (see Table 45). An example of the latter is rock chutes. The structure may survive, and protect the bed, at a slope of 10:1, but in many streams it has to be designed at a slope of around 20:1 to allow fish passage. Thus, provision of fish passage over the chute could double the cost of the structure. There is also the substantial cost of pre-project assessment and post-project evaluation required for stream rehabilitation. Such assessment is essential for stream rehabilitation because we are, as yet, so uncertain about the effectiveness of stream rehabilitation works.

Table 45. Some additional costs of steam rehabilitation.

Item	**Indicative unit rate**	**Source**
Reintroduction of coarse woody debris (large logs) (includes transport to site, positioning and ballasting the log).	$500–$700 per large log (Cost can be up to $3,000 per tree if tree is large and there is no local source)	Various projects
Additional cost of designing rock-chutes to provide fish passage (ie. halving design slope) plus added time by operator in providing for correct surface conditions on the chute.	Doubles the cost	L. White, pers. comm.
Cost of assessment of condition of streams in a catchment using the Anderson 'State of the Rivers' method (from NSW Department of Land and Water Conservation projects).	Average cost per site assessment $250	Allan Raine, DLWC
Cost of assessment of a single reach using the Index of Stream Condition.	$500	L. White, pers. comm.
Average cost of sampling fish population and diversity per site using a combination of techniques (eg. electro-fishing and netting).	$600 per site	T. Raadik, pers. comm. J. Harris, pers. comm.
Estimated cost per site for an AusRivAS macroinvertebrate survey (sampling, laboratory work & analysis).	Professional assessment $1,500	EPA, Victoria
Cost of a professional rehabilitation consultant (eg. specialist in ecology, engineering, geomorphology).	$400–$1,000 per day	
Additional cost of monitoring for biological change post–project.	On the Broken River the scientific evaluation cost more than twice the structural works.	Mike Stewardson, pers. comm.
Adding *Phragmites australis* or broken concrete pipes (obtained at no cost) to a bank stabilisation project to enhance habitat.	5–10% of project cost	R. Morrison, pers. comm.; L. White pers. comm.

BIBLIOGRAPHY OF SOME TECHNICAL INFORMATION AVAILABLE IN AUSTRALIA

A great deal of valuable information on stream rehabilitation exists in the form of fact sheets. These information sheets are produced mostly by government departments and community groups, and often consist of information in a form that is simple, clear and easy to use. Most of these sheets are produced at a State or even catchment level. This means that, although the information is often more widely applicable, the community groups and stream managers outside the region where the fact sheet was produced are unlikely to know of its existence. In this section we present a list of the fact sheets that we are aware of, as well as the contact details of the organisations that distribute them. In this way, we hope to encourage communication within the Australian stream management community.

1. A bibliography of fact sheets

The fact sheets below are arranged by broad subject, and, where relevant, the specific subjects are listed in italics after the entry. Table 46 explains the abbreviations and provides addresses of organisations that produce the sheets.

1.1. Assessment of stream condition

Anderson, J. (1993). **State of the rivers: Maroochy River and tributary streams**. Maroochy, Qld, Maroochy Shire Council & Department of Primary Industries.
(State of environment reporting, bank erosion, riparian vegetation, assessment, Aust. aquatic habitat, conservation, riparian vegetation, bed, bank, bar, overall condition rating, Coolum Creek, Doonan Creek, Yaninda Creek, Petrie Creek, Browns Creek, York Creek, Eudli Creek)

AVRMA (1994). **River management works—the picture after the '93 floods**, Association of Victorian River Management Authorities.
(Broken river, Ovens river, Victoria, brushing, riprap, riffle, rock weir)

Brierley, G. J., K. Fryirs and T. Cohen (1996). **Geomorphology and river ecology in southeastern Australia: An approach to catchment characterisation: Part one: a geomorphic approach to catchment characterisation**. Sydney, Australia, Graduate School of the Environment, Macquarie University.
(geomorphology, descriptors, Australia, river structure, stream classification, restoration, rehabilitation, hierarchical, procedure, prediction)

DNRE (1997). **Index of stream condition: Trial applications**, Department of Natural Resources and Environment (Vic).
(Victoria, stream conservation, stream measurements, stream ecology, water quality, Gippsland)

DNRE (1997). **Index of stream condition: A reference manual**, Department of Natural Resources and Environment (Vic).
(Victoria, stream conservation, stream measurements, stream ecology, water quality, Latrobe catchment, Broken River)

DNRE (1997). **Index of stream condition: Users manual,** Department of Natural Resources and Environment (Vic).
(Victoria, stream conservation, stream measurements, stream ecology, water quality, planning, data collection)

QDPI (1993). **The condition of river catchments in Queensland**, Queensland Department of Primary Industries.
(Queensland, rivers, catchment management, erosion, flooding, salinity, chemicals, water quality, weeds, urban expansion, channel instability, habitat loss, vegetation, wetlands, fish, fauna, ecology)

Waterwatch Victoria (1995). **A waterwatch guide to conducting habitat surveys**. DNRE (VIC). *(evaluation, monitoring)*

1.2. Stream stability

Carter, J. and E. Cottingham. **A guide to erosion control measures for small watercourses in the Mount Lofty Ranges**, Water Resources Group, Department of Environment and Natural Resources, SA. *(bed erosion control, bank erosion control, terminology and definitions, watercourse management, problem assessment, strategies, soil stabilisation, riparian vegetation, techniques, slides)*

DWR. **River wrongs: over removal of gravel,** New South Wales Department of Water Resources. *(gravel removal, channel straightening, excavation, cut-off, New South Wales)*

DWR. **The 7-Step method of controlling bank erosion and sediment build-up** Plus: **Prevention methods you can use now**, New South Wales Department of Water Resources. *(maintenance, expert advice, sedimentation, permission, funding, advice, New South Wales)*

Hader, W. and D. Outhet (1995). **Works to control stream bed erosion. Treatment option: Boulders,** DLWC. *(Schauberger weirs, bed stabilisation, artificial riffle)*

Hader, W. and D. Outhet (1995). **Works to control stream bed erosion. Treatment option: Log/timber v weir (horizontal or vertical logs),** DLWC. *(Schauberger log sill, bed erosion, riffle, pool, scour)*

LWRRDC. (1996). **Streambank stability. Riparian management.** *(bank erosion, riparian vegetation, stabilisation, plant species, revegetation)*

Outhet, D. (1995). **Extractive industries on floodplains. Best management practices.** DLWC. *(sand extraction, gravel extraction, mining, NSW)*

Outhet, D. (1995). **Extractive industries on river bars. Best management practices**. DLWC. *(sand extraction, gravel extraction, bed degradation, flow diversity, river turbidity)*

Outhet, D. (1995). **Works to control stream bed erosion. Treatment option: log and rock bed control and road crossing (gravel/sand/silt road surface) on small intermittent flow stream**, DLWC. *(headcut, ford, vehicle crossing)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: Brush groynes and vegetation.** *(bank stabilisation)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: Gravel mesh sausages and vegetation.** *(bank stabilisation)*

DLWC Riverine management unit (1994). **Works to control stream bank erosion. Treatment option: Heavy duty mesh fencing and vegetation.** *(retards, bank stabilisation)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: Jacks and vegetation.** *(bank stabilisation, jacks)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: log wall and vegetation.** *(toe protection)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: Rock revetment and vegetation.** *(riprap, revegetation)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: Timber groynes and vegetation.** *(bank stabilisation, groynes)*

DLWC Riverine Management Unit (1994). **Works to control stream bank erosion. Treatment option: Rock groynes and vegetation.** *(bank stabilisation)*

West, S. and D. Outhet (1995). **Restoring urban streams. Treatment option: reconstructing vegetated meander bends in straightened channels,** DLWC, NSW. *(channelisation, channelisation, pool, riffle, meander)*

1.3. Vegetation

Anon. (1995). **Hand direct seeding of native plants**, Primary Industries, SA.
(native vegetation, revegetation, weed control, sowing, native trees, South Australia)

Ardill, S. (1994). **Wetlands on your farm**, DLWC, NSW.
(wetland restoration, wetland rehabilitation, definition)

Carter, J. (1993). **WATERWISE—exotic trees along watercourses**, Water Resources Group, Department of Environmental and Natural Resources.
(siltation, willows, ash, poplar, weed control)

Carter, J. (1993). **WATERWISE—woody weed control along watercourses**, Water Resources Group, Department of Environment and Natural Resources.
(gorse, blackberry)

Cremer, K., C. Van Kraayenoord, N.Parker and S.Streatfield(1995). **Willows spreeding by seed,** Australian Journal of Soil and Water Conservation 8 (4): 18–27.
(exotic, weed)

DENR (1993). **WATERWISE: Revegetation of watercourses**, Water Resources Group, Department of Environment and Resources (SA).
(bank stability, buffering)

LWRRDC (1996). **Land-based ecosystems**, Riparian management fact sheet.
(riparian vegetation, ecology)

LWRRDC (1996). **River ecosystems**, Riparian management fact sheet.
(riparian vegetation)

LWRRDC (1998). **Managing snags in rivers**, Riparian management fact sheet.
(fact sheet, LWD, desnagging, resnagging)

QDNR. **Control of azolla: red water fern**.

QDNR. **Control of cumbungi**.

QDNR. **Control of exotic vines**.

QDNR. **Control of salvinia**.

QDNR. **Control of water hyacinth: the worst aquatic weed in the world**.

QDNR .**Growing trees in frost-prone areas**.

QDNR. **Planting trees in dry areas or with limited water**.

QDNR. **Plants suitable for salty soils**.

QDNR. **Plants suitable for sandstone or shale areas**.

QDNR. **Plants suitable for western Qld**.

QDNR. **Propagation of trees and shrubs from seed**.

QDNR. **Seed collection, storage and testing**.

QDNR. **Tree retention**.

QDNR. **Water requirements for trees**.

QDNR. **Weed control for tree planting**.

Raine, A. and J. Gardiner, 1997a. **Revegetating streams in the Clarence Catchment. A guide to species and planting methods**, New South Wales Government.
(riparian vegetation, revegetation, suitable species, bank stabilisation)

Raine, A. and J. Gardiner, 1997b. **Revegetating streams in the Macleay Catchment. A guide to species and planting methods**, New South Wales Government.
(riparian vegetation, revegetation, suitable species, bank stabilisation)

Raine, A. and J. Gardiner, 1997c. **Revegetating streams in the Manning Catchment. A guide to species and planting methods**, New South Wales Government.
(riparian vegetation, revegetation, suitable species, bank stabilisation)

Raine, A. and J. Gardiner (1997). **Revegetating streams in the Bellinger Catchment. A guide to species and planting methods**, New South Wales Government, DLWC.
(riparian vegetation, revegetation, suitable species, bank stabilisation)

Raine, A., J. Golding, *et al.* (1997). **Revegetating streams in the Brunswick Catchment. A guide to species and planting methods**, New South Wales Government, DLWC.
(riparian vegetation, revegetation, suitable species, bank stabilisation)

Raine, A., T. Hudson, *et al.* (1997). **Revegetating streams in the Nambucca Catchment. A guide to species and planting methods**, New South Wales Government, DLWC.
(riparian vegetation, revegetation, suitable species, bank stabilisation)

DLWC Riverine Management Unit (1994). **Controlling willows.**
(willow eradication, drill and fill, poison)

Roberts, K. (1992). **Buffer zones along rivers and creeks,** DWR.
(water quality, riparian vegetation, buffer strips)

S.A. Department of Environment and Natural Resources. **Exotic trees along watercourses**.

S.A. Department of Environment and Natural Resources. **Revegetating watercourses**.

1.4. Animals

Anon. **Electric fencing for sheep and cattle in the hills**, Tungkillo and Harrogate Landcare Groups.
(stock exclusion)

Anon. (1997). **Ripples. Newsletter of the Australian Platypus Conservancy**, Philips and Father.
(platypus, stream health, ecology, community, habitat improvement)

Nicholas, S. and Mack, P. (1996). **Manage your banks: A practical guide to stream-side management, fencing and water supplies,** The Goulburn Valley Environment Group.
(protection of stream banks, fencing, watering systems, stock management, weed control, vermin control, fire hazard control, flood gates, creek crossing, water distribution, restricted access, water diversions, dams, groundwater, pumping, offstream watering, Australia)

QDNR. **Trees attractive to birds**.

1.5. Water quality and pollution

Anon. (1994). **Disposal of farm chemical containers**, DWR (NSW).
(pollution, contamination, water quality)

Anon. (1994). **Filter zones for farm dams,** DWR (NSW).
(buffer strip, water quality, silt trap)

Anon. (1994). **Small farms and septic tanks**, DWR (NSW).
(nutrient, water quality)

Bek, P. (1992). **Blue-green algae in farm dams**, DWR (NSW).
(water quality, nutrient, toxic blooms)

Carter, J. (1993). **WATERWISE—farm dams for stock, wildlife and improved water quality**, Water Resources Group, Department of Environmental and Natural Resources (SA).
(features, intake, filters, fencing, vegetation silt traps, islands)

LWRRDC (1996). **Water quality. Riparian management**.
(riparian vegetation, buffer strips)

QDNR. **Water requirements: stock and domestic purposes**.

Smith, M., W. Kay, *et al.* (1997). **Spineless indicators**, Department of Conservation and Land Management (WA).
(macroinvertebrate, monitoring, Western Australia)

LWRRDC (1996). **Water quality.** Riparian management fact sheet. *(riparian vegetation, buffer strips)*

1.6. Environmental flows

Anon (1995). **Water allocation & management planning**, DPI, Queensland.
(ecologically sustainable development, management, water entitlements, Queensland)

Cullen, P. (1994). **A rationale for environmental flows**. AWWA Environmental Flows Seminar.
(water entitlements, water quality, river channels, floodplain areas, river regulation, aquatic life, maintenance flows, major floods)

1.7. Management of rivers: procedures and examples

Burston, J., and Good, M. (1995). **Watercourse management guidelines for the Inman River catchment**, Adelaide, Department of Environment and Natural Resources, Adelaide, South Australia.
(riparian zone, stream order, channel change, gravel extraction, urbanisation, erosion, management issues, rehabilitation, community participation, point source pollution, water quality)

Burston, J., Aucote, M., Eaton, A. and Prider, A. (1997). **Torrens 1997—an action plan for better watercourse management**, Adelaide, Department of Environment and Natural Resources, Adelaide, South Australia.
(riparian zone, stream order, channel change, erosion, management issues, rehabilitation, community participation, revegetation, bird life, weed removal, stabilising structures, fencing, native flora, soils in research area, macroinvertebrates)

Carter, J. (1993). **WATERWISE—watercourse management**, Water Resources Group, Department of Environmental and Natural Resources.
(erosion, water quality, wildlife, property value, stream processes, riparian zone, native vegetation, willows, buffer zones, revegetation, total catchment management)

DWR. **A guide to stream channel management**, New South Wales Department of Water Resources.
(clearing, excavating, diverting, management, infilling)

Victorian Department of Conservation and Environment (1990). **Environmental guidelines for river management works**, Vic DCE.
(morphology, ecology, rock beaching, brushing, groynes, alignment training, snag management, revegetation, sand and gravel extraction, rock chutes, drop structures, channel modification, bank battering, meander cutoffs, lopping, levee banks, LWD, channelisation)

Myers, R., Ed. (1993). **Watercourse management: A field guide**. Upper River Torrens Landcare Group (SA).
(Upper Torrens Valley history, revegetation of watercourses, bird life, stabilisation of watercourses, management of watercourses, weed removal, stabilising structures, fencing, native grasses, soils in research area, pasture establishment, frogs, macroinvertebrates)

NSW DWR. **A guide to stream channel management: clearing, diverting, excavating, infilling**, New South Wales Department of Water Resources.
(clearing, excavating, diverting, management, infilling, legal requirements, regulatory bodies, permits, New South Wales)

Queensland DPI (1993). **A guide to integrated catchment management in Queensland**, ICM and Landcare Unit, Brisbane.
(rivers of Queensland, treecare, Mary river, Murray Darling Basin, Johnstone River, Lockyer Valley, Pioneer River, Mitchell River, catchments)

Raine, A.W. and J.N. Gardiner (1995). **Rivercare: guidelines for ecologically sustainable management of rivers and riparian vegetation**, LWRRDC.
(rehabilitation, restoration, NSW, revegetation)

RCMU (1993). **River management: why bother?** Riverine Corridor Management Unit, Department of Water Resources (DWR) (NSW).
(New South Wales, River Management Program, community)

Working Group on Waterway Management (1992). **Guidelines for stabilising waterways**, Melbourne, Standing Committee on Rivers and Catchments, Victoria.
(river management, design guidelines, problem assessment, drop structures, drainage, waterway outlets, low flow pipelines, floodways, retarding basins, rock riprap, rock chutes, retards, groynes)

1.8. Policy guidelines and legal considerations

DPI. **The sustainable use and management of Queensland's natural resources: polices and strategies**.
(discussion of approach to developing long term planning for Qld's natural resources)

Parlavliet, G. J. (1993). **Proceedings of the Blackwood Catchment Drainage Workshop**, Blackwood Catchment Drainage Workshop, Bridgetown, November 1993, Blackwood Catchment Coordinating Group.
(community management, government planning, community consultation, WA)

Parlavliet, G. J. (1993). **Proceedings of the Blackwood Catchment Drainage Workshop**, Blackwood Catchment Drainage Workshop, Katanning, September 1993, Blackwood Catchment Coordinating Group.
(community influence, government policy, WA)

Parlevliet, G. J. (1994). **Proceedings of the Blackwood Catchment Drainage Workshop**, Blackwood Catchment Drainage Workshop, Kojonup, April 1994, Blackwood Catchment Coordinating Group.
(remnant vegetation, protection, policy, economic value, community consultation, government, WA)

WRC (1993). **The NSW State Rivers and Estuaries Policy**, NSW Water Resources Council, New South Wales Government.
(New South Wales)

1.9. General information about rivers

CRCFE (1996). **The Murray–Darling Freshwater Research Centre's Lower Basin Laboratory. Working together for the future of freshwater resources**, Cooperative Research Centre for Freshwater Ecology, The Murray–Darling Freshwater Research Centre.
(floodplains, billabongs, floods, ecology, algae, Barwon–Darling River, Murray River, carp)

Department of Land and Water Conservation (1996). **Rivercare 2000—Achievements Year Book 1995.**
(wetland rehabilitation, urban run-off treatment, salinity, realignment)

Department of Land and Water Conservation (1996). **Rivercare 2000 Special Edition—CURRENTS**.
(stream rehabilitation, New South Wales, community awards)

Department of Land and Water Conservation (1995). **Managing the water resources of New South Wales: A survey of landholder and community attitudes,** Sydney.
(landholder survey, sustainable riverine management, community perception)

Myres, R. (1993). **Watercourse management. A field guide**, Landcare South Australia. Upper River Torrens Landcare Group.
(weed removal, stream bed stabilisation, bank stabilisation, native plant revegetation, pasture establishment, Mount Lofty Ranges, macro invertebrates, fencing, woody weeds, native grasses, birds, direct seeding)

2. Abbreviations and contact details

Table 46. A list of abbreviations and contact details.

Abbreviation	Name	Address
	Association of Victorian River Management Authorities (VIC)	See DNRE (VIC)
AWWA	Australian Wastewater and Water Association	PO Box 388 Artarmon NSW 1570 Ph (02) 9413 1288
	Catchment Resource Centre	Mount Lofty Ranges Catchment Group 5c Cameron St Mount Barker SA 5251
DEHAA	Department for Environment, Heritage and Aboriginal Affairs (South Australia)	GPO Box 1047 Adelaide SA 5001
DC&E (VIC)	Department of Conservation and Environment (Vic) — see DNRE (Vic)	
CALM (WA)	Department of Conservation and Land Management (Western Australia)	General Switch Ph 08 9334 0333
DENR (SA)	Department of Environment and Natural Resources (South Australia)— see DEHAA	
DENR	Department of Environment and Natural Resources (VIC) — see DNRE	
DLWC	Department of Land and Water Conservation	10 Valentine Ave PO Box 3720 Parramatta NSW 2150 Ph +61 (02) 9895 6211 Fax: +61 (02) 9895 7281
QDNR	Department of Natural Resources (QLD)	General Enquiries Ph (07) 3896 3111
DNRE	Department of Natural Resources and Environment (VIC)	PO Box 500 East Melbourne Vic Ph (03) 9412 4011
DPI (Tas)	Department of Primary Industries (Tas) — see DPIWE	
DPIF (Tas)	Department of Primary Industries and Fisheries (TAS) — see DPIWE	

Table 46 (cont'd). A list of abbreviations and contact details.

Abbreviation	Name	Address
DPIWE	Department of Primary Industries, Water and Environment (TAS)	GPO Box 44A Hobart Tasmania Ph (03) 6233 6496
DWR	Department of Water Resources, NSW— see DLWC	
GVEG	Goulburn Valley Environment Group (Vic)	
LWRRDC	Land and Water Resources Research and Development Corporation	Level 2, UNISYS Building 91 Northbourne Ave Turner Canberra 2612 Ph (02) 6257 3379 www.rivers.gov.au
	Melbourne Standing Committee on Rivers and Catchments — see DNRE (Vic)	
	Primary Industries of South Australia — see DEHAA	
QDPI	Queensland Department of Primary Industries	General Enquiries Ph (07) 3239 3111
Ripples	Ripples Newsletter of the Australian Platypus Conservancy	PO Box 84 Whittlesea VIC 3757
	Upper River Torrens Landcare Group	PO Box 250 Birdwood SA 5234 Ph (08) 8568 5339
	Water Resources Commission — see DLWC (NSW)	

PART 3: INTERVENTION TOOLS

INTRODUCTION TO THE INTERVENTION TOOLS SECTION

This chapter describes some of the structural tools available for rehabilitating streams. It is broken into two sections, Intervention in the channel, and Intervention in the riparian zone.

> Note that this is not a structural design manual. Detailed design procedures for many of the structures described here are provided in texts elsewhere, such as the 'Guidelines for Stabilising Waterways' (Working Group on Waterway Management, 1991). In this section we will emphasise the environmental role of each design. Where a technique is new, and has not been described elsewhere, we may include some general design information. Please note that very useful information on a range of interventions is provided in the New South Wales Department of Land and Water Conservation's 'Riverwise' guidelines for stream management.

1. Intervention in the channel

Most attempts at improving in-stream habitat are based first on providing a stable channel, and second on providing increased hydraulic diversity. Examples of increased hydraulic diversity include the creation of deep, slow sections of the channel with scour pools, and higher velocity riffle areas. Shields (1984) argues that the most effective habitat structures create a diversity of velocities, depths, substrates, and illumination conditions that mimic the natural stream. Note that the rehabilitation benefits of many in-stream structures come from the reduced erosion, altered flow hydraulics, and local scour. The local scour around structures is discussed in *Predicting the scour produced when you put things into streams*, in Natural channel design, this Volume.

Note that there are some fundamental concepts underpinning the use of in-stream structures. These principles are discussed in *Step 9. What is the detailed design of your project* in the Stream rehabilitation procedure, Volume 1.

This chapter has ten sections:

1. Full-width instream structures

Full-width instream structures are used primarily to stop bed degradation and to enhance in-stream habitat by pool formation. A general rule is that the stream bed must be stabilised before the stream banks are considered. Hence, for many incising streams, full-width structures are the starting point for stream rehabilitation. Full-width structures covered in this manual are low weirs, including log sills, rock and gabion dams, artificial riffles, and rock chutes. Special attention is paid to the ability of fish to negotiate full-width structures. Fishway design techniques for modifying full-width structures so that they are not a barrier to fish passage are described.

2. Partial-width instream structures

Partial-width instream structures are commonly adopted to stabilise eroding banks. Partial-width structures can be either impermeable, eg. groynes or low deflectors, or permeable, eg. retards. Which particular type of partial-width structure is applied depends on stream conditions, available material and the desired result. Depending on the structure used, partial-width structures can:

- protect the banks;
- create deposition zones;
- realign the channel;

- train the channel to a new course;
- narrow an overwide channel; and/or
- create low-velocity zones suitable for the establishment of vegetation.

3. Longitudinal bank protection techniques

The most direct way to treat unacceptable rates of bank erosion is through direct armouring of the bank surface. This section provides details of environmentally friendly methods of protecting the toe of the bank and the bank face, including longitudinal stone toe protection, brushing, beaching, rock revetment, and hybrid techniques.

4. Bed replenishment

5. Reinstating meanders that have been artificially cut off

6. Fish cover

7. Boulders

8. Overcoming barriers to fish passage

9. Management of large woody debris

10. Sand and gravel extraction as a rehabilitation tool

Commercial sediment extraction from non-tidal streams usually leads to environmental damage. Nevertheless, there are a few situations in which extraction can be a useful tool for stream rehabilitation, particularly in managing sediment slugs.

2. Intervention in the riparian zone

The stream ecosystem does not stop at the water's edge, but includes the riparian zone and floodplain habitat. Riparian vegetation is dependent on the stream for water supply, and is often influenced by the flooding regime. The vegetation also plays a major role in the in-stream ecology, providing food (leaf litter and insects), and habitat (snags) the stream, and influencing bank stability and water quality. Intervention in the riparian zone comes in the form of managing the plant species present, and managing stock access. This chapter has four sections.

1. Vegetation management

This section discusses how vegetation acts to stabilise stream banks, and therefore what you should plant where, to get the best effect on bank stability. It also describes the methods available for establishing riparian vegetation.

2. Streams infested by exotic weeds

This section briefly describes the problems exotic (ie. not locally native) weed species can cause in the riparian zone, and lists some fact sheets available from government departments which provide advice on the control of many common weeds.

3. Willow-infested streams

Willows are only one of many types of exotic vegetation, but so much effort is put into their control in south-eastern Australia that they have their own section outlining the effects they have on streams, and the methods that have been developed to control them.

4. Managing stock access to streams

This section outlines the pros and cons of the different types of fencing that are suitable for excluding stock from the stream, and the options available for off-stream watering of stock.

INTERVENTION IN THE CHANNEL

- Full-width structures
- Partial-width bank erosion control structures
- Longitudinal bank protection
- Bed replenishment
- Reinstating cut-off meanders
- Fish cover
- Boulders
- Overcoming barriers to fish passage
- Management of large woody debris
- Sand and gravel extraction as a rehabilitation tool

FULL-WIDTH STRUCTURES

Full-width structures are low structures that span the full width of the channel and are overtopped by water under most flow conditions. They provide a backwater pool upstream of the structure and lead to scour pool and bar formation immediately downstream. Full-width structures are also referred to as grade control structures, low weirs, plunges or sills.

Full-width structures are the most common tool used to stabilise stream beds. By acting as a hard point in the bed, full-width structures stop the upstream migration of headcuts. All full-width structures can be applied as a hard point, but some are more susceptible to undermining by the upstream migration of headcuts, as found in actively incising streams.

The rest of this chapter and the next two chapters are split into two groups: the first contains techniques that are more or less proven and are commonly used due to their wide spread suitability (although this does not mean they will work on every stream). The second section contains techniques that are proving popular, but must still be considered experimental.

1. Tried and true full-width structures

The most successful full-width structures tend to be those that can tolerate high shear-stress conditions. Thus, rock structures tend to be the most commonly used. The 'rock chutes' chapter in the *Guidelines for stabilising waterways* (Working Group on Waterway Management, 1991) provides detailed guidelines on the construction of rock full-width structures so they will not be repeated here. Rather, the following details are some environmental considerations you should apply to get the best ecological value from rock, full-width structures. These issues can equally be applied to most of the full-width structures in the 'experimental full-width structures' section.

2. Design considerations for full-width structures

When considering a full-width structure as part of your stream rehabilitation strategy, take note of the following siting constraints.

Full-width structures should be used in straight sections of the channel (at the inflection points between bends) (Wesche, 1985). On curved sections of the channel, the high-flow depth and velocity are greater at the outside of the bend, and the flow over a full-width structure is faster than normal because of the reduced cross-sectional area. In this situation, scour on the outside of the bend will be greater than normal, and as a result the structure is likely to be outflanked.

Full-width structures should be keyed into stable bank material for 1–2 m, or 1/3 channel width, on both sides of the channel (Wesche, 1985). A well-defined bank profile with established vegetation is usually evidence of stable bank material. A gravel bar that looks solid may nevertheless be mobilised with the next large flood. The construction of full-width structures usually requires bank stabilisation, such as rock riprap up and downstream of the structure to avoid outflanking.

A conservative approach to protect against downstream scalloping due to eddy scour is to armour the channel bank with rock for approximately 1–3 channel widths downstream (Shields, 1984). This guideline was developed from work on rapidly incising Mississippi streams, so for most streams approximately 1 channel width is likely to be sufficient protection against eddy scour.

Shields (1984) suggests that a full-width structure should be keyed into the bed to a depth at least twice the height of the weir. This guideline was also developed from work on rapidly incising Mississippi streams, so keying structures into the bed to a depth equal to their height above it should be sufficient in most cases.

Several, smaller full-width structures are preferable to a single large structure (Conrick and Ribi, 1996), because large structures can act as a barrier to fish passage and are more likely to fail. White and Byrnildson (1967) in (Wesche, 1985) recommend a minimum spacing for full-width structures of 5–7 channel widths. This spacing corresponds to a typical natural spacing of riffles.

2.1. Rock size

Quarried rock is used for low weirs, riffles, and rock chutes. Well-graded quarry rock is usually recommended for riffles and other rock structures because it packs well to limit interstitial water flow and resists 'plucking' of rocks from the structure. The hydraulic and substrate conditions present on the downstream face of a rock structure provide valuable macroinvertebrate habitat.

Use of oversized, poorly graded rock material will limit the habitat value because the interstices between rocks are too large and conditions too turbulent for macroinvertebrates.

A structure made of poorly graded rock is also likely to be leaky, acting as a sieve (effectively blocking fish passage) rather than replicating a natural riffle.

When building a rock structure, the base of the structure is usually well-packed rock with larger material on the surface of the structure to act as roughness elements, creating local hydraulic diversity on the face of the structure (Figure 1).

Figure 1. Rock grade-control structures in Bell River (Wellington, New South Wales) have been constructed to protect the bed, but also incorporate a low gradient to allow fish passage (figure by Wal Hader).

2.2. Allowing for fish passage

Full-width structures across streams are a major constraint to fish migration (see *Barriers to fish migration* in Common stream problems, this Volume). Stream managers must consider the possibility that every structure could have this effect, even on small streams. Details on how to provide fish passage over full-width structures is provided in *Overcoming barriers to fish passage*, in Intervention tools, this Volume).

3. Design variations for rock full-width structures

3.1. Rock-boulder structures

Rock-boulder full-width structures are large boulders placed across the stream bed, and then packed with well graded smaller rock (Figure 2). The smaller rock is sized in the same way as rock structures; the boulders are generally much larger. Their size depends on what is available locally, but they are usually around 0.5–0.7 m diameter. The row of well-packed boulders across the bed produces a low dam. Rock-boulder dams are well suited to the construction of pre-formed downstream scour pools that are armoured with stone. Pre-formed scour holes prevent the structure from being undermined because the downstream scour pool is created at the time of installation of the structure and lined with rock so that it is artificially armoured against further scour.

3.2. Gabion structures

Gabion structures are constructed from wire mesh 'baskets' that are filled with local stone and rubble, that is

Figure 2. Rock-boulder structures on Eastern Creek (Sydney) (by Wal Hader).

often relocated from a point bar. They are quite time-consuming to build and the life of the gabion mesh is limited to about 10 years (House, 1996), but they have the advantage of enabling designers to shape dams according to their needs. Gabion dams have the added benefit of requiring little heavy equipment for construction, although they are much easier to build if a front-end loader can be used to fill the gabion basket and excavate the bed. Gabion dams probably find their best application in wide, shallow streams that have abundant coarse gravels (Wesche, 1985).

Cobble of around 0.1 m diameter is suitable for gabions, and special wire mesh that is easy to form into the baskets is also available (Wesche, 1985). The following design tips for gabion construction come from successful rehabilitation of a coastal stream in Oregon, USA (House, 1996).

- Gabions were anchored to the stream bed by driving 1.2 m steel rebar (metal rod used in reinforced concrete) through the gabion dam into the stream bed.
- A cable was threaded through the gabion baskets before filling, and anchored to deadmen on each bank.
- Gabions were keyed 1–5 m into the banks.
- To prevent outflanking, gabions were riprapped immediately upstream and downstream of where they were connected to the banks.

The limited life of gabion structures is probably the reason they are not used more often. Remember the golden rule for instream structures—if the system is not changed permanently even after the structure has failed then it is not a successful technique. This means gabion structures should probably be limited to applications where the gabion material will be stabilised by vegetation such that the structures will not be destroyed after corrosion of the wire baskets.

3.3. Riffles

Artificial riffles are rock structures designed to replicate natural riffle formations (Figure 3). They are a common habitat enhancement technique because they produce upstream pools, and are designed to allow fish passage. Artificial riffles can also act as a bed control structure like traditional rock chutes. A well-designed grade control structure made from rock should incorporate the fish passage capabilities of riffles.

An example of the application of artificial riffles for bed control and habitat enhancement is shown in Figure 4. Riffles were installed to create a backwater to protect the cracking clays of the stream bed and banks, and to enhance habitat by creating pools in this steep section of stream (Figure 4). Although the riffles are much better that the original clay channel, their design could be improved by rectifying the following problems:

- the rock material is of a uniform large size, so the riffles are very porous and there is not a full-height backwater behind the structure;
- the riffles do not completely armour the bed (ie. not enough rock is used) so the bed is scouring from flow between the rocks; and
- the riffles are not keyed into the bed or banks.

Figure 3. A natural riffle in the Campaspe River, Victoria.

Many manuals cover design of riffles, probably the best known being Newbury and Gaboury's *Stream Analysis and Fish Habitat Design* (Newbury and Gaboury, 1993). Riffles are generally located at the inflection point between two bends. This is the point where the stream approaches a straight course and symmetrical cross-section, the flow spreads out and the bed shear-stress is evenly distributed across the bed at high flow. During high flows, larger material such as cobbles may be deposited in these areas of lower shear stress, forming low rock weirs or riffles. It is important to note that the material that forms natural riffles does so because it is moved during large flow events. Artificial riffles are usually constructed as fixed features, and the riffle material should therefore normally be larger than that found in natural, 'mobile' riffles, or you will have to continue to replace the bed material.

Figure 4. Artificial riffles created in a re-meandered, cohesive bed stream in Brisbane. The riffles act as low dams, effectively reducing the scour velocity on the cohesive bed material.

3.3.1. Spacing

Consecutive riffles are commonly built 5–7 stable channel widths apart (Keller, 1978; Newbury and Gaboury, 1993; Gregory *et al.*, 1994). Riffles have been observed to form naturally at the point of inflection between bends, indicating that riffle spacing should be similar to meander arc length (see *Natural channel design*, in Planning tools, this Volume), for which the value 2p times the width has been adopted. This riffle spacing is not universal. Figure 5 illustrates the variability of riffle spacing found on a 6 km reach of a stream in southern England.

> Artificial riffles should be located on inflection points between bends (as a guide, the spacing should average about 5–7 channel widths).

Unstable streams will often develop rudimentary riffle forms quite early in their recovery. These can be seen as clumps of coarser sediment at low flow. If the width of the channel is reasonably stable, then the spacing of the riffles should be too. Riffles tend to be very stable once formed, so these rudimentary riffles can be used as the core of a more substantial artificial riffle. Rock can simply be spread out on the riffle and allowed to redistribute.

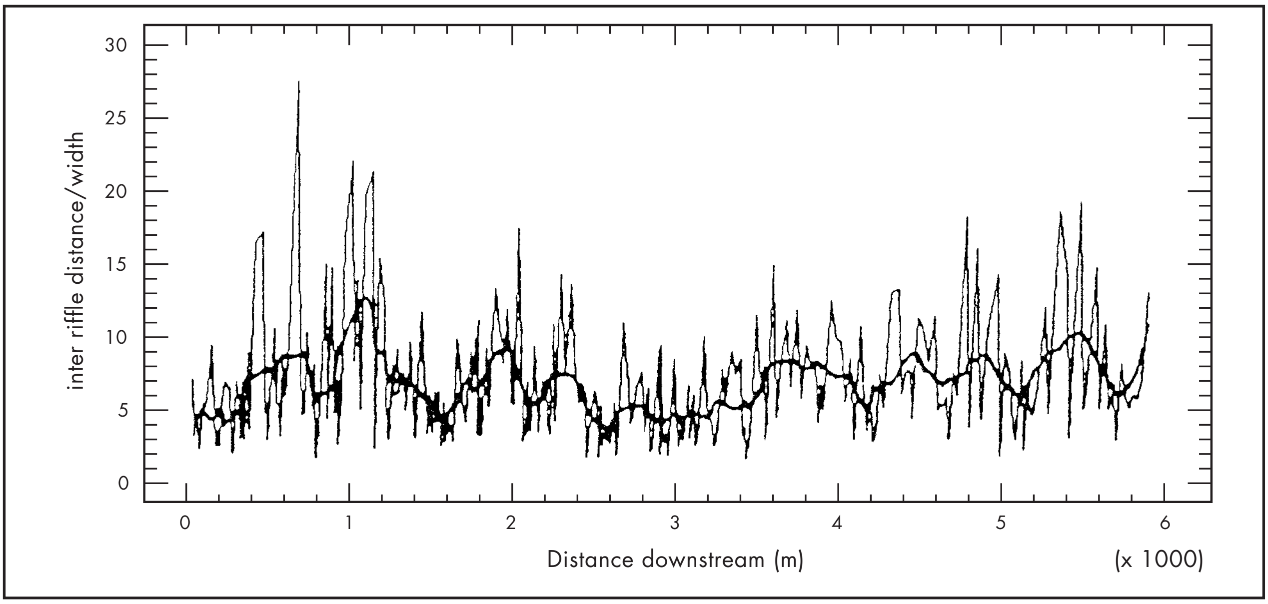

Figure 5. This graph shows the natural variability of riffle spacing. The average riffle spacing fluctuates around the generally accepted value of 5–7 stable channel widths, but fluctuations up to 15 stable channel widths are common (from Gregory *et al.*, 1994). Reproduced with permission from John Wiley & Sons Ltd.

3.3.2. Height

It is important that riffles do not form a barrier to fish migration during low flow. A first step in avoiding this is to ensure that the gradient of the downstream face is not too steep (less than 1:20).

If riffles are too high, they will act like a porous dam, with water passing through the structure at low flow rather than over it. This porous type of structure should be avoided wherever possible because it can form a barrier to fish passage and can also result in piping failure of the riffle.

3.3.3. Downstream face slope

Fish must be able to swim up the downstream face of the riffle during most flow conditions. The design slope of the downstream face recommended by Newbury and Gaboury (1993) is 1:20. The slope of the upstream face of the riffle has been adopted as 4:1 and is controlled by the angle of repose of the material used to construct the riffle.

3.3.4. Channel slope

Riffles occur naturally in streams with gradients in the range 0.0015–0.005 and possibly up to a gradient of 0.01 (Keller, 1978).

3.3.5. Construction

There are two basic approaches to riffle construction: (a) recreate a natural riffle formation made up of mobile bed material; or (b) make a permanent riffle structure where particles are sized to resist movement in most flows.

Natural riffle form

This type of recreated riffle requires an artificial source of cobbles and gravel to form the riffles (see *Bed replenishment*, below). The method of construction is to leave piles of imported material with a size distribution close to the existing bed material, at approximately the natural riffle spacing of 5–7 channel widths (Conrick and Ribi, 1996). Pools can be excavated between riffle locations. The material is left in the channel to be smoothed out by the next few floods (Conrick and Ribi, 1996). This approach implies that bed material is limited (otherwise riffles would form without additional material). If this is indeed so, then the stream will require the continued addition of bed material as the riffle material moves downstream.

Attempts to recreate natural riffles have the following disadvantages.

- Substantial volumes of material are required. If mobile bed material is used, only some of it will be deposited to form downstream riffles; some will be deposited throughout the downstream pools and some on point bars. Thus, to build mobile 'natural' riffles the volume of material required will be much greater than that for the riffles alone.

- Local bank erosion may be increased if riffle material is dumped in a pile in the stream bed for subsequent distribution by flood flows. The material must be placed in the stream in a natural way, such that it is distributed to a relatively uniform depth across the channel and continues up the bank to armour the bank against local scour. A pile of rocks placed in the channel might divert the flow and cause local bank erosion.

- The naturally formed riffles may increase bank erosion. Naturally formed riffles are not at right angles to the flow, and they thus redirect flow into the banks. This is a quite predictable process and part of the evolution of a straight channel into a meandering one (Keller, 1978). Thus, artificial riffles formed by natural transportation of introduced rock will probably cause bank erosion, whereas permanent riffles (constructed of non-mobile sized rock) will probably not (permanent riffles are orientated at right angles to the flow).

Permanent riffles

Permanent riffles are constructed of angular rock so that they pack more tightly, reducing the porosity of the structure. The rocks used on permanent riffles must resist erosion, so they are larger than those found on natural riffles. The sizing of rocks for permanent riffles is most easily achieved by the tractive stress method. When constructing the riffle, some oversized rocks should be incorporated into the structure. These will protrude from the riffle and create a complex hydraulic flow down its face. This complex flow is much better than a smooth, paved surface because it provides a range of habitat conditions, including low velocity areas behind boulders where fish can rest as they negotiate the riffle. Newbury and Gaboury (1993) recommend constructing the riffles with a slight depression in the centre of the channel so that low flows are concentrated at one point. This will allow fish passage for a greater range of flows than if the riffle crest is flat.

An example of riffle construction from Mink Creek in Manitoba Canada

Presented in Newbury and Gaboury (1993)

Hamilton Creek and its tributaries in Manitoba, Canada, were channelised in the 1950s to improve agricultural drainage and reduce spring flooding. The stream channels were straightened and uniformly graded to increase their discharge capacity for higher run-off peaks from the increasingly cleared catchment. Sediment from the stream discharged into a shallow downstream lake. As a consequence of the channelisation of Mink Creek and other tributaries, sediment input to the lake filled it to one quarter of its mean depth (0.8 m) over the period 1959–1980, and fish catch from the lake has dropped to 5–10% of its pre-1950 level. The goal of the Mink Creek rehabilitation project is to recreate the natural biological habitat with a view to increasing the fish population. The channelised stream lacks pool and riffle habitat required for walleye trout spawning, and has an increased slope and poor instream hydraulic diversity.

The approach to rehabilitating this reach was to construct artificial riffles in the channel, based on the spacing of riffles in the original channel. The original stream characteristics were compiled from early surveys, air photographs and the recollections of local fishermen and farmers. Natural spawning riffles for walleye were also studied. (See Natural channel design, in Planning tools, this Volume, for more advice on how to develop a template for your rehabilitation project.)

To achieve the pool depths, riffle gradients and flow diversity observed in the template site, the riffle crests were set to follow the average slope of the stream segment. The maximum slope of the downstream face of the riffles was 5% (20:1), and riffle material was sized on the basis of tractive stress at the riffle—calculated for bankfull flow and for when flow was a critical height over the riffle. In several cases the riffles were located at the same location as the riffles had occurred before channelisation and, on average, the riffles were spaced at 6.4 times the pre-channelisation channel width. Riffle crests were elevated from 0.5 to 0.8 m (average 0.6 m) above the channel bottom to create pools that extended to the mid-point of the upstream riffle slope (ie. net drop of 0.3 m at each riffle) (see Figures 6 and 7).

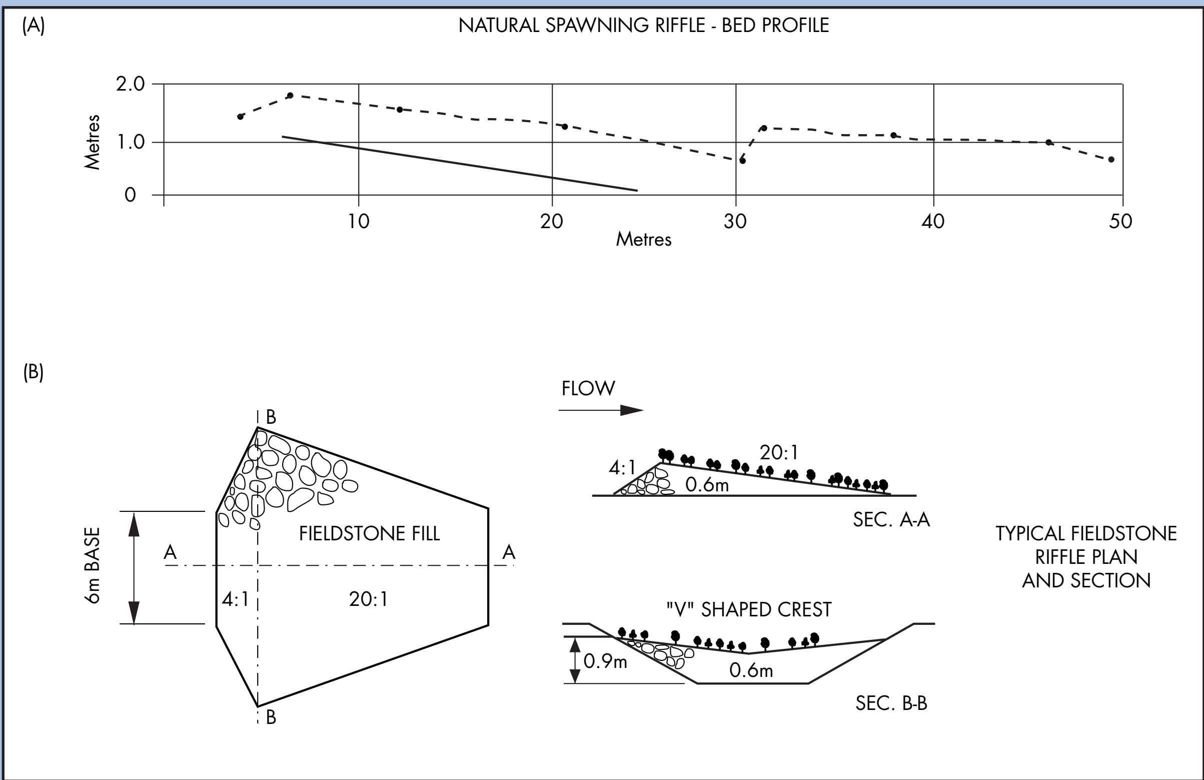

Figure 6. Profiles of natural riffles and design details for artificial riffles constructed in Mink Creek, Manitoba, Canada (Newbury and Gaboury, 1993). Reproduced with permission from Newbury Hydraulics Ltd.

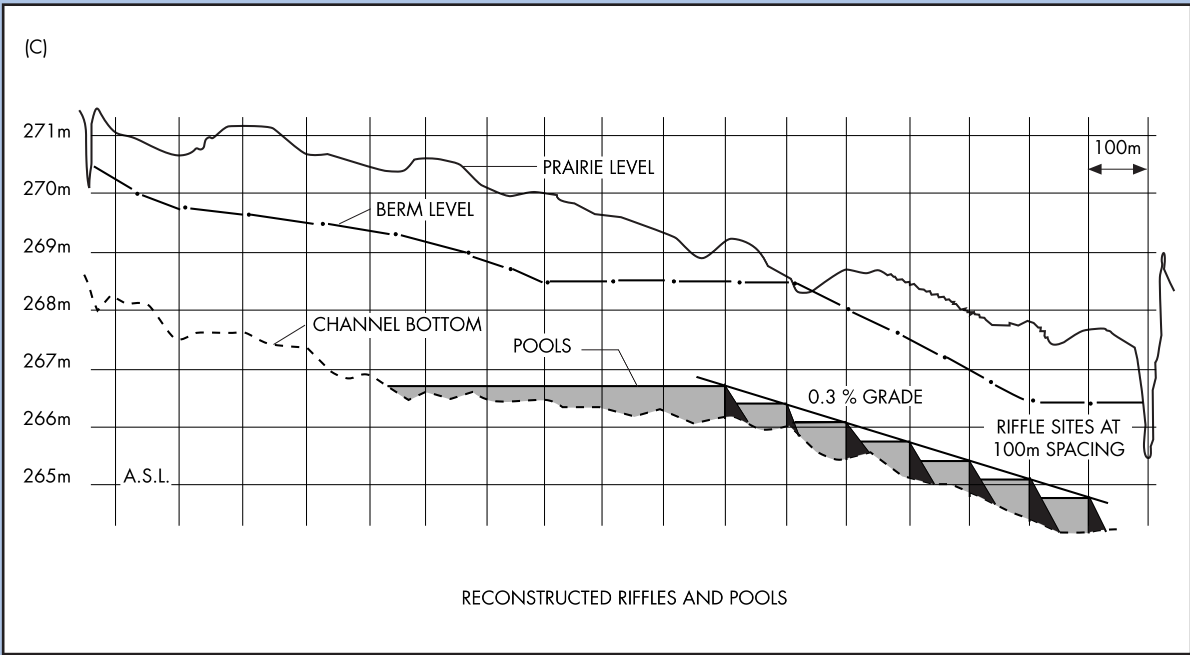

Figure 6 (cont'd). Profiles of natural riffles and design details for artificial riffles constructed in Mink Creek, Manitoba, Canada (Newbury and Gaboury, 1993). Reproduced with permission from Newbury Hydraulics Ltd.

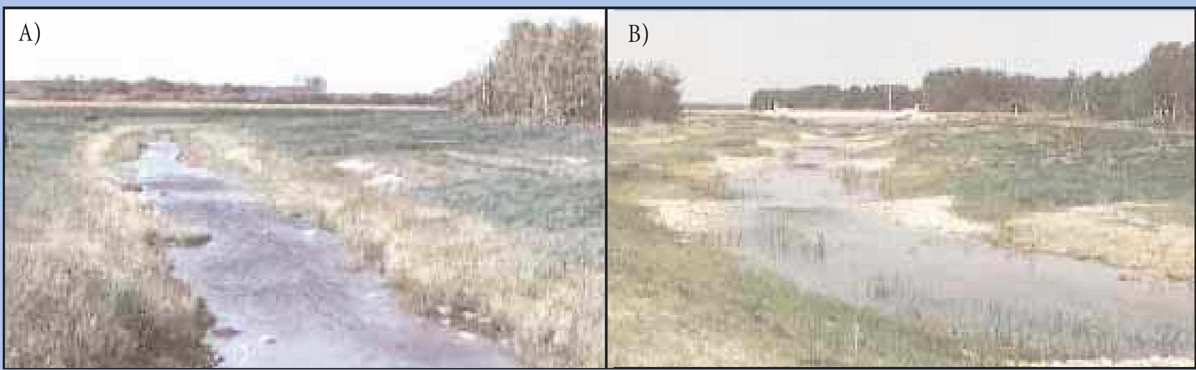

Figure 7. Channelised stream before artificial riffles were introduced (A), and stable spawning riffles in Mink Creek (Manitoba, Canada) following rehabilitation (B) (Newbury and Gaboury, 1993). Reproduced with permission from Newbury Hydraulics Ltd.

4. Experimental full-width structures

There are several variations in design of full-width structures; the appropriate design for any given location will depend both on the available materials and the intended function of the structure. The following alternative full-width structures can be classed as experimental in that they have not been installed for long enough to appraise their performance or their application has been restricted to just a few streams so the suitability of their wider application is not known. Most of the structures here are more affordable, and are therefore more likely to be embraced by community groups, but along with the lower cost, the structures tend to be less robust and are more likely to fail.

4.1. Log dams

The most common experimental full-width structures are constructed with logs instead of rock. Log sills or dams can be constructed in various forms. They are usually built of logs that either span the entire channel, or logs that meet in the centre of the channel and can be angled to concentrate low flows. Wesche (1985) presents four basic types of log sill (Figure 8): the single log dam; the stacked (stepped) log dam; the three log dam; and the pyramid dam.

Log dams are often preferred for stream rehabilitation work because of their low cost (around $1,000–1,500

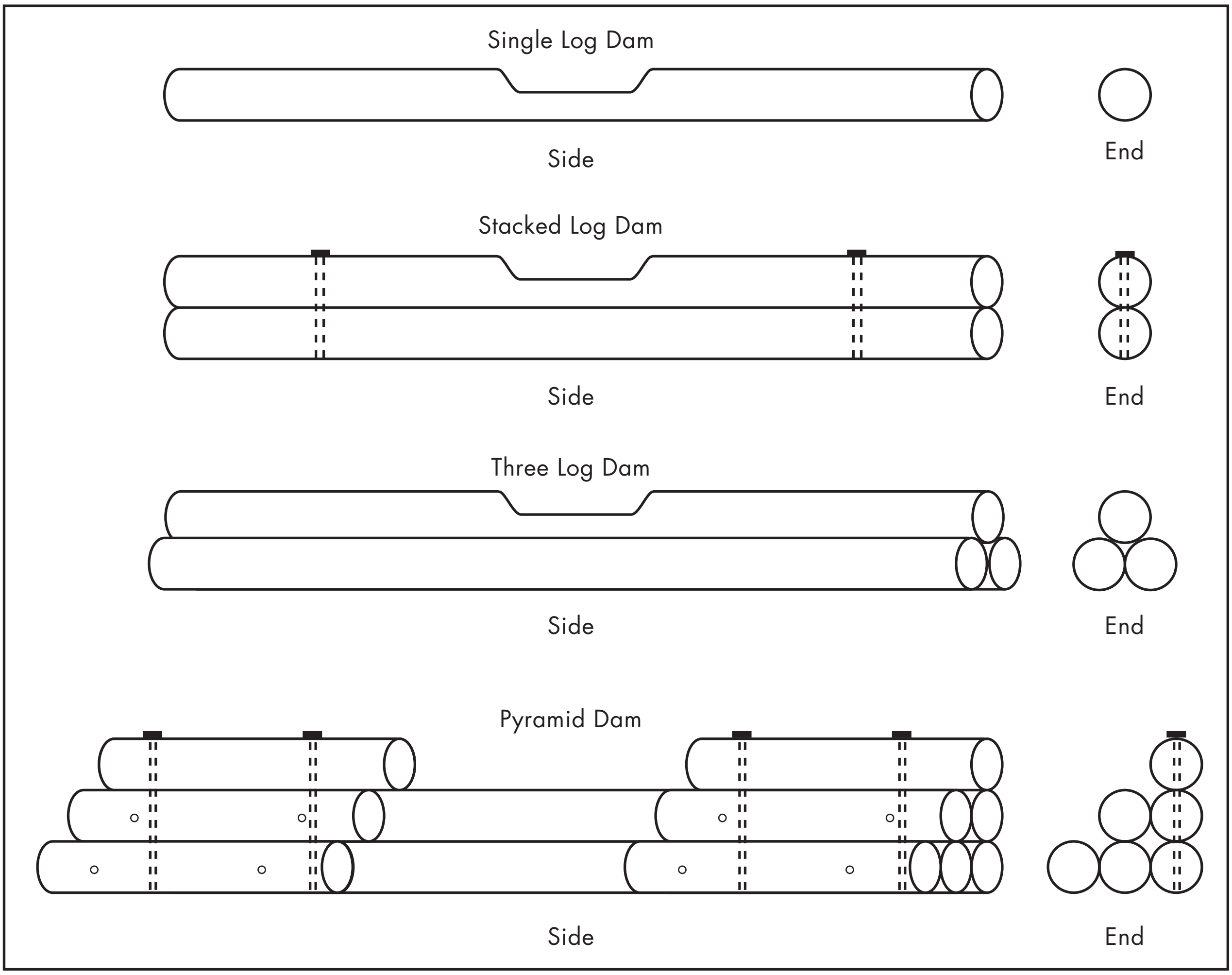

Figure 8. Basic log dam configurations (from Wesche, 1985). Reproduced with permission from Butterworth Publishing.

(Allan Raine, personal communication)) and natural appearance. Log sills are more prone to failure than rock full-width structures because the downstream face of the log sill is steeper, and energy dissipation thus occurs in the scour pool. Even steep-faced rock weirs provide some energy dissipation down the face of the weir. The failure of log sills by undermining due to expansion of the scour pool is even more prevalent if the flows are concentrated, such as with Schauberger sills (see section 4.2, below).

Below are two important requirements in designing and installing a log dam.

1. Provide protection against undercutting from scour under the structure. In areas where the bed material is not coarse enough to form an armouring layer, use rock to form an armoured, pre-formed scour hole. Protect from undercutting by piping under the sill, or by using geotextile to seal the weir (Shields, 1984). Note that the dam in Figure 9 did not incorporate geotextile or a pre-formed scour pool. The success of this example is probably because of the wide, level sill that did not concentrate flow, so that scour formation occurred across the whole bed. The upstream pool quickly filled with bedload, limiting the potential for piping failure under the structure.

Figure 9. A flat-crested log dam on Taylors Arm, a tributary of the Nambucca River in New South Wales (photo by Allan Raine).

2. To prevent outflanking, anchor log sills at least 1.2–1.8 m into 'non-mobile' bank material (Wesche, 1985).

It is important to consider the quality of the materials used in constructing log structures. Often, these structures incorporate dead timber found on the bank or floodplain near the site. On the Nambucca River in northern New South Wales, the log sills were constructed from low-grade timber from nearby forestry operations. When constructing multiple log weirs, straight logs are better because they are easier to work with and the logs pack more tightly, which helps avoid a 'leaky' dam. It is also important to consider how a timber will perform under wetting and drying. As a rule, hardwoods will decay more slowly than softwoods under these conditions. If at all possible, the structure should be designed to stay continuously saturated by ensuring the weir is submerged for most flow conditions (Shields, 1984).

Construction of a straight, stepped log sill

*by Allan Raine **

The New South Wales Department of Land and Water Conservation is overcoming the problem of undermining of log dams by constructing multiple log structures, and offsetting the bottom log in the downstream direction. This dissipates some of the energy before it enters the downstream pool, thus reducing the size of the scour hole.

A large log (minimum diameter 0.6 m) is keyed into the bed, with a maximum of 0.3 m above bed level, and into the banks, with a minimum of 1.5 m in either bank. A wooden pin (at least 2 m in length) is driven into the bed at each end of the log. A second log of similar size is placed downstream of the first structure, with the top of the log level with the bed. Two wooden pins are driven into the bed at the front of the log (Figures 10 and 11). This technique is thought to be suitable for narrow streams (usually less than 15 m width) with stable, vegetated banks. However, other factors which must be considered.

1. Scour depth—this is particularly applicable to straight and V-shaped log sills. These structures create a hydraulic jump during small floods and, if the scour depth significantly exceeds the depth of the logs, the structure will be prone to failure due to undermining. V-sills are more prone to this because they concentrate flows in the centre of the channel. Scour depth should be determined before selection of this technique, particularly in streams where the bed does not armour.

2. Outflanking—most low-cost structures are suitable only where the banks are relatively stable. The stream may outflank those structures which are not sufficiently keyed into the bank or are keyed into highly erodible or unconsolidated material.

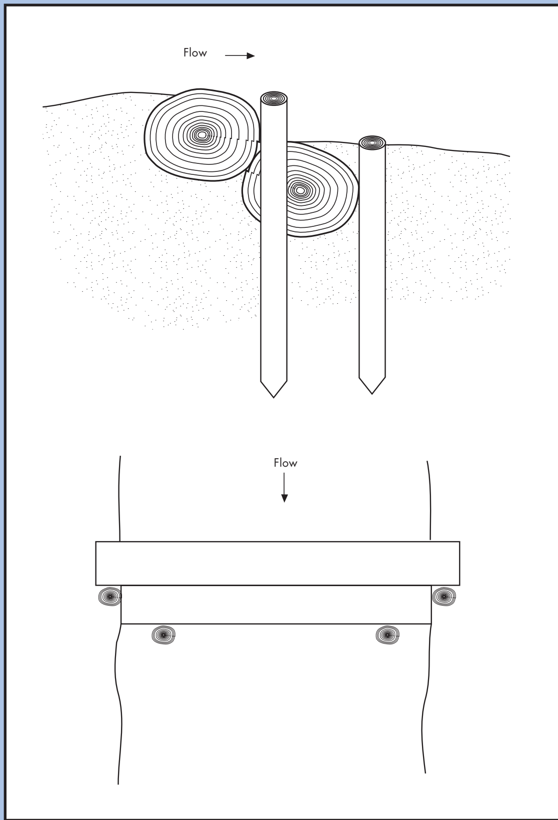

Figure 10. The design of a stepped log sill (diagram from Allan Raine).

Figure 11. A freshly constructed straight, stepped log sill on Taylors Arm, northern New South Wales (photo by Allan Raine).

* Resource Assessment Manager, Hunter Region, NSW Department of Land and Water Conservation, PO Box 424, East Maitland, NSW 2323.

4.2. Schauberger sills

The following information on European grade-control structures was supplied by Wal Hader (New South Wales Department of Land and Water Conservation).

Schauberger sills are built from either logs or, less frequently, rocks. The sill is V-shaped, with the apex of the V pointing upstream. The two arms are also sloped from the bank end into the stream, so that the apex of the sill is the lowest point, corresponding with the thalweg of the channel. Thus, in cross-section a Schauberger sill looks like a gentle V-notch weir. Low flows are concentrated in the centre of the structure, providing maximum depth of water for fish passage. The upstream orientation of the two arms of the Schauberger sill also concentrates flows in the centre of the channel (Figure 12). This maintains a large scour pool downstream of the sill. This is excellent for fish habitat, but may also result in the structure being undermined. The potential for undermining is particularly high when the bed material is not coarse enough to produce an armouring layer to maintain the scour hole size.

Figure 12. A Schauberger sill (flow from left to right). Note that the apex of the sill is the lowest point, and is pointing upstream. As a result, the flow is concentrated in the centre of the channel, and there is a deep scour pool downstream of the structure (photo by Wal Hader).

4.3. Mangfall sills

Mangfall sills were developed in Germany by the Bavarian Water Authority. The crest is constructed in a series of arches, one of which can incorporate a fishway. The abutment boulders of the arches are supported by piles. A scour bed of boulders is provided immediately downstream of the crest. The arches concentrate flow and restrict low flow to the central fishway (Figure 13). The fishway finishes level with the base of the structure. This is a preferred condition when designing for fish passage, because fish can more easily find the fishway if all discharge occurs at the same cross section. The height of the Mangfall sill drop is dependent on the size of boulders available for constructing the sill crest. The plunge pools immediately below the sill crests should be armoured with rock keyed into the bed.

Figure 13. An example of a Mangfall sill with a central fishway (photo by Wal Hader).

PARTIAL-WIDTH BANK EROSION CONTROL STRUCTURES

Partial-width structures are usually employed to stabilise the bank by moving the attack point to a hard structure, or by moving the thalweg of the stream away from eroding banks. There are many additional applications of partial-width structures such as for realigning the channel (as for overwide channels), creating a narrower, deeper, low-flow channel, or creating local scour and depositional features to enhance the rehabilitation of the in-stream habitat.

As a general rule, the following outcomes can be expected when using partial-width structures.

- Reduced sediment load to streams by protecting eroding banks and storing sediment in the embayments between structures.
- The construction material provides a substrate, and gaps between the substrate (interstices) provide habitat for macroinvertebrates.
- Hydraulic diversity is increased through the formation of scour pools at the tip of partial-width structures.
- Low-flow water depths are increased by narrowing the channel, and a low velocity zone behind the structures can create conditions suitable for revegetation and long-term stability of the bank.
- Varied hydraulic conditions create downstream bars which, depending on the bed material of the stream, may expose spawning gravels required by some native species.

1. Tried and true partial-width structures

This section provides details about how to maximise the environmental benefit of partial-width structures that are commonly used. Alternative partial-width structures are provided in the next section, on experimental partial-width structures.

1.1. Groynes

Groynes are stream management structures used to stop bank erosion and train the channel. They are built to abut into the stream channel from an eroding bend, at around 90° to the stream flow. Their main function is to reduce water velocities and shear stress in the vicinity of the eroding bank. The creation of lower velocities and shear stress on the outside bank reduces erosion and can create conditions suitable for deposition of sediment if the flow velocities are low enough.

Groynes are an erosion control tool: the benefits for stream rehabilitation are a constrained low-flow channel and localised bed scour features. Similar or better stream-habitat enhancement results can be achieved more cost-effectively with other partial-width structures, so groynes are not covered in detail in this manual. There are various design manuals for groynes, the most commonly referred to in Australia being the 'Guidelines for Stabilising Waterways' (Working Group on Waterway Management, 1991).

The difference between retards and groynes

There is often confusion in terminology between retards and groynes. Retards are permeable structures, and are usually lower than groynes. This confusion has led to the incorrect naming of structures such as brush groynes and pin groynes, which are in fact types of retards.

1.2. Traditional retards

Retards are permeable structures used for bank stabilisation and/or river training. Because they are relatively cheap and effective, they are a common erosion control and channel alignment tool. Traditional retards are a series of piles which extend from the bank toward the centre of the channel. Cross members may be attached to create a permeable barrier to flow (Figure 14). Retards are designed for erosion control; they are usually constructed on an artificial bench (often referred to as a berm) on the outside of eroding bends. The structures are intended to reduce the erosion of the bank, maintain the stability of the artificial bench, create low velocity conditions behind the structure suitable for the establishment of vegetation and to encourage deposition of fine sediment on the bench to improve the moisture retention needed for revegetation of the bench. The usual intention is that the vegetation will ultimately stabilise the bench after the retard has disintegrated (in 10–20 years).

Basic alternatives for retards are:

- timber or steel piles with horizontal rails;
- piles or posts supporting cables and wire mesh;
- lines of lightweight post-and-wire structures known as 'jacks';
- piles or posts supporting logs or brush (ie. 'brush retard, see Experimental partial-width structures, below);
- open timber or steel pile structures without rails (ie. 'pin retard, see Experimental partial-width structures, below); and
- live tree cuttings supported by piles and cables (Working Group on Waterway Management, 1991).

The main points to consider in the design of retards are height, orientation, stability under bed scour conditions, strength to withstand hydraulic forces and their porosity, or percentage of retard open to flow.

A report by Dyer *et al.* (1995), based on field observations and a flume study of retards, has improved our understanding of the mechanisms by which they protect banks, and has added some key design considerations for their construction. The results of this study have been included in a revised version of the retards and groynes section of the 'Guidelines for stream stabilisation' (Drummond *et al.* 1995). The following are some conclusions from the study that impact directly on retard design:

- Vegetation establishment is a critical feature for long-term stability of the artificial bench on which retards are constructed.
- Fine sediment is collected in low spots on the artificial bench, around the roots of trees (willows) and in grass located on the bench, so the establishment of vegetation will accelerate deposition.
- The height of the retard relative to the depth of flow is important—retards are more effective at reducing downstream velocities when they are submerged.
- Retard angle to the flow has little effect on the hydraulic characteristics in the embayment behind the retard (but see *bendway weirs* below).
- Retards do not cause major deflection across the channel into the opposite bank; rather they retard flow in the area of the retard and increase the velocity in the rest of the stream cross-section.
- A reduced velocity behind the retard is observable for up to 40 times the height of the retard (when tested in a straight flume).
- The streamward end of retards should be steeply angled downstream (45–30° to the flow) (ie. a small hook placed on the end at this angle downstream) to limit scour near the structure, and move the main scour formation towards the centre of the channel.
- Maximum velocities for the stability of bed particles behind retards have been verified; hence retards can be designed on the basis of the maximum velocity acceptable for the particle sizes on the artificial bench.

1.2.1. Where are retards used?

Retards are used mostly for narrowing and stabilising over-wide streams. They are used for a range of stream types, such as gravel bed streams (Figure 15), or rivers with mostly fine, non-cohesive bed and bank material.

Where retards are used in attempts to increase local deposition, it is important that there be a sediment supply

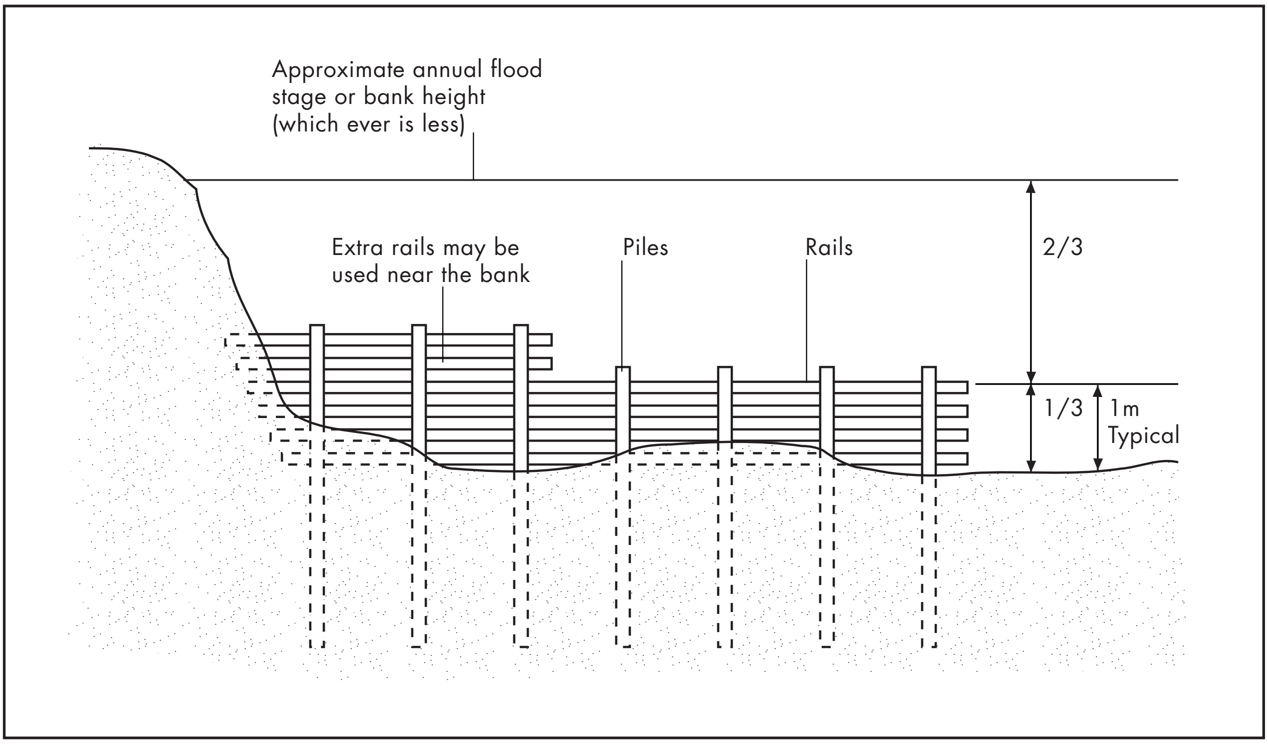

Figure 14. Traditional retard design (from Working Group on Waterway Management, 1991)

to the reach. Where they are used simply as stabilisation structures, they can be applied to practically any stream but are unlikely to be successful in narrow, high energy, incised streams.

1.2.2. Retards with alignment fences

Alignment fences can be built between retards the ends of retards. They produce embayments which trap debris, further reducing the flow velocities and encouraging deposition (Conrick and Ribi, 1996). Alignment fences are often used to protect vegetation planted on artificial benches. Be warned that alignment fences are not universally applicable and have failed at many sites because they were washed out.

The construction of alignment fences depends on the intensity of flow through the embayment. For fences that are likely to be completely submerged, and subject to flow velocities of the order of, say, 0.5 m/s or greater, fences should be of sturdy design. An example of this type of fence is made from steel railway lines driven into the bench to approximately 2 m depth with heavy gauge wire tightly connecting the posts, and galvanised mesh or chainwire also tightly connected between the posts.

Benches such as those in the Wilson River example, which are not likely to receive high velocity flows, could suffice, with wooden posts firmly secured in place to say a depth of 1 m, with lighter gauge wire and lighter mesh between the posts.

2. Experimental partial-width structures

The following experimental partial-width structures are mostly variations of groynes or retards. These are not necessarily new concepts but include those that have been tried at only a few sites or have not been fully evaluated.

2.1. Pin retards

Pin retards consist of series of unconnected piles driven into the stream bed to act as a retard. Pin retards have been used in Victoria for some time and are currently being tested on Taylors Arm in the Nambucca River Catchment in New South Wales. They are relatively simple to construct, and are a low-cost technique, particularly if cheap timber is available. Pin retards have the structural advantage of resisting major failure from scour at the tip, because each element, or pin, which makes up the retard is unconnected. Thus, if the tip of the structure is subject to deep scour, only the most streamward pins will be washed out, with the bulk of the structure retained (Figure 15).

The design criteria for the pin retards used at Taylors Arm on the Nambucca River (from Allan Raine) are:

- drive the pins to a depth of 2 m;
- pins to extend 0.5 m above the bench height;
- pins to be spaced at 0.5 m intervals; and
- retards to be spaced and angled according to standard retard design guidelines.

2.2. Brush retards

Brush retards are low-cost retards built from locally available materials. The basic design technique is to attach brush (branches) between retard pins. An example of their application on Taylors Arm in the Nambucca River in New South Wales (Figure 15) shows the use of the local casuarina (river oak) as the retarding material. These retards are cheap to maintain, and provide a more aesthetic alternative to traditional retards for stabilisation.

The brush retards used on Taylors Arm were constructed in the same manner as the pin retards, but with the pins approximately 3 m apart and installed as a pair with a gap between them in which to place the brush. The pins could equally have taken a different spacing and the brush could have been wired, or woven between the pins.

2.3. Jacks

Written with the assistance of John Gardiner (formerly of the New South Wales Department of Land and Water Conservation, Muswellbrook Office)

Jacks are another low-cost stream stability tool. The term 'jacks' includes a variety of wooden, metal and concrete configurations. In Australia, jacks are usually constructed of timber, and consist of three elements fastened at their midpoints such that each member is perpendicular to the other two (Figure16). A common alternative is a double jack with two sets of two logs fastened at right angles to form the ends of the jack and a fifth log attached between the two ends to form a free standing structure like a horse jump. The joining element of these jacks can be cut in half to form two 'single' jacks.

Unlike other retards, jacks are not attached directly to the bed and so are useful in areas prone to bed scour. In the event of bed scour, the jack simply rides the scour down to the new level of the scour hole. Traditional structures fixed to piles may be left high and dry, or fail due to the scour hole. This versatility makes jacks applicable in streams with highly mobile beds, such as sand bed or incising streams.

Figure 15. Pin retards and brush retards used to stop bank erosion and stabilise an artificial bench on Taylors Arm, a tributary of the Nambucca River, in northern New South Wales.

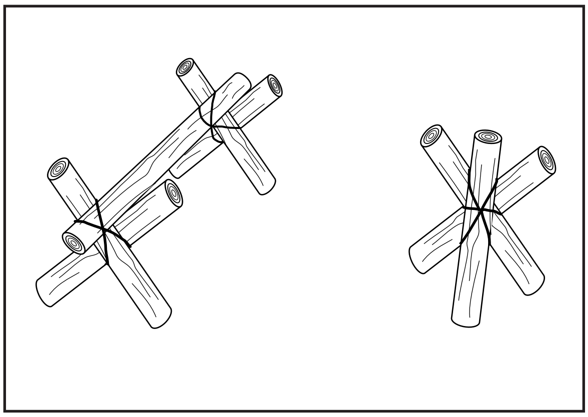

Figure 16. Schematic of jack configuration (from Riverwise Notes. Works to control stream bank erosion: jacks and vegetation. New South Wales DLWC).

Jacks work by introducing a roughness element into the flow. They are more porous than traditional retards and are applied at closer spacing to achieve the required low velocity conditions behind the structures. Jacks are normally placed in an array along an artificial bench at the toe of an eroding bank. The array is fastened together by cable, and the jacks are usually anchored to the bank by deadmen (buried logs attached to jacks with a cable).

Jacks are extremely cheap structures for community groups to build because no heavy machinery is usually needed for their construction and installation (although an excavator is required to form the artificial bench). The jacks are not fixed to the bed so their placement and alignment can be altered if initial placement is not successful. When installed on sediment-starved streams they are used to reduce the downstream flow velocity to allow the establishment of vegetation rather than encouraging deposition. In these cases, when deposition has not occurred (ie. the jacks are not buried), the jacks can be moved and reused on another eroding bend after vegetation is suitably established.

Jacks are normally recommended for wide, shallow, silt or sand-laden streams that are subject to severe scouring during high-velocity flow (Department of Water Resources, no date). Jacks have also been successfully used in streams with larger bed material size.

A project on the Gloucester River near the town of Gloucester (New South Wales) provides an example of the application of jacks in streams with larger bed material. At this point the Gloucester River has a catchment area of 260 km^2, $Q_{1.5}$ of 45 m^3/s, bed slope of 0.0022 and a bed material D_{50} of 6.75 cm. The site on the Gloucester River was an area where gravel had been extracted, and where the bank was rapidly eroding. The initial stabilisation technique was to construct an artificial bench and use retard fences. This technique failed (fences were washed away, or destroyed). In 1992, jacks were installed by the Gloucester Landcare group and the Department of Land and Water Conservation as a trial to see how they would perform in coarse bed material.

The area to be protected was 135 m long, and 37 jacks were used; a combination of single (at the leading and trailing

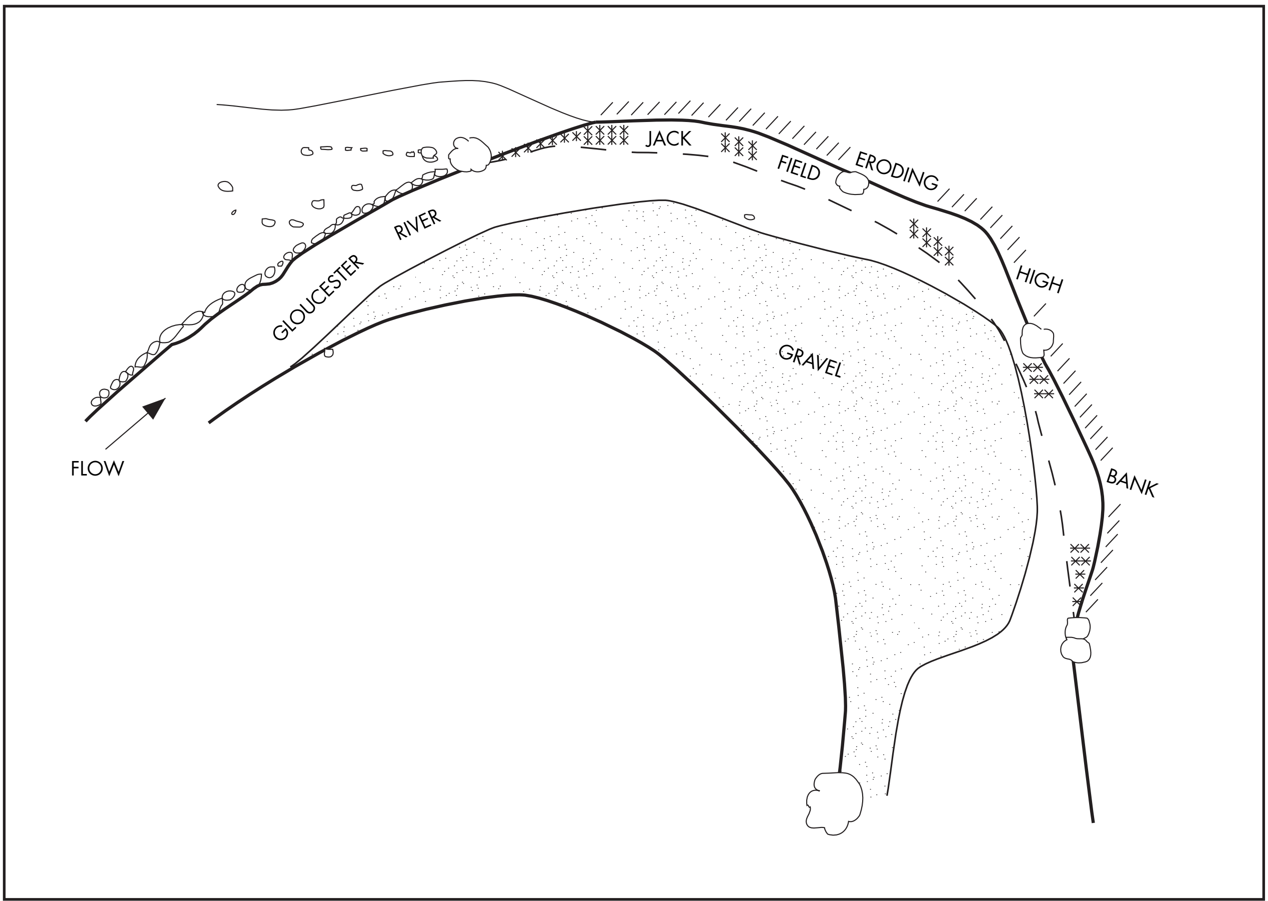

Figure 17. Plan of works on the Gloucester River, northern New South Wales (figure by John Gardiner). The alignment is shown by the dashed line, and the jacks are shown as ⋇.

edge of the protection) and double jacks was used (Figure 17). The jacks were made from timber-mill offcuts.

The outcome of this project is that, after a number of floods, at least 2 m over the jacks, the artificial bench has stabilised and native vegetation (and willows) are now recolonising the artificial bench (Figure 18). This project cost $10,000.

Figure 18. Jacks at the Gloucester River site, 5 years after installation.

2.4. Low deflectors

Deflectors are any in-stream structure used to change the direction of flow. For stream rehabilitation work, deflectors are generally low structures that break the flow into higher-velocity scour areas and low-velocity deposition areas. The generally low profile of low deflectors ensures their hydraulic effect is usually drowned out at bankfull conditions (with the exception of 'bendway weirs', which are covered in the next section). Hence, they provide minimal bank protection, and their main purpose is to create habitat.

Various configurations for low deflector are shown in Figure 19 and described in the following section.

Submerged vanes are the most sophisticated type of deflector, and are discussed in the following section.

Bendway weirs are low deflectors which are angled upstream into the direction of flow. Design details for bendway weirs are provided in section 2.6 below.

Straight deflectors are traditional, low deflectors angled downstream at approximately 45° to the flow. They are designed to create a scour pool at their tip and a bar behind them (Hey, 1994).

Multiple deflectors can be double straight (V) and Y-double deflectors, and are designed to create a scour pool in the centre of the channel and bars behind the deflectors. This application is preferred for streams without stable banks. A-deflectors are designed to split the flow into two scour channels and create a centre bar.

Wing deflectors are used in faster-flowing rivers, where a separation zone or vortex can develop on the streamward tip of straight deflectors. This separation zone and associated flow expansion downstream of the low deflector can cause bed scour and bank erosion. Wing deflectors are designed to reduce the angle between the trailing edge and flow direction, thus allowing a gradual downstream expansion of flow that reduces the generation of turbulence (Hey, 1994). Wing deflectors are essentially low height, impermeable training arms, as mentioned in the retards section.

2.4.1. Design tips for low deflectors

There are variations in design of low deflectors, depending on the application and the availability of materials. Generally, low deflectors are used in mid to low gradient (slope less than 3%) over-wide gravel bed streams. However, as a general rule the following deflector siting criteria apply (adapted from a review in Wesche, 1985).

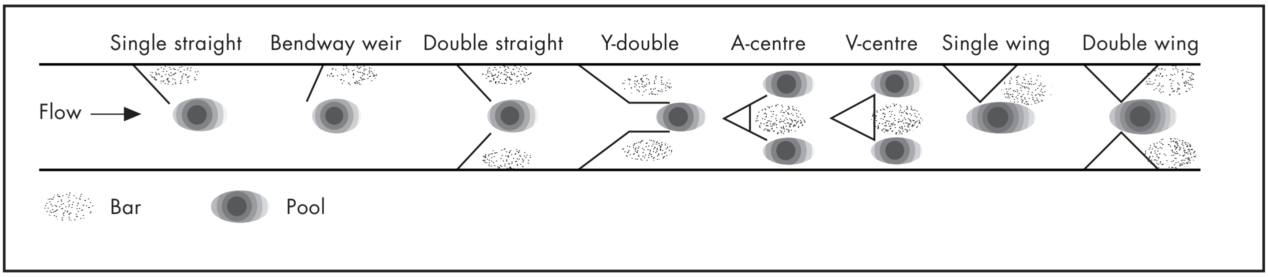

Figure19. Alternative low deflector configurations, and the scour and deposition that they are likely to produce (from Stewardson *et al.,* 1997). Reproduced with permission from the Centre for Applied Environmental Hydrology.

- Deflectors are not limited to smaller streams (Seehorn, 1982).

- Typical placement is in wider, shallow, lower gradient stream sections lacking pools and cover (Seehorn, 1982).

- In straight reaches, alternating deflectors spaced 5–7 channel widths apart can produce a natural, sinuous pattern of flow (Nelson *et al.,* 1978; Lere, 1982).

- Avoid steep, high, eroded banks unless the entire height of the bank is to be stabilised (Seehorn, 1982).

Low deflectors improve the instream habitat by creating zones of scour and deposition, but placing them in low velocity (0.6 –0.9 m/s) streams may not result in the formation of scour holes (Shields, 1984). 'Double wing' deflectors (flow constricted by placing deflectors on opposite banks) (Figure 20) or notched sills can concentrate low flow to scour a downstream hole in these low-velocity environments (Shields, 1984).

At intermediate water depths, low deflectors act as low weirs until they are drowned out. Water is directed at right angles to the deflector, forming a plunge pool in this direction. Hence, if the low deflectors are facing downstream, the plunge pool created during intermediate water depths can extend back toward the bank, creating localised bank erosion. For straight deflectors, and 'Y' and 'V' deflectors, the upstream end is attached to the bank, and the secondary circulation that results will cause scouring at the base of the banks and may lead to bank erosion. With the 'A' deflector and bendway weir, overtopping will promote scouring in mid-channel (Hey, 1994).

What size to make low deflectors depends on channel width and normal depth of flow. Wesche (1985) outlines the following key areas of deflector design.

- **Structure height.** For straight deflectors, 0.15–0.3 m above low-flow elevation; for A-deflectors, approximately half the bankfull depth.

- **Intrusion into channel.** Low deflectors extend from the bank into the channel to 30–80% (typically 50%) of the channel width. The extent of intrusion into the channel depends on the desired end width of the

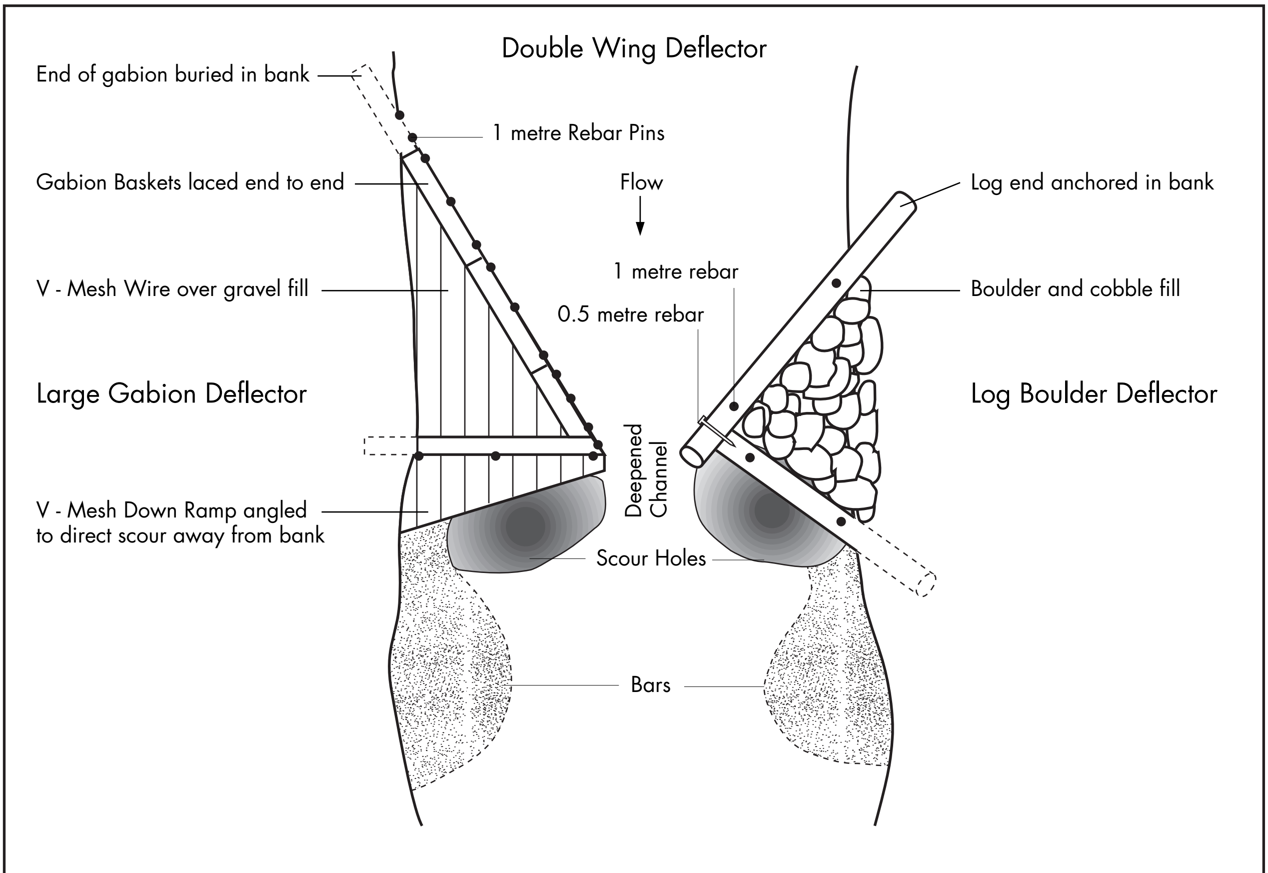

Figure 20. Example of double-wing deflector construction (from Wesche, 1985). Reproduced with permission from Butterworth Publishing.

channel (see *Natural channel design*, in Planning tools, this Volume).

- **Key structures into the bank.** If deflectors are constructed of logs, they should be anchored into the bank by 1.2–1.8 m (Wesche, 1985) or until well into non-mobile material. There is little value in anchoring deflectors to mobile gravel bars.

- **Bed anchoring.** Low deflectors are usually fixed in position by rebar (metal bar used for reinforcing concrete), although steel fence posts for small steams, or piles driven into the stream bed for larger streams, are also suitable.

2.5. Submerged vanes

Submerged vanes are flow-training structures designed to modify the flow pattern near the bed by generating a secondary circulation in the flow (Hey, 1994). They have the effect of redistributing flow and sediment transport within the channel cross-section (Odgaard and Wang, 1991a). Both deposition and increased scour can be achieved with submerged vanes by manipulating their location and angle. In terms of increased scour they can be used to create scour pools for habitat enhancement (Hey, 1994), and to erode and deepen channels for navigation (Odgaard and Spoljaric, 1986). They can be used to protect banks by disrupting the natural helical flow pattern which causes erosion of the toe of the bank at bends (Odgaard and Mosconi, 1987). Submerged vanes can also be used to increase deposition, such as in artificial bench formation at the toe of outside bends, or at the mouth of a cut-off (Odgaard and Spoljaric, 1986). Further, they can be used to promote deposition zones such as side bars, for re-meandering of over-wide sand and gravel bed streams (Stewardson *et al.,* 1997).

Submerged vanes exercise their effect through the creation of a secondary current induced by the vertical pressure gradients between the flow on either side of the vane. Because the vane is at an angle to the flow, a pressure differential will be established between flow on either side of it, in much the same way as a pressure differential caused by wind flowing over an aircraft's wing creates lift. There is also a vertical pressure gradient which, on the low-pressure side of the vane (downstream) increases from top to bottom, and decreases from top to bottom on the high-pressure side (upstream). The combined effect of the horizontal and vertical pressure gradients is a helical motion of flow downstream of the vane. This downstream spiral motion causes bed profile changes in a fashion similar to helical flow in bends.

Submerged vanes have several applications: small local variations in bed form can be created by single or double vanes, while larger scale channel bed changes can be instigated by vane fields made up of parallel formations called vane arrays (Figure 21). The effectiveness of an array depends on the number, spacing and dimensions of the vanes.

Single, symmetrical and asymmetric vanes can be used to produce local scour and bar formation. They are applied in much the same way as deflectors, with the exception that the vanes are not attached to the bank. The general effect of vane arrays is to scour pools on the high-pressure (upstream) side of the array, and bars on the low-pressure (downstream) side.

Submerged vanes have not (to the knowledge of the authors) been used for sediment management in Australia, and have had only limited application for bank protection in the United States. Current information indicates that the angle of the vanes is critical to their success, and that the margin for error is small. Submerged

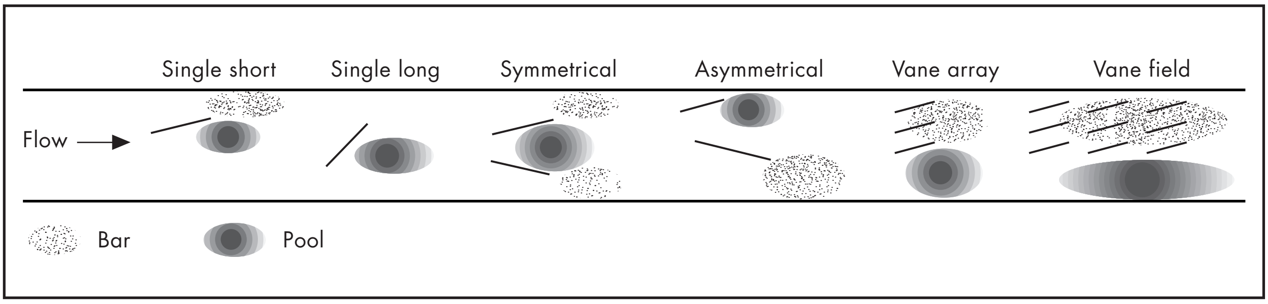

Figure 21. Alternative configuration of submerged vanes, and the scour and deposition that they produce (from Stewardson *et al.,* 1997). Reproduced with permission from the Centre for Applied Environmental Hydrology.

vanes may therefore require some form of adjustment after installation. Constructing vanes which are robust enough to withstand the hydraulic forces and can be adjusted poses a challenging design problem for stream managers.

2.5.1. Where can submerged vanes be used?

Submerged vanes are suitable for a range of applications, but are particularly useful in low-energy streams (Hey, 1994) such as lowland sand and gravel bed rivers (Stewardson *et al.,* 1997). Hey (1994) suggests that submerged vanes are not well suited to high-energy streams, such as upland rivers, and recommends that more substantial rock structures be used for maintaining channel morphology at high energy sites.

One of the advantages of submerged vanes, demonstrated in flume experiments, is that they do not cause a net change in the cross-sectional area of the channel or the longitudinal slope of the water surface. This implies that submerged vanes locally redistribute sediment but do not affect the overall sediment budget of the reach (Odgaard and Wang, 1991b). Other channel alignment methods (retards) are based on trapping sediment to prevent it from influencing downstream channel morphology. A detailed design procedure for vane arrays is presented in Odgaard and Wang (1991b).

In conclusion, vanes are potentially a powerful tool for stabilising streams and creating artificial habitat, but they are complex hydraulic structures that require detailed design and, for the present, must be considered as experimental.

2.6. Bendway weirs

Bendway weirs are not weirs at all, but low height deflectors that are unusual in that they are angled upstream (into the flow). This is in contrast to most retards that tend to be higher, and to be angled downstream (with the flow). Bendway weirs are reputed to protect eroding banks by interrupting secondary circulation (similar to vanes), and by deflecting flow away from the eroding bank. For most angles of interception, water will leave a sill at 90° degrees to the crest. Therefore, if a deflector is angled upstream, flow is diverted toward the centre of the channel.

The information in this section comes from unpublished reports produced by David Derrick (US Army Engineer Waterways Experiment Station, Vicksburg). Bendway weirs are a quite new stream management tool, conceived in 1988, and only recently tested in New South Wales by the Department of Land and Water Conservation. This section is concerned with the use of bendway weirs for erosion control and habitat enhancement in non-navigable streams. In non-navigable streams, bendway weirs are normally emergent during low flows, angled between 80 and 65° (to the flow direction) upstream, usually slope from the bank into the stream and are constructed of rock or logs.

2.6.1. Where can you use bendway weirs?

There is limited information currently available for the application of bendway weirs, and where they are appropriate. They have been used in a range of stream types (sand, gravel and clay bed), and in conjunction with other stream stabilisation techniques, including revegetation and Longitudinal Peaked Stone Toe Protection (LSTP), and revegetation.

The literature does not suggest any particular locations that may be unsuitable for the application of bendway weirs, but they are usually not designed to extend the full width of the channel, and would therefore be prone to failure in unstable bed streams.

> Do not install bendway weirs in streams that are actively incising. Stabilise the bed first.

The erosion protection benefit of bendway weirs appears to come from their dampening of the secondary circulation. They will therefore be less effective for erosion control where the secondary circulation is weak. Secondary circulation is weak in very tight bends, where the ratio between the radius of curvature and the channel width (Rc/w) is less than 2, because the flow tends to short circuit the bend and flow across the point bar, so there is not a smooth flow as in a sweeping bend. Open bends (Rc/w > 4) approach the conditions of a straight channel, the bed is flatter and secondary circulation is not well established, so bendway weirs are not likely to be as effective in open bends as they are in sweeping bends (Rc/w ~ 3) .

2.6.2. Design of bendway weirs

Derrick describes the design of bendway weirs as an "art rather than a science". In general, bendway weirs are angled to direct the flow away from the eroding bank and into the next downstream weir. Here are the design steps that can be gleaned from Derrick's descriptions.

1. Draw the planform of the bend and identify its centroid.

2. Draw rays out from the centroid to act as guides for design.

3. Select the length of weir that will constrict the channel as much as is necessary (see below).

4. Position the first weir (the weir furthest upstream) at the entrance to the bend, with an angle that will direct flow roughly parallel to the bank. It is important not to angle weirs too sharply into the oncoming flow, because if the weir is close to parallel to the oncoming flow it will act as a flow divider and split the flow, causing erosion behind it. In general, the weirs will have an angle that is less than 20 degrees to the rays projected from the centroid (see Figure 22).

5. The second weir is positioned such that a line drawn from perpendicular to the centre of the first weir intercepts the centre of the second weir (Figure 22). The same is true for each successive weir. This means that the spacing of weirs is dependent on the radius of the bend and angle of the weirs. For tight meander bends or bends with a long arc radius (horseshoe bends) the weirs will be spaced closer than for more gradual bends.

2.6.2.A. Length of bendway weirs

There are no specific guidelines for determining the appropriate length of bendway weirs. Derrick suggests the following factors:

- how far from the eroding bank the thalweg needs to be moved;

- the width of water (percentage of cross-section) the weirs need to control to be effective;

- how erodible the point bars appear to be; and

- how much the point bars could be safely eroded without detrimental side effects .

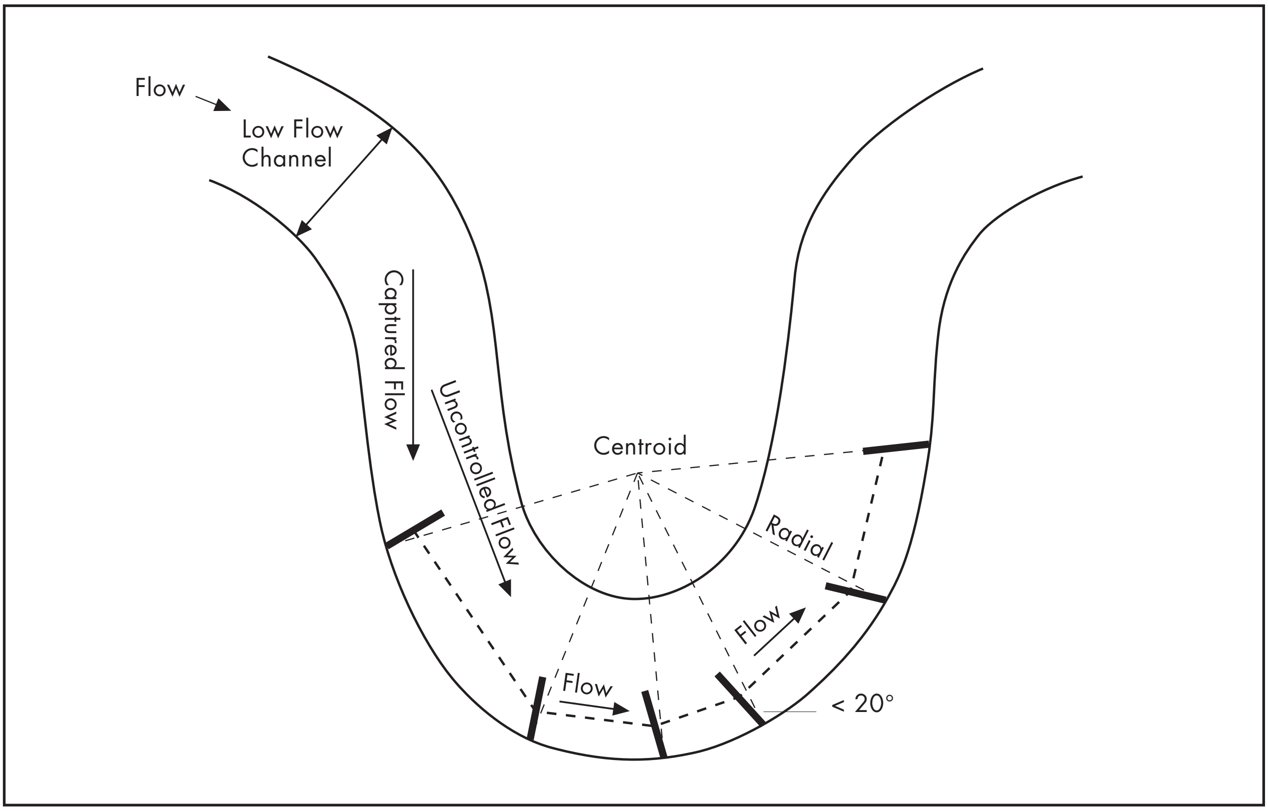

Figure 22. The design of a bendway weir field, including alignment and spacing, and the redirection effect on the water (modified from Derrick, 1997).

Four stream rehabilitation projects that Derrick has designed use bendway weir length between 1/4 and 1/2 the pre-rehabilitation channel width.

2.6.2.B. Height of bendway weirs

The heights of bendway weirs will be determined largely by the materials at hand. Originally only stone was used, and such weirs could be built to any height desired. However, bendway weirs have successfully been constructed of single and multiple logs, and of geotextile socks filled with river sand. Bendway weirs are designed to be overtopped, and it is claimed by Derrick that the redirecting effect of bendway weirs is not drowned out at high flow but rather that the weirs work best under such high-energy conditions. For stream rehabilitation work it is often advantageous to narrow the low-flow channel width to provide increased water depth during periods of low flow. Hence, it is recommended that, in over-wide streams, bendway weirs be installed at a height higher than the low-flow water depth.

2.6.2.C. Key bendway weirs into the bed and banks

Bendway weirs, like other in-stream structures, are at risk of being outflanked if they are not keyed into the bed and banks. The bank depth to which bendway weirs need to be keyed depends on the erodibility of the bank material. As a minimum, the most upstream and downstream bendway weirs should be keyed into the bank and the bottom 1/3 of the bank should be revetted to protect against eddy scour.

In order to stop failure by undercutting resulting from the expansion of the downstream scour hole back under the structure, it is important to key bendway weirs into the bed. For low weirs which extend the full channel width, Shields (1984) recommends keying them into the bed to a depth at least twice their height. However, Derrick has shown that, for single-log bendway weirs, it is adequate to bury approximately half the log and leave the other half above the bed level to act as the bendway weir. It is important that the log is stable when keyed into the bed and banks.

> It is recommended that bendway weirs be dug down into the stream bed to about half of their total height (eg. half of the total diameter of the logs).

2.6.2.D. Slope bendway weirs into the channel

Rock bendway weirs designed by Derrick feature crests that slope into the stream. The slope usually adopted is a 30 cm drop from the bank to the stream end of the weir. The crest is sloped to reduce the flow concentrations at the bank end of the weir. For log bendway weirs, it is not possible to effectively key the structure into the bed and create a sloping crest, so in this case the bendway weirs should be installed with a level crest.

2.6.2.E. Anchoring

For rock bendway weirs, hydraulic failure is most likely to occur as the 'washing' of rocks from the weir, flattening the structure. Logs are likely to be completely displaced downstream or against the bank.

There are various methods for anchoring log structures to the bed:

- screw type anchors;
- piles— timber or steel posts—driven into the bed;
- pins, usually of rebar (reinforcing bar), driven through the log into the bed; and
- deadmen, which are solid objects (usually logs but clean 200 litre drums have also been suggested) buried in the bank and attached by cable to the object to be anchored.

> In sand and gravel streams, deadmen are likely to be the most effective way to stabilise bendway weirs.

2.6.3. Australian application of bendway weirs

Bendway weirs have been used by the late John Gardiner (DLWC) on Pappinbarra Creek, a tributary of the Hastings River in New South Wales (Figure 23). Pappinbarra Creek is a high-energy gravel bed stream that is prone to widening and channel avulsion across the narrow floodplain. This is a result of upstream straightening, and clearing of the floodplain. Further widening of the channel has been prevented using log toe protection, and bendway weirs have been used to confine the low-flow channel and to move the thalweg from the outside of the bend to the centre of the channel during high flows.

Figure 23. Bendway weirs used to move the thalweg from the bank to the centre of the channel on Pappinbarra Creek, a tributary of the Hastings River, in New South Wales.

LONGITUDINAL BANK PROTECTION

Longitudinal bank protection structures (also known as revetment) directly armour the bank to protect it from abrasion. They include rock beaching, riprap, brushing, longitudinal toe protection and hybrid alternatives.

Potential negative ecological impacts of longitudinal bank protection include:

- restricting the establishment of bank vegetation (depending on method of bank protection);
- preventing access to the bank by burrowing animals like platypus if extended for long lengths of the channel; and
- reducing instream cover because they prevent the undercutting of banks, and impede the growth of reeds and other emergent macrophytes of the stream edge.

Longitudinal bank protection can also have the following environmental benefits, including:

- reduced sediment yield from eroding bends;
- enhanced pool depth. As a general rule, the more resistant an outer bank, the greater its depth. This applies to both natural and artificial bank material. In a large study on the Red River, Thorne (1992) found that revetted banks were deeper than unrevetted banks, but that the difference was less in bends with high ratios of radius of curvature (Rc) to width. Thus, for the same width, revetted bends with a radius of curvature of twice the width would be nearly 20% deeper than unrevetted bends, but if the radius of curvature rose to three times the width, they were only about 10% as deep (Figure 24); and
- a stable bank toe can allow vegetation to establish where it otherwise would not be able to survive.

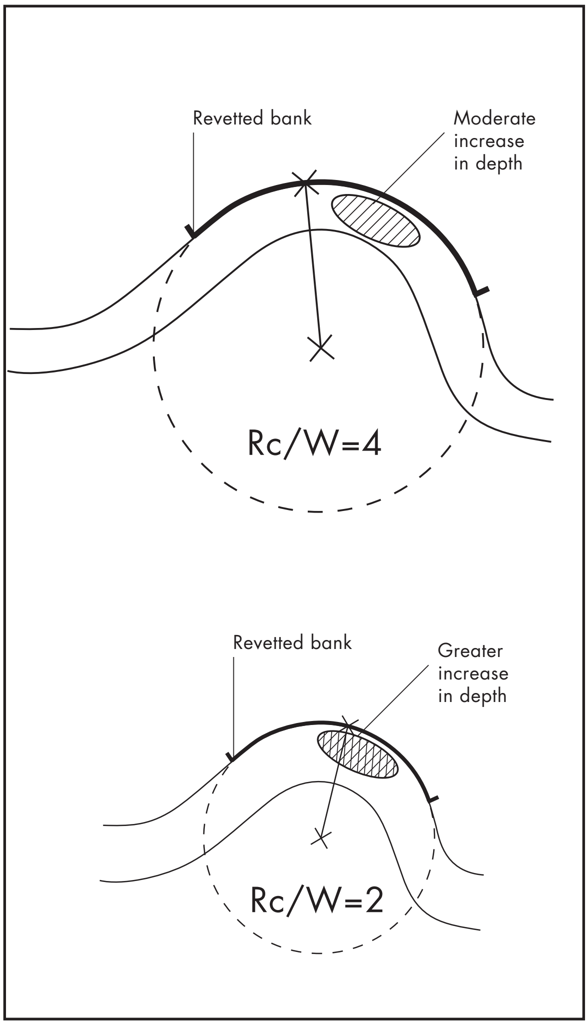

Figure 24. The effect of revetment on near-bank channel depth. Tight revetted bends (radius of curvature less than 3) tend to be deeper than open revetted bends, and much deeper than unrevetted bends.

The aim of this section is not to discuss the details of designing bank protection. Instead we will touch on some modifications that you could make to your revetment design in order to make the result more environmentally friendly. Most of these suggestions relate to methods for incorporating vegetation directly into the design.

1. Incorporating vegetation into bank protection

Eight approaches to incorporating vegetation into bank protection design are described briefly below. Figure 25 illustrates seven of them.

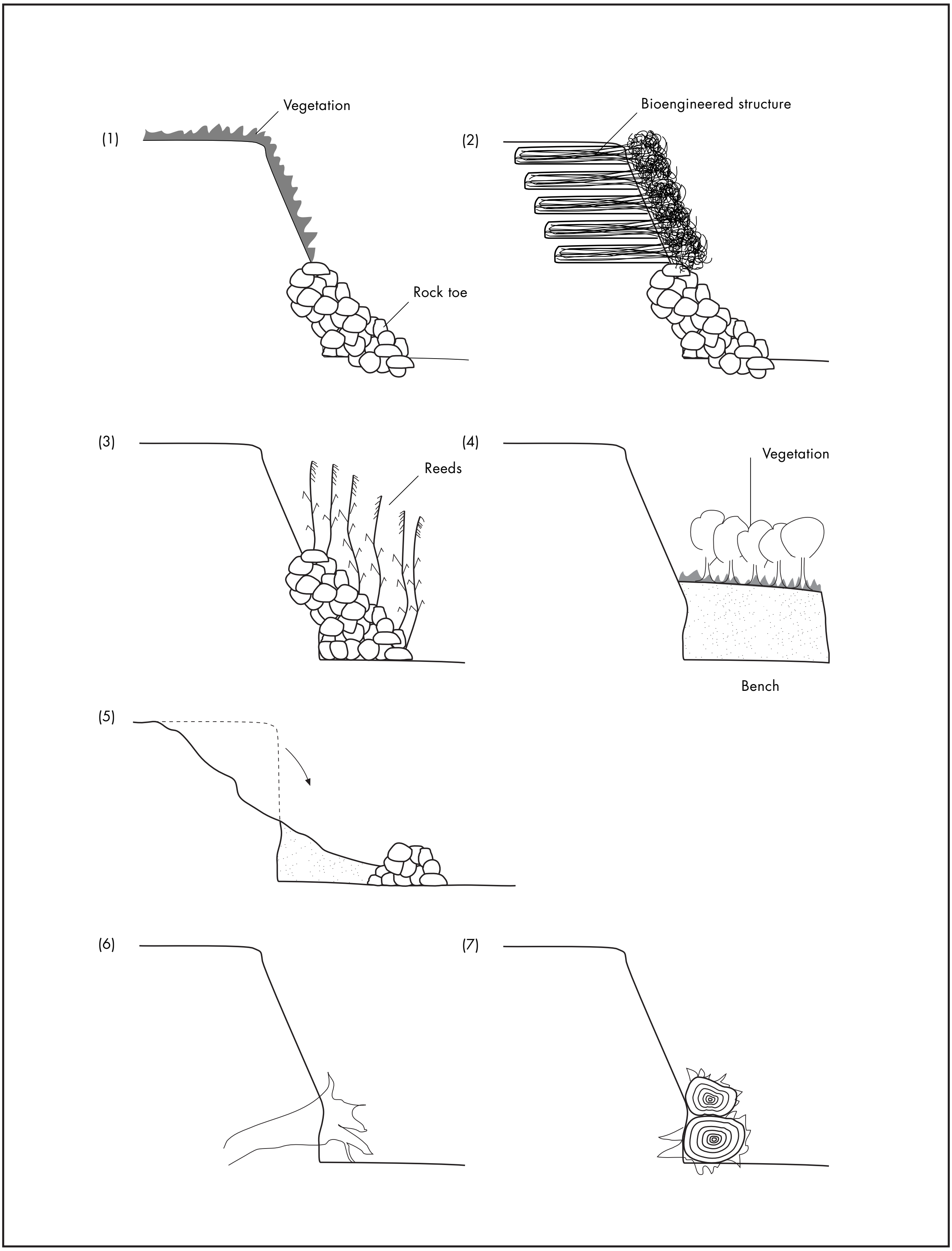

Figure 25. Methods for incorporating vegetation into bank protection. 1. Rocking the toe of the bank and revegetating the bank above the toe. 2. Rocking the toe and stabilising the bank face with a bio-engineered geo-grid. 3 Incorporate reeds directly into the rock toe. 4. Build a bench at the toe of the bank and revegetate. 5. Build a peaked stone toe along the bank and allow the bank to batter and revegetate behind. 6. Stabilise the toe by driving local material such as tree trunks into the bank. 7. Protect the toe with logs (brushing). Note: each of these methods is described in the text.

1.1. Method 1: Revegetate above a protected toe

There is generally no need to extend bank protection to the bankfull height, except where strong overbank flows are expected. Experience has shown that protection of the lower two-thirds of the bank is usually sufficient (Working Group on Waterway Management, 1991). This height can be reduced to a third of the bank height, or less, by combining traditional rock protection for the toe, but stabilising the rest of the bank face with vegetation. Combining rock at the toe with bank revegetation has obvious ecological benefits.

1.1.1. Use mulch for bank protection

For small streams whose banks are exposed following the removal of exotic woody vegetation, a variation to standard longitudinal bank protection structures would be the use of mulch as a temporary protection. Dead exotic vegetation (such as camphor laurels) is chipped and held on the bank by geotextile webbing as an erosion control measure for the period between the removal of exotic plants and the establishment of native vegetation (Figure 26).

Figure 26. Camphor laurel mulch held down with geotextile webbing while replanted revegetation is establishing on the banks of Kelly's Creek in Brisbane.

1.2. Method 2: Biotechnical stabilisation and soil bioengineering

Biotechnical stabilisation is the combined use of vegetation and structures to achieve soil stabilisation. Bioengineering is a subset of biotechnical stabilisation where the plants (roots and stems) form the main structural and mechanical elements in a slope-protection system (Gray and Sotir, 1996). Soil bioengineering techniques have been developed in the United States using willows, dogwood and alder. Willows were extensively used for stream stabilisation in Australia from the 1950s, but there are now extensive campaigns to remove willows and other exotic vegetation from our waterways, so their use for stream stabilisation is inadvisable. Unfortunately, there are few native species that have the mat-like root system of willows and therefore are as good for provide erosion control and, of those, there are none that are as easy to propagate as willows (see *Intervention in the riparian zone*, this Volume). The following bioengineering approaches are not directly appropriate in Australia because they are based on willows. They are included in the manual to to catalyse the development of Australian alternatives. The hope is that the following examples will stimulate experiments with different native species in an attempt to develop low-cost, locally applicable bioengineering alternatives. The series of publications by Raine and others (eg. Raine *et al.,* 1997) list other species that may be useful for incorporation into bio-engineered structures.

1.2.1. Live staking

Live staking is the insertion and tamping of live (dormant) cuttings (usually willow) into the ground. Some Australian woody species can propagate from cuttings. An example is the swamp paperbark.

1.2.2. Live fascines

Live fascines are constructed by burying bundles of live (dormant) stems and branches across the bank face. The bundles are tied together with twine, and the trench they are buried in is dug across the slope face and is about the same depth as the bundle. The trench is backfilled with soil and stakes are driven through the fascine to anchor it to the bank (Figure 27).

1.2.3. Brush layering

Cuttings of living branches are interspersed between layers of soil. The brush is placed in a crisscross, or overlapping pattern so that the tips of the branches protrude just beyond the face of the fill (Gray and Sotir, 1996).

1.2.4. Vegetated geogrids

A vegetated geogrid installation consists of brush placed, as with brush layering, in a criss-cross pattern, but between geotextile 'sausages' (Figure 28). The geotextile may be synthetic or a natural jute type matting.

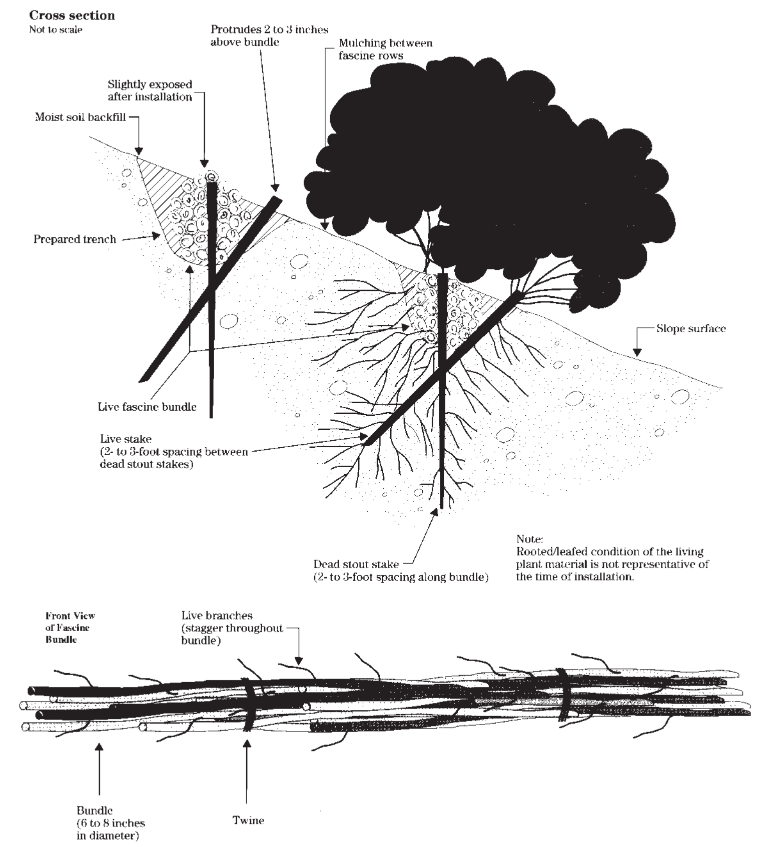

Figure 27. Live fascines are bundles of live brush buried in the slope and anchored with stakes. (This figure is taken from the WTEC bioengineering web site, which is a great source of information. Find it at://www.wcc.nrcs.usda.gov/wtec/soilbio.html)

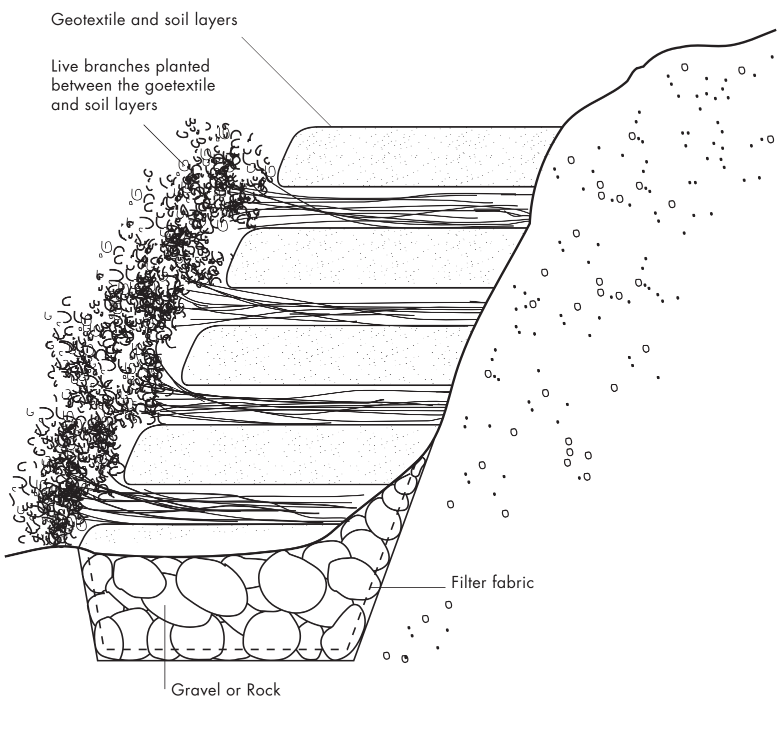

Figure 28. A vegetated geogrid, with layers of live brush between geotextile sausages filled with soil (modified from Gray and Sotir, 1995).

1.2.5. Branch packing and live repair fill

Branch packing consists of alternating layers of live branch cuttings and soil. Long wooden stakes are driven through the fill to anchor it to the undisturbed ground below. Live repair fill differs in that the long wooden stakes are not used to anchor the filled area. Live repair is more suitable for elongated voids in a slope, such as gullies (Gray and Sotir, 1996).

1.3. Method 3: Vegetated rock toe

Reeds and other vegetation have been successfully incorporated directly into rock bank stabilisation. In Victoria this has been achieved by simply digging up truck-loads of phragmites reeds from wetlands and mixing them with the rock used to stabilise the eroding toe. The rhizomes of the reeds take hold and soon the rock work can barely be seen amongst the reeds.

1.4. Method 4: Bench formation

Many incised streams will naturally stabilise by developing a new floodplain within the alluvial trench (see *Valley floor incised streams*, in Common stream problems, this Volume). This can be accelerated by forming an artificial bench. Forming a bench can also be used to modify the channel alignment, usually moving it away from an eroding bank. By forming a bench between the new stream alignment and the eroding bank, vegetation can be established on the bench to provide long-term bench stability and consequently halt erosion of the bank. The most straightforward way to construct an artificial bench is to place the toe protection away from the bank, leaving a gap between it and the bank in which deposition will eventually form a bench (as in LSTP below). In this case, the toe protection must be well-keyed into the bank at the upstream and downstream ends of the protection (and at several intermediate locations) to make sure a new, high-flow channel is not formed behind the toe protection (Figure 29). This method is appropriate only in sediment-rich streams where deposition behind the toe protection is likely to occur rapidly, or where the bench is formed artificially by, for example, transferring material from the point bar, or battering the original bank down to the bench level. Work on the Wilson River near Telegraph Point in New South Wales is an example of this type of project. The over-wide gravel bed stream was realigned and logs lashed together with cable was used as toe protection. Gravel from the over-wide channel was used to artificially form a bench. A retard was built on the bench to further enhance deposition (Figure 30).

Figure 30. Benching and toe protection on the Wilson River at Telegraph Point.

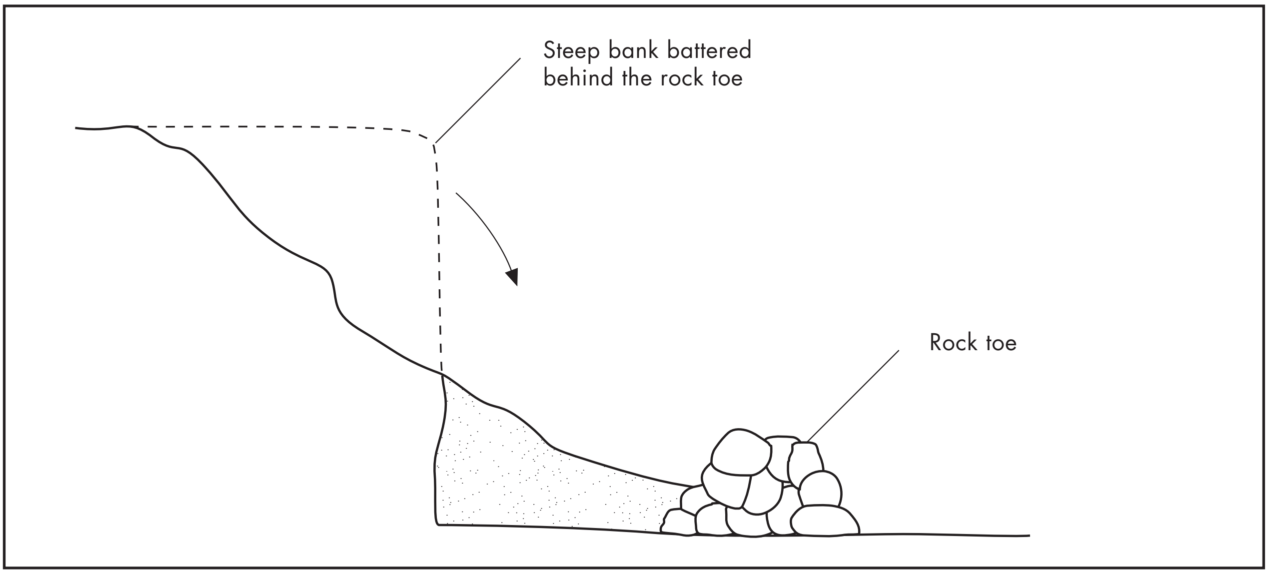

Figure 29. Toe protection constructed away from bank to allow natural bench formation.

The lack of fine material and the fully exposed conditions on the artificial bench make establishment of vegetation difficult without careful follow-up work like watering, weed removal and mulching. The experience of the New South Wales Department of Land and Water Conservation is that if the artificial bench is built only slightly (say 10 cm) higher than low-water level, then artificial and natural regeneration of artificial benches is much quicker and no follow-up watering is required because seedlings can quickly reach the moist conditions below the gravel (Allan Raine, personal communication).

1.5. Method 5: Longitudinal peaked stone toe protection (LSTP)

LSTP is the placement of a ridge of stone along the toe of an eroding bank. This is effectively a 'windrow' structure which acts to remove the attack point from the toe of the bank. The banks behind the toe protection are either pushed down into the space behind the rock, or left to naturally batter back. LSTP is one of the most reliable and economical approaches for stabilising incised streams (Shields *et al.,* 1995c), and is frequently used to stabilise incised sand-bed channels (Shields *et al.,* 1998). The in-stream habitat of incising sand-bed channels is usually highly degraded, with limited depth variation and cover. Stone is placed in a ridge, or windrow, several metres out from the toe of the bank in a triangular or trapezoidal cross-section with sides at the angle of repose. Crest elevations are not specified, but the rate of application per unit length of stream is normally set between 1,500 and 6,000 kg/m (Shields *et al.,* 1995c; Shields *et al.,* 1998). Observations at the same sites over 18 years have shown that LSTP applied at 1,500 kg/m to an incised stream provided reasonable toe protection for a stream with slope 0.001–0.005, and banks 4–5 m high (Shields *et al.,* 1995c).

LSTP is improved by the addition of small groynes (spur dykes) which act to emulate some of the features of the woody debris that would have been a natural feature of the stream before incision (Figure 31) (Shields *et al.,* 1998). The habitat provided by stone toe protection alone is inferior to that provided by spur dykes (small groynes) (Shields *et al.,* 1998). This is largely because of the uniformity of the flow and depth near toe protection. Where spur dykes or groynes are used, the hydraulic diversity and depth variation increases, resulting in improved habitat features.

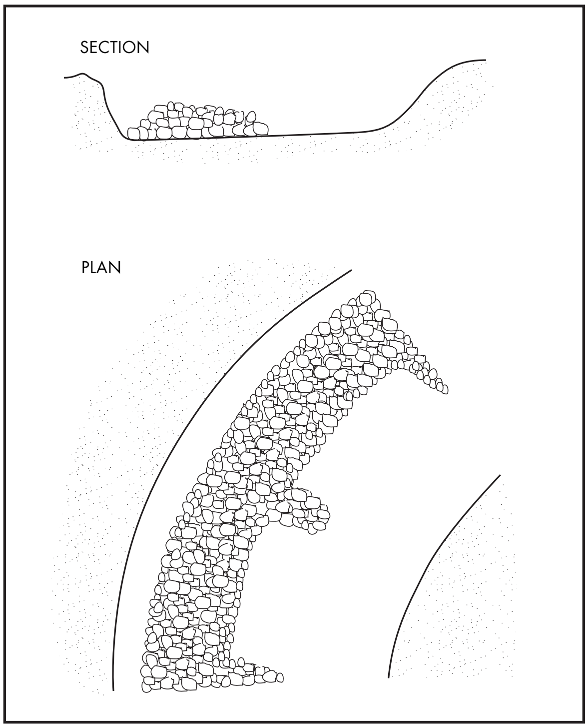

Figure 31. Adding spur dykes to longitudinal stone toe protection (from Shields *et al.,* 1998). Reproduced with permission from the American Water Resources Association.

The best example of the use of spur dykes to date is from research in the US, where a site modified with spur dykes and a control site without spur dykes were monitored over four years. Results of the study showed that, in the modified site, median water depth increased, the pool habitat area increased, fish numbers tripled, median fish size increased, and the species richness increased (Shields *et al.,* 1995c).

Spur dykes cost more than traditional toe protection alone. Shields *et al.* (1998) found that 16% more stone was required to include spur dykes in longitudinal toe protection.

A successful stream restoration project by Shields *et al.* (1998) used the following geometry for spur dykes:

- spur lengths approximately 40% of the channel width;
- crests of the spurs were level;
- crests were 2 m wide and 1 m above the bed (baseflow depth approx 0.4 m); and
- stone size was from 0.2 to 450 kg with 50–85% of stones less than 36 kg.

By adding spurs to stone toe protection, the sinuosity of the stream is effectively increased. The spacing of spurs can then be based on recreating a natural meander pattern. The main habitat feature of spur dykes is the creation of downstream scour pools. The spacing of spur dykes should be based on 5–7 times the final rehabilitated channel width (Shields *et al.,* 1995b).

1.6. Method 6: Native material bank revetment

Logs, root wads and rocks can be combined to form a bank protection that provides sound stream habitat and has a natural appearance. The construction of such revetment is based on the materials at hand. Rosgen (1996) provides an example of local materials used for bank revetment (Figure 32). In many of these applications, whole tree trunks, with root-wad intact, are pushed down into the bank using an excavator. This leaves the root wad exposed at the bank face as a hydraulically and biologically complex bank protection.

1.7. Method 7: Brushing

Brushing is the anchoring of logs, whole trees or brush against the stream bank to armour against erosion. It is an alternative to riprap for full bank protection (Figure 33).

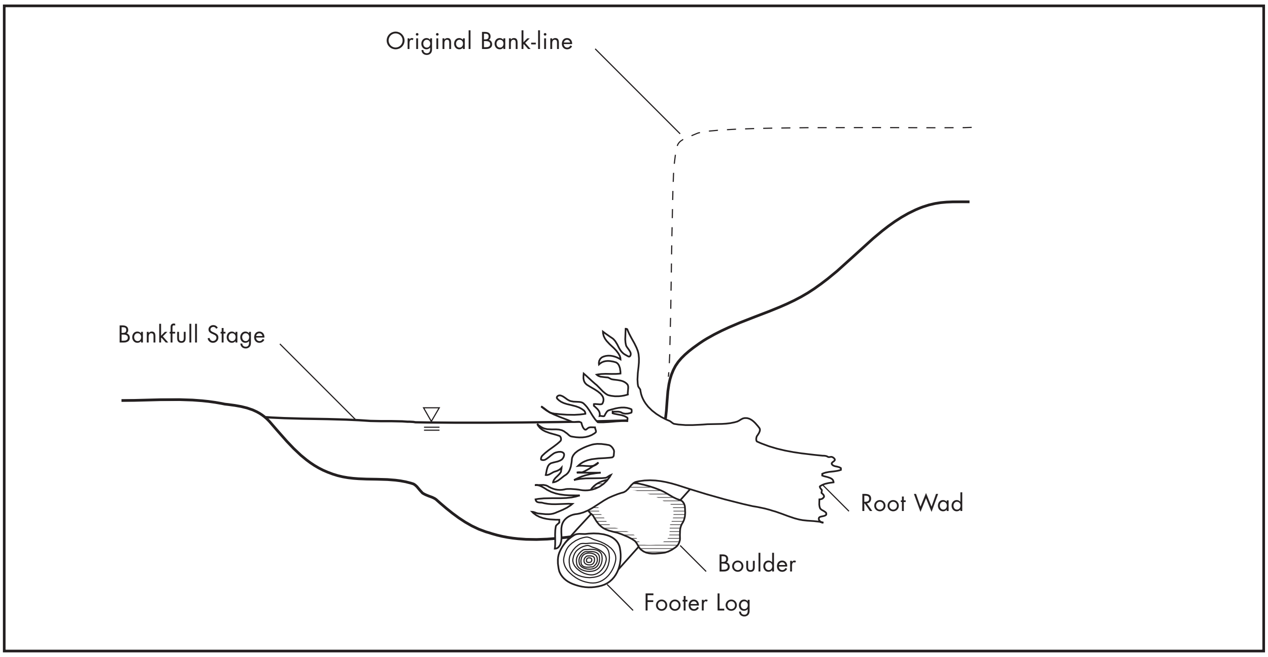

Figure 32. Using local material such as tree root wads for bank protection (from Rosgen, 1996). Reproduced with permission from Wildland Hydrology.

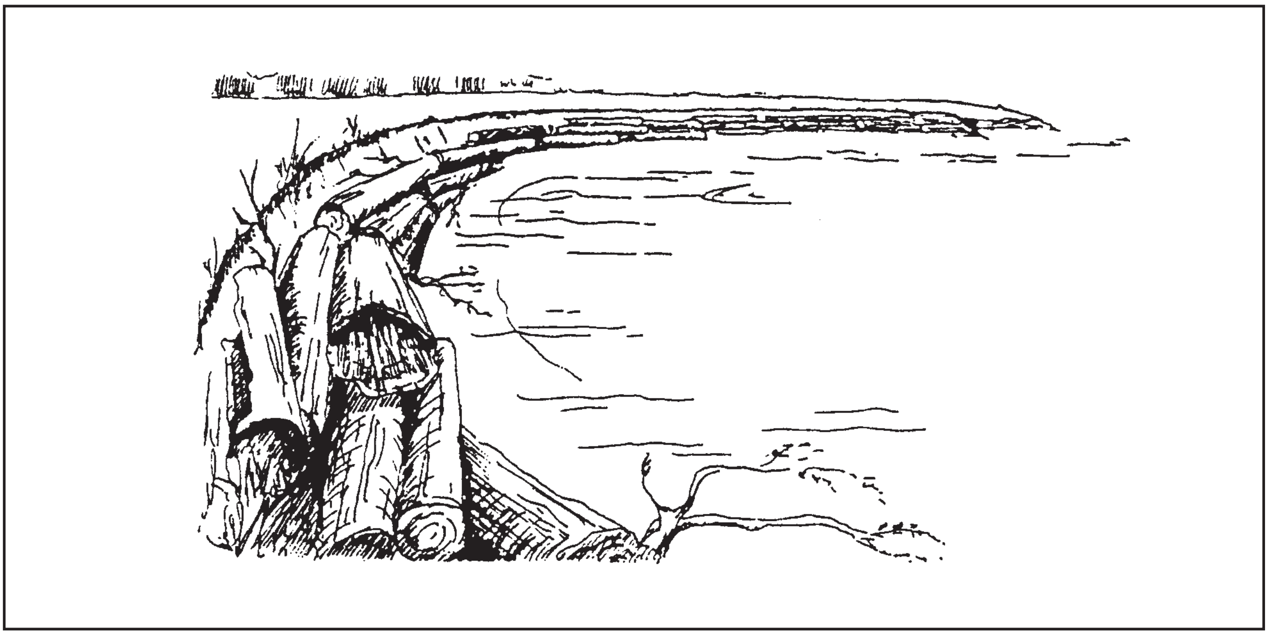

Figure 33. The use of brushing for bank protection (from Victorian Department of Conservation and Environment, 1990).

The aim is to reduce scour velocities near areas prone to erosion. With large logs, as in the accompanying example, the bank is completely armoured (just as with riprap or beaching). Brush provides less protection than solid logs, but provides greater habitat value, because of the complex hydraulic diversity where the brush extends into the flow, and because burrowing animals can easily access the bank.

A disadvantage in using logs for toe protection is that they are more difficult to handle than rock, and they don't settle into zones of undercutting as rock would. As with traditional rock protection, brushing needs to be keyed into the toe of the bank to prevent undermining.

A site 3 km downstream of the Pappinbarra Creek Environment Centre, on Pappinbarra Creek, New South Wales provides an instructive example of brushing. The logs used at this site completely armoured the channel. Given the high energy of the stream at the site, using lighter brush material would probably have been insufficient to stop further erosion. The logs were sourced cheaply as low-grade timber from a nearby logging operation and all labour was volunteered by the local Landcare group. The problem at this site was a channel avulsion which threatened to cut off a meander bend. The whole bank had to be protected. The logs shown in Figure 34 are about 0.4 m diameter, are piled as a pyramid of three logs (the third is buried in the bank), and are lashed together using wire cable. The outcome is a stable bed and bank at a cost of around $8,000 for a length of about 150 m.

Figure 34. Logs used as bank protection on Pappinbarra Creek, a tributary of the Hastings River, northern New South Wales. Logs are about 0.4 m diameter.

1.1. Method 8: Vegetating rip-rap

Normal practice is to keep rip-rapped (revetted) banks free of vegetation. Vegetation on revetted banks reduces the channel conveyance, impairs the visibility of revetment for maintenance, and may increase the risk of flooding by weakening natural and man-made levees. It has also been claimed that it may have an adverse effect on revetment durability (Gray and Sotir, 1996) presumably through debris build up, increased flow scour around trees and damage from tree fall (Shields, 1991).

A study by Shields (1991) of a 57.5 km reach of the Sacramento River has shown that revegetated revetment was less likely to sustain damage than unvegetated revetment. Approximately 70% of the study reach was revetted and, of this, approximately 10% supported some form of woody vegetation (cottonwoods and willows). Of the revetment included in this study, damage rates for revetments supporting woody vegetation tended to be lower than for unvegetated revetments of the same age, located on banks of similar curvature. Hence, vegetation did not to reduce revetment durability in this case.

BED REPLENISHMENT

In northern hemisphere streams the limiting ecological feature is often that the bed material is either too fine or too coarse. Sediments that are too fine will prevent water flow through the stream bed, depriving any invertebrates or fish eggs of oxygen. Sediment can be too coarse for salmonid spawning, because the fish need to move the gravel around to make nests. It is common for gravels to be coarser below dams and gravel extraction sites. We doubt that coarse sediment is as important for Australian fish, but if it is decided to artificially add finer material to the bed, Kondolf *et al.* (1996) provides guidance.

In Australia, the problem is much more likely to be bed material that is too fine. Examples are sand slugs, sands and silts filling interstitial spaces in gravels, and incised streams that have been stripped of any coarse material. In all of these cases, the artificial addition of coarse bedload is unlikely to contribute to rehabilitation of the stream. In sand-slug streams, the coarse material will be buried by sand. In incised streams the load would have to be very coarse not to be washed away.

Nevertheless, there are opportunities for stabilising and rehabilitating incised streams by adding large volumes of coarse material to the bed. This load could then redistribute as riffles and accelerate the stabilisation and recovery of the bed. The problem with this strategy is that, if the coarse load can be moved to form riffles, it can also be carried through the channel. This means that the coarse material would have to be repeatedly added to the stream.

An alternative to adding material to the bed is to use the bed material being carried through the stream by capturing some of it with sediment trapping devices. Sediment traps could be installed downstream of a head-cut, at parts of the stream where natural riffles would normally form. One example is a gravel trap (Figure 35) constructed of logs lying parallel to the flow, with wire mesh between the logs to help retain sediment that is deposited. An alternative is vertical pin ramps. The New South Wales Department of Land and Water Conservation is currently testing these structures.

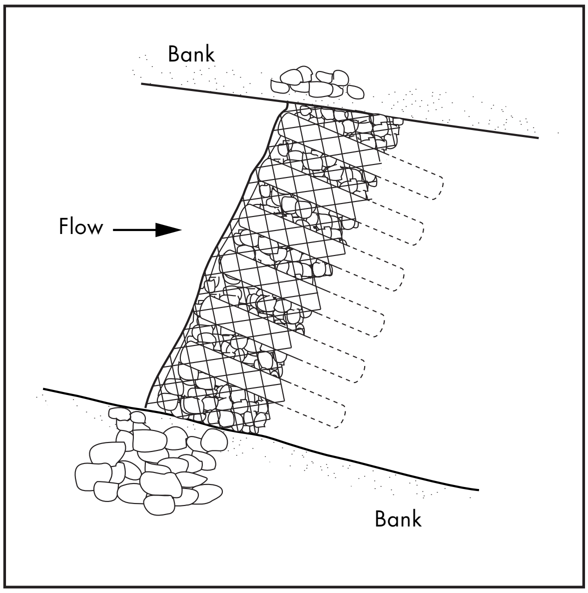

Figure 35. A gravel trap (from Rosgen, 1996). Reproduced with permission from Wildland Hydrology.

1.1. Vertical pin ramp

*By Allan Raine **

Vertical pin ramps are full-width retard structures designed to increase local deposition. A series of vertical pins is driven into the bed of a degraded stream to increase roughness and encourage deposition at a degraded riffle (refer Figure 36). The design flows from observations of mid-channel bars colonised by vegetation which, as a result of increased roughness, aggrade during floods.

Wooden pins at least 2.5 m long and 15 cm wide are driven into the bed of the stream at the site of a degraded riffle, using an excavator with a hammer attachment. Pins are driven in at a spacing of 0.5 m. The riffle crest should be no greater than 0.5 m above bed level, so as to reduce dislodgment or breaking of pins by debris, and to discourage outflanking. Each row of pins is offset against the other, with a maximum slope of the downstream face

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of 10:1. An upstream slope of 4:1 has been adopted (as per riffle design). The structure is lowest in the centre and keyed into the bank to prevent outflanking. Figure 36 illustrates the design details.

Vertical pin ramps are currently being tested on two New South Wales north coast streams where the controls (riffles) are degrading, leading to the loss of the upstream pool and an influx of sediment to the downstream pool.

Three structures are being trialed on Buckrabendinni Creek, a tributary of the Nambucca River (Figure 37). Sediment size, pebble; approx. slope, 0.00165; catchment area, 10 km^2.

Two structures being trialed on Blaxlands Arm (tributary of Wollombi Brook, Hunter Catchment). Sediment size, sand; approx. slope, 0.00526; catchment area, 18 km^2.

The structures have been installed downstream of the nick-point at the degraded riffles and are designed to trap the sediment released by it so as to assist in riffle reinstatement. Small floods over the structures in Buckrabendinni Creek have raised the bed level at the riffle by up to 0.3 m, thus increasing the pool height upstream by the same depth.

Figure 37. A vertical pin ramp on Buckrabendinni Creek (photo by Allan Raine).

Vertical pin ramps are likely to be most suitable for narrow streams where the banks are relatively stable. The structure should be located at a degraded riffle or inflection point. Vertical pin ramps are not being tested on steep, high energy, or large streams.

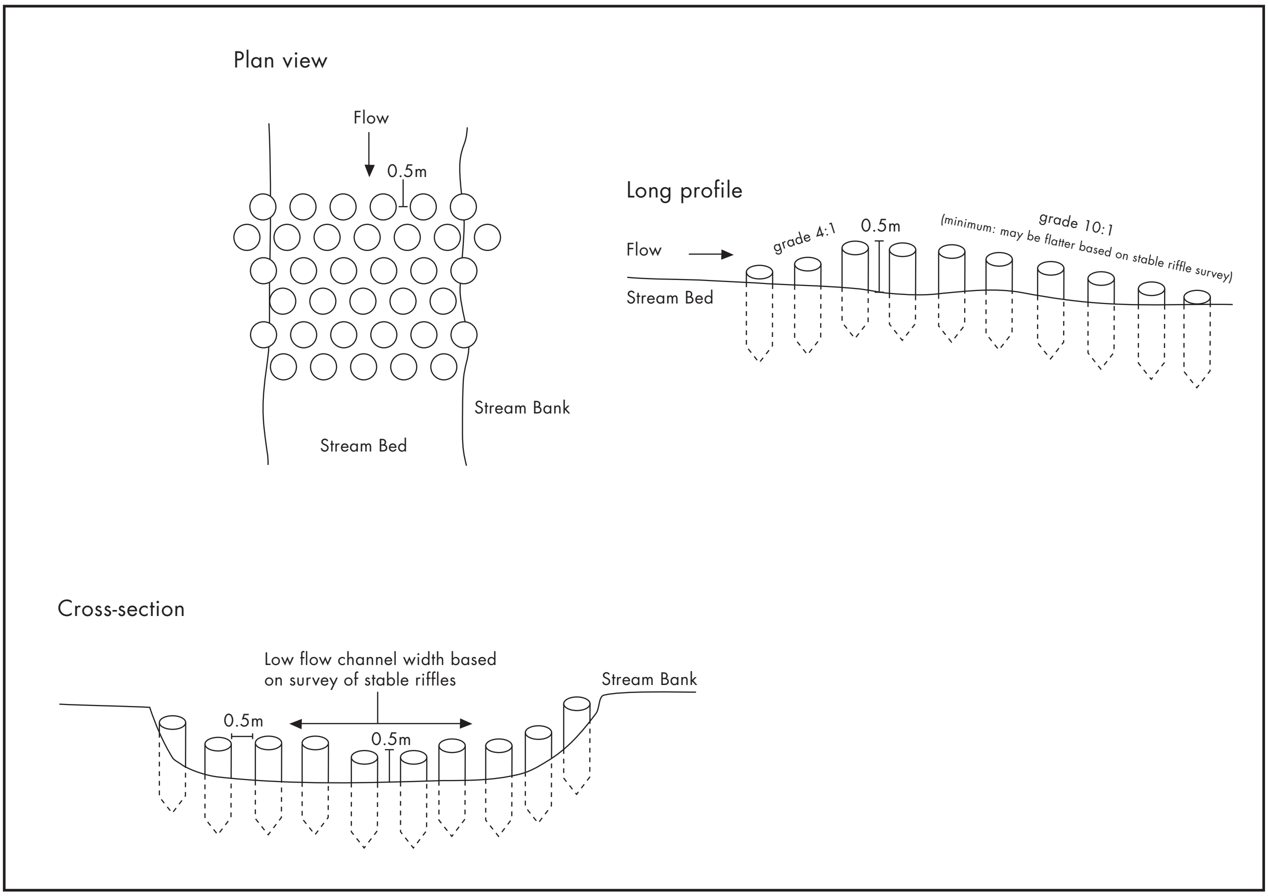

Figure 36. Design details of trial vertical pin ramps (design from Allan Raine).

REINSTATING CUT-OFF MEANDERS

1. Introduction

Between the 1870s and 1970s numerous Australian streams were artificially straightened. The aim of these works was to increase the flow conveyance of the channel in order to improve the drainage and reduce the frequency and duration of overbank flooding. The consequences of this type of 'improvement' have been documented in Australia (Reinfelds *et al.*, 1995) and in many studies around the world (Brookes, 1988). They include deepening and widening of the channel, and major decline in ecological function.

In order to rehabilitate straightened channels, streams are being returned to their original courses (Keller, 1995). Meanders can be rehabilitated in two ways: by the reintroduction of meanders that were previously cut off; and by the construction of new bends in undisturbed floodplain sediment (Brookes, 1996). There are several procedures for the design of meanders, as discussed in the *Natural channel design*, this Volume. Below is a description of the reinstatement of cut-off meander bends on the Latrobe River in Victoria—probably the largest exercise of its kind in Australia.

Meander reinstatement on the Latrobe River

The lower Latrobe River (Gippsland, Victoria) is a clay and sand bed stream, approximately 240 km long, with a catchment of 5,200 km^2 and an average width of about 30 m. Sixty-six artificial meander cut-offs have been made in the Latrobe since the 1870s, with most occurring in the 1960s (Figure 38). The length of stream was reduced by 25%, and sinuosity decreased from 2.12 to 1.59 (Reinfelds *et al.*, 1995). The cut-offs where installed to improve the hydraulic capacity of the river and get floodwaters away more quickly. They were excavated as depressions lower than the bankfull conditions, so high flows would preferentially flow through the cut-off before overtopping the bank. Unfortunately, the cut-offs quickly downcut and eroded to become the main channel and the original meanders became backwaters.

Figure 38. Aerial view of a meander cut-off on the Latrobe River. Crown (State of Victoria) Copyright. Reproduced with permission of Land Victoria, Department of Natural Resources and Environment.

The meanders were reinstated:

- to reduce accelerated bank erosion on the bends downstream of the cut-offs; and
- to restore a high-quality riparian zone along long reaches of the river by incorporating the isolated islands that were created by the cut-offs. These islands retained their original riparian vegetation.

The Lake Wellington Rivers Authority reinstated six of the original meanders while maintaining the original design flow conveyance conditions of the cut-offs. The openings to the artificial cut-offs were blocked with a rock weir up to the design height of the original chute. A narrow pilot channel was excavated in the natural channel that allowed water to flow through the original course. If the meanders had been partly or completely filled in, the whole meander would have been excavated to a bed slope that connects the upstream and downstream bed levels.

The meander bend reinstatement on the Latrobe River was based on the original cut-off plans for the stream. The eroded cut-offs each had a bench which represented the original excavation depth of the cut-offs, so it was easy to identify the design height for the weir. Rock material was brought in and dumped in the cut-offs up to the original depth of excavation. The rock material was won from a local quarry operated by the Lake Wellington Rivers Authority. Because of the type of rock and machinery available, rock sizes could not be controlled easily, so what was used was larger than required for the hydraulic conditions, but cheaper than bringing in breaking and sorting equipment.

Following the meander reinstatement, Lake Wellington Rivers Authority began revegetation. The authority is selectively removing willows from the river banks and hand-planting swamp paperbarks (*Melaleuca ericafolia*) by boat along the stream banks.

The pilot cuts in the original channels developed rapidly (within 2 years). No formal evaluation of the effect of the reinstatement on bank erosion was completed, although the stream managers are convinced that the erosion rate declined following the reinstatement. (Note that this is an example of a Plastic Medal evaluation design! See *Evaluation section*, this Volume or *Step 10* in Volume 1.)

A more effective evaluation would have been to measure the proportions of the discharge flowing down the original channel and the cut-off channel at low and high flows. A comparison of such measurements from before and after the reinstatement of the meanders would allow assessment of how much the work had increased the flow through the original channel.

2. Where is re-meandering inappropriate?

Several bends on the Latrobe river were not suitable for reinstatement because the new channel had deepened up and downstream of the cut-off, to the extent that the old channel was perched above the level of the present channel. For this reason, the reinstatement program was restricted to the lower reaches of the river where the river did not incise following the cut-offs.

The feasibility of meander bend reinstatement will depend on the extent of degradation and the availability of the original meander bends. Where the bends have been completely filled, or the land ownership makes the purchase of the bends prohibitive, it is probably more cost effective to rehabilitate a less-degraded part of the stream. The reinstatement of meanders on the nearby Moe River (Gippsland, Victoria) would, for example, be prohibitively expensive. Following stream straightening, the river has incised over 1.5 m and the meander bends have been filled (Figure 39).

Another important point in determining where to reinstate meanders is the establishment costs of the work. The major cost of the Latrobe River meander reinstatement work was providing machinery access to isolated sites. To get the machinery and rock to the sites was a major exercise, with roads constructed at many sites. Total reinstatement costs were about $25,000 for each cut-off.

Figure 39. Twenty kilometres of the Moe River in Victoria has been straightened and original meander bends have been backfilled, making reinstatement of meander cut-offs uneconomical.

3. Secondary effects of re-meandering

Re-meandering will have two secondary effects:

- there will be a pulse of sediment from the newly meandered channel; and
- the flood stage will rise for the same discharge.

At a minimum, the sediment filling the former meander channel will be remobilised, leading to an increase in turbidity downstream. Also, if a new meandering channel has been cut it will certainly erode to some extent as it stabilises.

Re-meandering projects are common in northern Europe, particularly Denmark (Brookes, 1996), but there is a fundamental difference between the situation there and that in most of Australia. The primary objective in many northern European schemes (especially in Denmark) is to raise the watertable in the adjacent floodplain and increase the frequency of overbank flows, in order to regenerate degraded riparian wetland ecosystems (Neilsen, 1996), and to promote sports fisheries. In Australia, on the other hand, remeandering is usually undertaken with the specific aim of improving the instream habitat while generating the minimum increase in flood risk.

There are several ways in which it is possible to estimate the impact of re-meandering on the flood characteristics of a stream, including using *How changing the channel can affect flooding*, in Natural channel design, this Volume. Alternatively we can consider what happens when we channelise a stream, and assume that re-meandering should have the opposite effect. For example, Shankman and Pugh (1992) examined the changes resulting from the channelisation of the Obion River in Tennessee. If we think in terms of a reversal of the effects of channelisation, we might predict the following effects of re-meandering.

- Decreased peak discharge downstream of the scheme, as the increased flow resistance prevents the floodwaters from converging so quickly at a downstream point.
- The increased resistance is a result of a rougher channel perimeter, reduced uniformity in cross-section, decreased hydraulic radius and decreased slope.
- The frequency of flooding will decrease downstream of the reintroduced meanders, but the duration of those floods may increase as the flow in the channel is not as efficiently removed from the site of the flooding.
- The importance of position in the stream network was stressed by Shankman and Pugh (1992), whose work was conducted on a stretch of the Obion immediately upstream of a confluence with the lower Mississippi River. When the Mississippi was at a high stage, it produced a backwater that extended some distance up the Obion, and controlled flooding in its lower reaches. Any channelisation or re-meandering work that might have been carried out in that reach would have had no effect on the flood characteristics, as discussed in *How changing the channel can affect flooding*, in Natural channel design, this Volume.

Of course re-meandering will not immediately reinstate the pre-channelisation flood regime. It is likely that the channelised river is now larger than its predecessor, and the channel would almost certainly have been cleared of LWD.

To conclude, the Latrobe River example demonstrates that remeandering can be feasible, and probably effective. However, in channels that have deepened and enlarged, and where the old cut-off channels have filled with sediment, re-meandering will be less successful.

FISH COVER

Cover refers to instream and overhead features that protect fish from high current velocities, provide concealment for both predators and prey, and maintain water temperature by controlling illumination of the water (Swales and O'Hara, 1980; Wesche, 1985; Gore and Shields, 1995). Cover requirements (as with other habitat features) are species and life-stage specific for aquatic organisms. The cover requirements for salmonid fish have been well researched. One study by Elser (1968) compared an unaltered stream section with an altered section with 80% less cover. The results of the study showed 78% more trout in the unaltered reach. Cover is also a key habitat element for Australian native fish. The specific requirements of some fish are known: trout cod and freshwater blackfish, for example, prefer hollow logs for spawning (Koehn and O'Connor, 1990). Recent surveys of platypus habitat have found that the presence of these animals is strongly associated with undercut river banks. As a general rule, the addition of cover will improve the in-stream environment for aquatic biota, particularly if LWD is used to create cover. The following illustrations (Figures 40 and 41) are some examples of artificial cover taken from the international literature—they may help to inspire local adaptations that can be incorporated into other in-stream works, or indeed can be installed on their own.

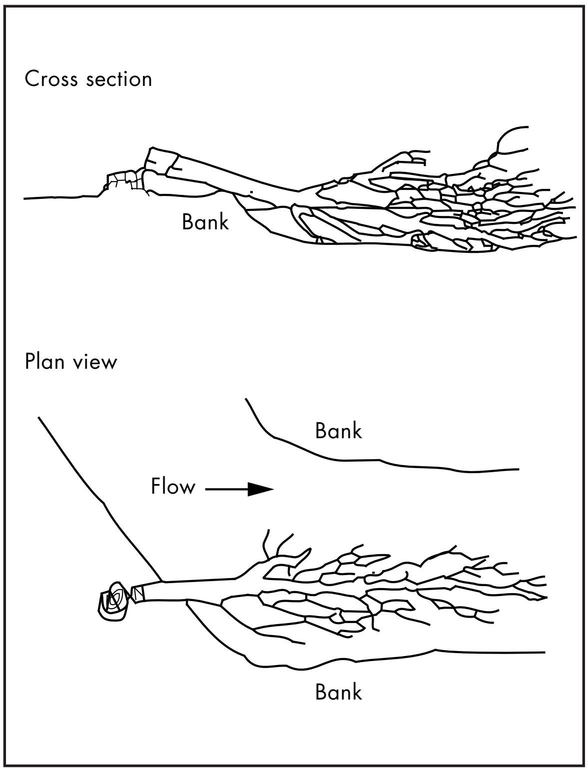

Figure 40. Floating log and tree cover used in North America as fish shelter (from Rosgen, 1996). Australian riparian vegetation species often do not float, so an adaptation of this type of cover might be the introduction of large woody debris to the stream and anchoring it into place. Reproduced with permission from Wildland Hydrology.

Figure 41. This snag (perfect habitat!) was reintroduced to Ryans Creek in Victoria. The cost of relocating the debris from the floodplain and securing it in the stream was about $500.

BOULDERS

The addition of boulders to a stream flow creates hydraulic diversity. As flow accelerates around boulders, scour pools are created and downstream bars are formed. The boulders create cover and substrate for macroinvertebrates, and the turbulence generated aerates the water. Boulders are normally placed mid channel, where they produce localised bed scour and deposition. When placed near the bank they may cause localised bank erosion. An example of the use of boulders to create improved instream habitat is Ryans Creek (a tributary of the Broken River in Victoria). The rehabilitation strategy for a section of shallow, fast-flowing water (glide), was to place boulders downstream of a log sill, use artificial riffles to add water depth, introduce large woody debris (one large snag introduced) and narrow the low-flow channel using low deflectors (Figure 42).

Figure 42. Boulders used to create habitat in Ryans Creek, a tributary of the Broken River, in Victoria.

Boulders are a low-cost alternative stream rehabilitation structure. For example, the cost of extensive use of boulders (2,000 × 0.5 m^3 boulders) in the rehabilitation of the Snowy River is estimated at around $30 per boulder (installed) (Stewardson *et al.,* 1997). There are large economies of scale with this project, and establishment costs are not included.

1. Installing boulders

The overall consideration when installing boulders is to ensure that they add to the channel as much hydraulic disturbance as possible, so as to encourage scour and bar formation for improved in-stream habitat. This is generally achieved by selecting large angular boulders which are placed in the highest-velocity zone of the stream and orientated to create the greatest hydraulic disturbance.

Quarried boulders are the best material to use, because their sharp edges enhance turbulence and create the greatest hydraulic flow diversity. Wesche (1985) suggests using hard rock (say basalt) in preference to soft rock (say sandstone), but this choice will be determined largely by the materials available. Almost anything could be used to create similar hydraulic disturbance to boulders, but an obvious consideration is the aesthetic appeal, so use natural products wherever possible.

1.1. Sizing boulders

- If the ratio of boulder to bed material size is less than approximately 20:1 the boulders may 'glide' over the bed material in high flows (Conrick and Ribi, 1996).
- Rocks could be sized on the basis of tractive force equations, but realistically, the size needed to create suitable habitat features is usually much larger than the critical size for transport. Wesche (1985) suggests a diameter between 0.6 m and 1.5 m.
- Barton and Cron (1979) (in Shields, 1984) recommend that boulders should be no larger in their greatest dimension than one fifth of the normal-flow channel width. This recommendation is presumably to avoid over-constricting the flow in the channel and thereby causing bank erosion.

1.2. Placement of boulders

- Wesche (1985) recommends embedding boulders into the stream bed, but if they are large compared with the minimum size required to resist tractive stress movement, there is little value in further anchoring them.
- Boulders are effective because they create hydraulic disturbance, so they should be positioned to maximise

that disturbance by orientating their longest dimension at right angles to the flow, as in Figure 42, and by placing them near the centre of the stream or fastest-flowing area (Shields, 1984).

- To ensure boulders have the greatest hydraulic impact they should not be placed in the downstream zone of influence (wake) of upstream boulders.

- Boulders can cause local bank scour, so do not place them near banks susceptible to erosion (Wesche, 1985).

- Shields (1984) suggests that boulders should project slightly above the water surface at normal flow. This is presumably for the benefit of non-aquatic wildlife such as birds.

- Boulders are best applied to shallow, high to mid-gradient streams. The main mode of failure of boulders is that they may be buried in low gradient sand-bed streams (Shields, 1984). In these stream types they tend to 'drill' themselves into the bed as sand is scoured from under them.

- In slower, deeper streams the effect of the boulder is drowned out.

- Boulders create only minor increases in channel roughness during bankfull flow conditions.

1.3. Spacing boulders

There are no Australian data on which to recommend the spacing of boulders. Shields (1984) presents the recommendations of two studies:

- one rock per 27 m^2 (Barton and Cron, 1979); and

- one 2 m diameter boulder approximately every 70 m^2 provided superior habitat to one boulder per 46 m^2 (Kanaly, 1975).

However, the optimum spacing of boulders is dependent on the habitat requirements of particular species, and the presence of other habitat features. One important finding of Kanaly (1975), as reported by Shields (1984), was that the pattern of boulder placement had no effect on fish density. Suggestions for suitable boulder placements are shown in Figure 43.

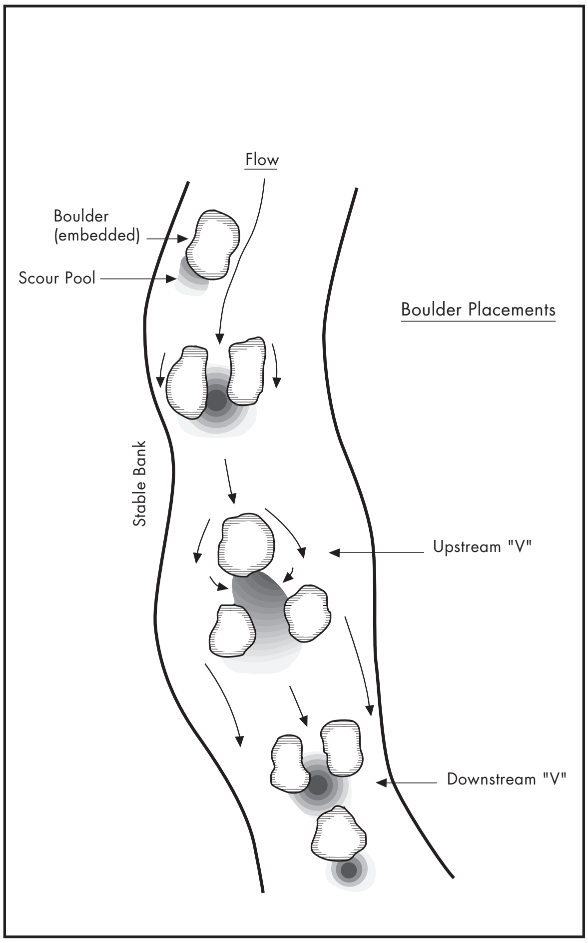

Figure 43. Patterns for boulder placements (from Wesche, 1985). Reproduced with permission from Butterworth Publishing.

OVERCOMING BARRIERS TO FISH PASSAGE

Compiled with the assistance of John Harris and Tim O'Brien†*

Fish move between habitats, both on a small scale, in a day-to-day search for food, and on a larger scale, between different habitats during different stages of life. Golden perch, for instance, spawn during floods in lowland river reaches; the young develop in floodplain or river margin nurseries; then eventually travel upstream as juveniles. Blocking fish passage between these habitats will have serious results for the fish population in the stream. Complete obstruction of migration will lead to local extinction of the species. Barriers to fish passage can be caused by perched streams—where a dam or weir causes a waterfall—and by very shallow or very-high-velocity reaches. For a more detailed discussion on how to identify barriers to fish passage, and the effects on the fish populations, see *Barriers to fish migration*, in Common stream problems, this Volume.

1.1. Fish passage past full-width structures—general points

Here are some key points to consider in the design of full-width structures so that they do not form barriers to fish passage (O'Brien, 1997); see also *Barriers to fish migration* in Common stream problems, this Volume).

- **Mimic natural conditions.** A general rule for fish passage is to assess the natural conditions and do not create a higher velocity or shallower depth of flow than can be observed in the natural stream. Headwater streams are quite steep, and small waterfalls and high velocity flows are quite common. The natural fish assemblage reflects these conditions, and the fish passage implications of a structure in this stream will thus be very different from those of a deep lowland stream meandering across an alluvial floodplain where velocity is low and there are rarely any natural full-width barriers to fish. Applying this rule you have to bear in mind the range of flows in the channel.

- **Think about to where the fish go.** Where do the fish go when they leave the top of the fishway? At one fishway in New South Wales, it is reputed that the fish leave the fishway only to be sucked straight into a power station off-take!

- **Limit free fall.** Many Australian fish cannot negotiate even small free-fall drops over low weirs. The characteristics of the target fish species must be reviewed. A conservative approach is to avoid drops of greater than 15 cm.

- **Minimise velocity**. Australian fish cannot sustain long periods of swimming headlong into fast-flowing streams. The downstream slope of full-width structures must be gentle enough to enable free fish passage, and resting areas should be provided at intervals corresponding to 1.0 m rises in elevation. Rest areas should consist of pool areas with close to zero gradient and which are at least 2.0 m long (O'Brien, 1997).

- **Limit downstream slope.** To make full-width structures passable by fish, the downstream slope must not be too steep. The gradient should be consistent through the full length (apart from designated rest areas) of the structure and in most cases should be no steeper than 1:20. Most rock chutes and rock weirs are constructed with a downstream slope of around 1:10 (DC&E, 1990; Working Group on Waterway Management, 1991). For a rock weir installed as a bed-control feature to also allow fish passage requires the downstream slope to be reduced from 1:10 to 1:20. The cost of this reduced slope is 100% more stone per unit width of the fishway (Figure 44), but note that the fishway need not extend the full width of the channel.

- **Maintain adequate water depth.** For fish to be able to pass a structure the water must be deep enough. The

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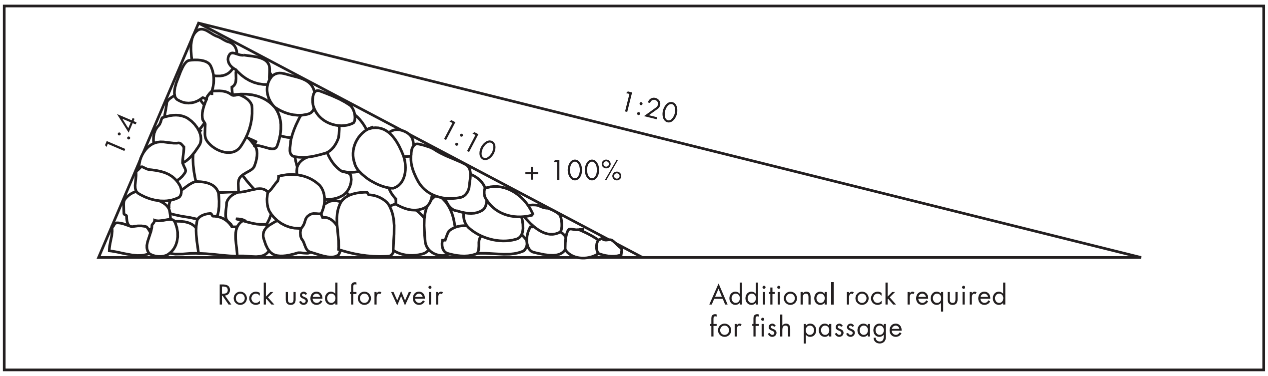

Figure 44. The additional volume of rock required when you halve the slope of a rock chute to provide fish passage.

depth of water required will depend on the fish assemblage present but, as a general rule, coastal streams should be at least 15 cm deep during the minimum design flow period, and inland streams may need to be deeper because of the larger species present in these river systems. The minimum design flow that should be used for designing fishways is unclear, but one suggestion is that fish should have free passage past channel obstructions for 95% of the time that the stream is actually flowing (J.Harris, personal communication).

Figure 45. A mangfall sill with central fishway (photo by John Harris).

There are several ways to maintain a minimum depth of flow over full-width structures. For the construction of riffles (rock weirs) Newbury and Gaboury (1993) recommend the structure be V-shaped to concentrate low flow at its centre. The slope of the crest into the V is only slight: Newbury and Gaboury (1993) use a drop of 0.1 m from the banks to the centre of the channel for streams 10–15 m wide.

Figure 46. A zigzag fishway, with transverse ridges of rock that effectively reduce the slope of the fishway (photo by John Harris).

The double arch sill in Figure 45 incorporates a similar concept, with a lower gradient, central chute for fish passage at low flow. An alternative design is the use of a zigzag fish ladder up the face of the grade control structure to reduce the effective slope of the low-flow water surface (Figure 46). For this design, rock should be oversized to resist movement in the high shear-stress zone down the face of the structure.

1.2. Fish passage over larger structures—rock-ramp fishways

There are many thousands of barriers to fish passage around Australia. The average cost to build concrete fishways, such as the vertical-slot design, for each of these structures would be measured in hundreds of thousands of dollars (Mallen-Cooper and Harris, 1990). Clearly, this is a daunting task and funding even a long-term program to restore fish passage will be difficult. If you need a large engineered structure like this, then seek professional advice! Most managers need a cheaper alternative, and the type of fishway that is most likely to be appropriate is the rock-ramp fishway. This is particularly suitable for the numerous barriers that are less than 1 m or so in height. Rock-ramp fishways are being tested by New South Wales Fisheries, the New South Wales Department of Land and Water Conservation, the Cooperative Research Centre for

Freshwater Ecology and the Freshwater Ecology Division of the Marine and Freshwater Resources Institute in Victoria. Based initially on designs for stream-bed control (see *Full-width structures*, above) and habitat-restoration structures used in Canada (Newbury and Gaboury, 1993), and later incorporating European ideas on 'nature-like' weirs (Hader, 1991), rock-ramp fishways mimic the flow conditions in natural stream riffles. Such designs have the advantage of being relatively inexpensive, because building materials, such as rocks or logs, are usually readily available. There are some critical design rules for fishways.

- The maximum height of rock-ramp fishways should be 1 m, unless substantial resting pools are included in the design.

- The effectiveness of a fishway is limited by the ease of passage of fish past its most difficult point (usually the crest of a weir).

- There must be sufficient depth over the crest to allow fish to use the fishway. A backwater created by the rock-ramp must submerge the weir crest. This can be achieved, either by building the uppermost ridge of the ramp above the height of the weir or, where the fishway does not extend the full width of the channel, the weir crest should be lowered at the point of the rock riffle (Figure 47).

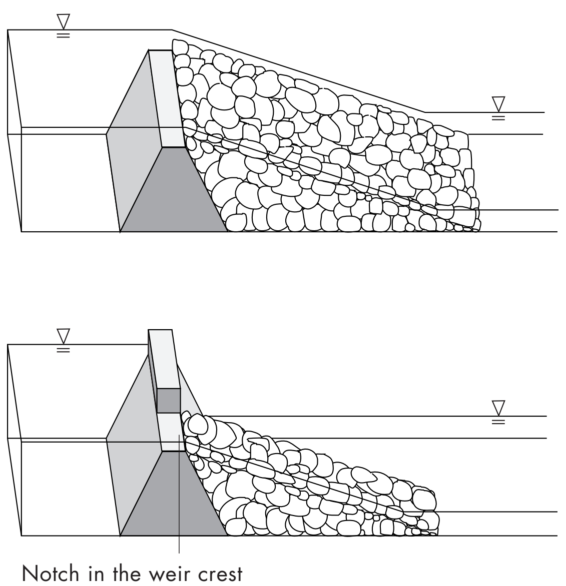

Figure 47. Submerge the weir crest either by building the rock-ramp above the height of the weir (full-width rock-ramp) or by lowering the weir at the rock-ramp to concentrate flow and subsequently increase the depth of flow over the weir lip at the fishway.

- Flow must pass down the face of the fishway, not be lost between the rocks (this can be achieved by incorporating finer sediments, or geotextiles).

- The flow pattern guiding fish into the entrance is critical (Mallen-Cooper and Harris, 1990; Clay, 1995). Fish locate the fishway entrance by flow sensing (rheotaxis), water quality, vibration of the falling water and by sight when close to the fishway.

- It is best to have only one attracting flow for fish below each weir (ie. do not have one flow at the fishway exit and another one flowing off the crest of the weir): see, for example, the Macintyre River weir example later in this section.

Rock-ramps can be built solely as fishways on existing low-level barriers, or as dual-purpose fishways and erosion controls. The initial designs for these ramps used a downstream slope of 1:20, and large rocks were placed in transverse ridges to provide roughness, increase the amount of riffle habitat, and create a series of pools and small falls. A total height of 1 m is set as the maximum for these structures, but a series of rock-ramps can be linked by deep resting pools to overcome barriers up to 3 m high.

Rock-ramps should ideally be built to occupy the full width of the stream channel at bankfull flow. To reduce capital costs, especially where there are no quarries close to the site, some have been designed to occupy only a portion of the channel width.

Structural problems may be encountered after construction of rock-ramps, including:

- settling movement in unsupported ramps during high flows;

- excessive drops (over 150 mm) at ridges at the upstream end;

- instability in ramps with transverse ridges; and

- leakage of flow from the sides of the ramps which do not cover the full channel width may result in many fish not being able to quickly find the entrance to the ramp.

The general layout of any fishway needs to be such that fish can easily find the entrance (Clay, 1995). Confined rock-ramp channels, such as the one at Goondiwindi Weir on the Macintyre River, on the border of Queensland and New South Wales, greatly reduce the width and cost of the fishway but, unfortunately, may result in the entrance being well downstream of the original weir crest. In such cases, the effectiveness of the fishway is greatly reduced during high flows, because many fish have difficulty locating the entrance of the fishway. Experimental studies at the Goondiwindi Weir showed a good passage through the fishway in low flows, when there was no confusing discharge over the side crest, and much poorer results in a moderate flow, when a large proportion of the fish missed the entrance. A permanent guiding wall will be needed at the level of the Goondiwindi fishway entrance to achieve acceptable performance. This will discourage the fish from swimming upstream past the fishway entrance.

Although there are some experimental limitations in making our assessments, it is clear that the general rock-ramp design tested is a useful, simple and relatively low-cost adjunct to more formal, technical fishway designs, particularly for overcoming low barriers.

Experience with experimental ramps showed the need to stabilise the toe of the structure to prevent downstream movement. For ramps on existing fixed-crest weirs, the crest should be lowered to ensure that it is drowned by the ramp, and that excessive upstream head-losses do not develop.

The rock-ramp concept has been further developed by Wal Hader of the New South Wales DLWC, to extend the initial designs and construction methods. Plan views of these structures show arched arrangements of boulders set on end and abutting each other to provide greater stability, roughness and habitat. These arches form one or more dished channels, sometimes occupying only a part of the width of the channel. The dished channels provide a variety of different depths, thus meeting the requirements for variable flows and for fish of different sizes. Boulders are placed on end using excavators with rotating grabs, without the need for additional stabilisers such as steel or concrete. Flow patterns produced by some of these newer designs appear very suitable for fish, and experimental assessments are planned to test their fish-passage efficiency.

Rock-ramp fishways can provide effective passage for native fish. Migratory small and juvenile fish are able to ascend rock-ramp fishways in low-flow conditions. However, variable discharges mimicking nature are needed, and higher flows may be necessary to stimulate some species to migrate or to allow larger fish to ascend the fishway. As with all Australian fishways so far, successful fish passage is certain only when the design and construction stages involve engineers and fish biologists who are experienced in fishways.

1.2.1. Rock-ramp case studies

The rock ramp at Macdonald's Weir, New South Wales

An experimental rock-ramp at Macdonald's Weir on the Macquarie Rivulet, on the south coast of New South Wales, illustrated some of the potential problems of ramps, and their solutions.

Problems with the Macdonald's Weir rock-ramp:

- The rock-ramp settled after construction and some movement of surface rocks occurred during high flows (Thorncraft and Wardle, 1991) (see Figure 48).
- The regular transverse ridges were displaced during a high-flow event within 12 months of construction.
- The weir crest was not submerged, because the top ridge of rock on the fishway was displaced during high-flow.
- Water percolated through the structure rather than flowing over it.

Figure 48. Macdonald's Weir rock-ramp showing dislodged downstream rocks (photo by John Harris).

Solutions:

- Substantial reconstruction was required to restore the fishway's function. The rock-ramp was repaired as follows.
- The problems with settling of the rock and displacement of the top ridge of rock were solved by placing larger rocks (diameter > 1 m) on the top ridge to submerge the weir crest.
- A geotech filter fabric was used to limit percolation of flow through the rock-ramp.
- Experience with instability of the Macdonald's Weirs rock-ramp showed that it would have been better to lower the old weir crest during construction, so that subsequent rock settling would not affect the fishway exit.
- If the lowering of an existing weir is not possible, only large rocks should be used on the surface of the ramp. Most importantly, the toe of the ramp should be stabilised to prevent downstream movement of the toe rocks and settling of the rest of the material. This can be done with large embedded rocks, sheet-pile, timber or railway-line driven into the river bed.

1.2.2. Fish bypass channels

Fish bypass channels are another potential fishway design for Australia. In Europe, bypass channels are being applied to provide successful passage for a wide range of fish species and sizes past low dams, weirs and other barriers up to 8 m in height. They are low gradient earthen or rocky channels that mimic the structure of natural streams, and are often described as 'nature-like' fishways. Few general rules apply to the design of bypass channels: each is created to suit the particular site, and is often part of a larger river-restoration project. Often, relatively small-scale channels are built, designed to carry different proportions of the dry weather flow of the main river channels. Bypass channels are usually built with meanders to suit the site while creating a more-or-less gentle gradient. Slopes differ widely, from less than 1:1,000 up to a maximum of about 1:30. To retain stability, discharge is controlled by carefully designed intake structures. Stability in channels lacking rocky substrates is also provided by low-level control weirs (<200 mm) of boulders and rocks separating a series of small pools. Bank stability is enhanced with rock or timberwork and plantings of local species. European experience suggests that by-pass channels have performed effectively, and in some regions technical fishways are being dismantled and replaced by bypasses. Australian water agencies need to experiment with this technology to determine its value for solving local fish-passage problems.

The bypass rock-ramp at Lower Barwon River barrage

An off-stream rock fishway was constructed around the Lower Barwon River (Victoria) barrage (see Figure 49). The barrage is a sheet pile weir approximately 0.75 m high for impounding water and acting as a tidal barrier. The construction of the rock-ramp fishway coincided with the refurbishment of the weir.

The rock weir extends across the width of the channel and has a slope of 1:16. The weir was lowered at the entry point of the rock-ramp by cutting a 2.5 m wide (fishway width) and 100 mm deep slot through one side of the weir. The rock ramp was lined with geotextile material, and the final layer of rocks placed on the ramp. Large rocks were placed on the rock ramp under the direction of a fish biologist while the water was being released down the ramp. This allowed the selection and adjustment of rocks so that flow patterns allowed fish passage by providing low enough velocities, sufficient depth and resting sites up the ramp. The materials for this project were: 24 m^3 of quarried rock 200–700 mm diameter; 6 m^3 of quarry scalpings; and 8 x 3.6 m polyweave-F geotextile filter fabric. Two days of front-end loader time plus labour were needed, and the total cost of the project was approximately $10,000. The fishway has been tested by two major floods with no significant damage. Based on this and the shallow channel and wide floodplain at the site, the fishway is not expected to be damaged by floods.

Electro-fishing of areas above, below and within the fishway, showed that the completed rock-ramp posed only a minimal impediment to fish movement. Catches from these areas were similar in terms of both relative abundance and fish size range, and fish were relatively evenly distributed throughout the fishway itself (O'Brien, 1997).

Figure 49. An off-stream rock-ramp fishway constructed by Melbourne Water around a weir on the Maribyrnong River, Melbourne. This is a similar design to the bypass structure on the Barwon River.

1.3. Fish passage through culverts

The solution to perching in culverts is to create downstream pools which back the water up to the culvert invert level, effectively flooding the outlet. This can be done by any number of methods depending on the materials available. One option, shown in Figure 50, is to install low weirs downstream, effectively flooding the culvert. Care must be taken that the weir does not form a barrier itself. Another approach, suitable for a small channel, is to use large rocks and logs to create a riffle downstream of the culvert. Water cascades down the improvised structure in much the same way as flow down a natural riffle.

To maintain adequate conditions for fish passage there should be times when flow through a culvert does not exceed 1 m/s, allowing at least some fish passage (though even this will be too fast in long smooth culverts). The problem with many culverts is that their low velocity flows are too shallow for fish passage, and their deep flows are too fast.

One solution practised in the United States (Clay, 1995) and Europe (Hansen, 1996) is to increase the bed roughness and provide low-velocity resting areas by fixing larger elements such as rocks or baffles to the floor of the culvert (Figure 51). If the culvert is slightly over-designed, then such baffles should not cause an unacceptable increase in flood risk, but check with the local authority or main roads department before you even consider tampering with a culvert!

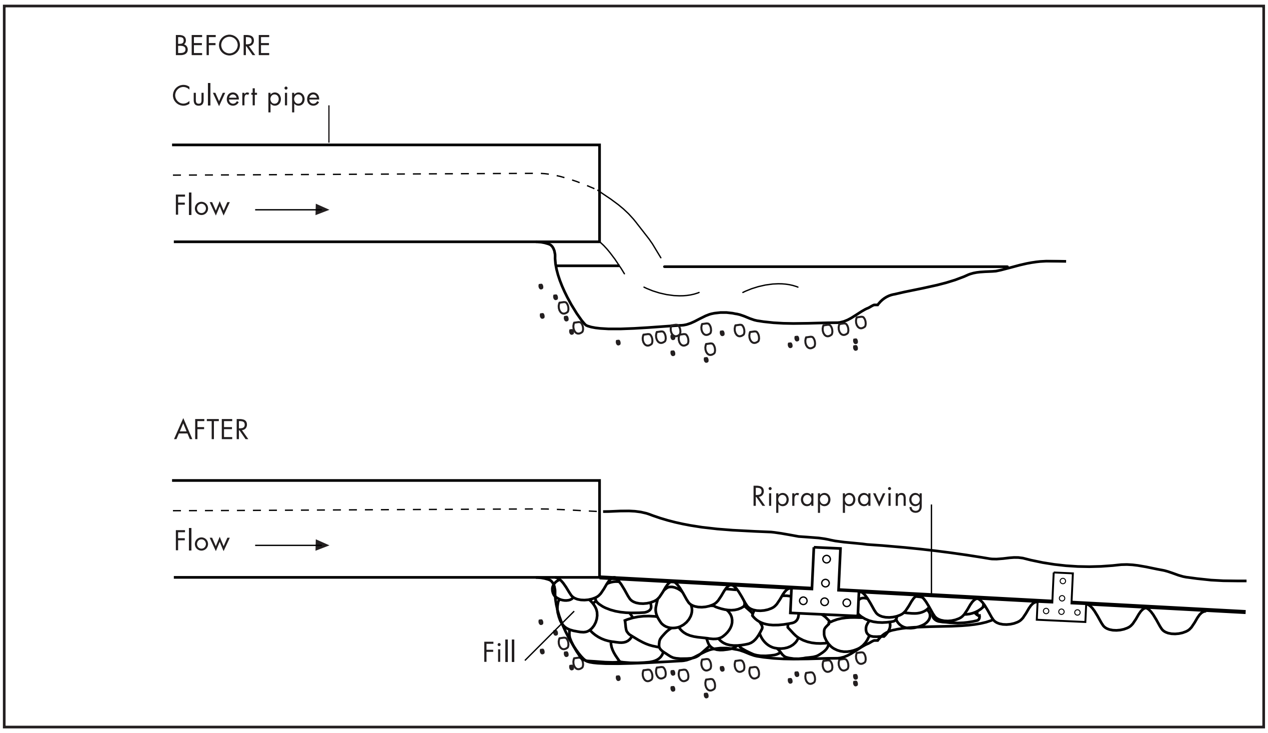

Figure 50. Flooding a culvert with a backwater (from Clay, 1995).

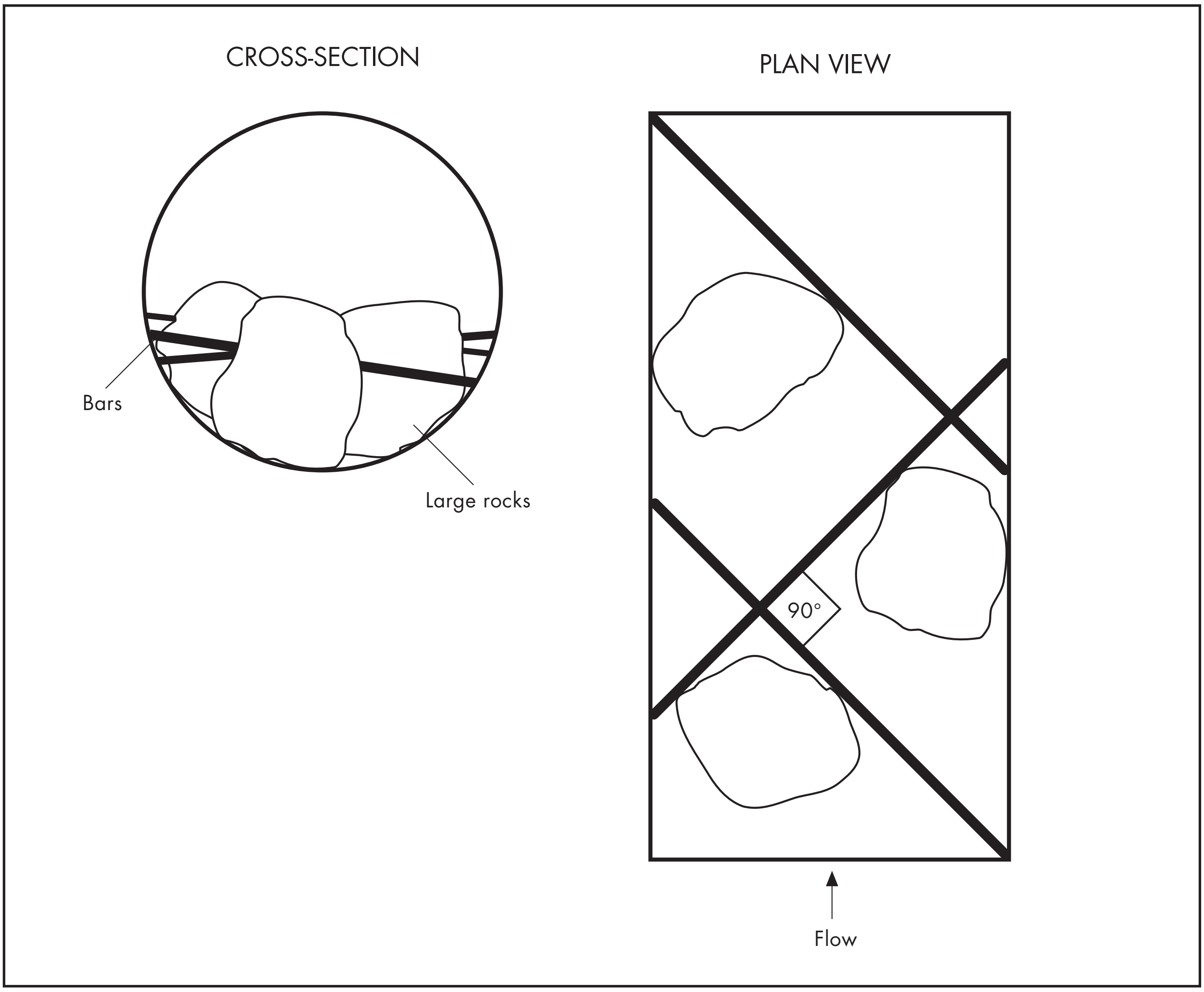

Figure 51. Design concepts for improving fish passage through culverts (from Clay, 1995).

MANAGEMENT OF LARGE WOODY DEBRIS

1. Re-introduction techniques for instream large woody debris

By Christopher Gippel and Karen White†, with additions by the editors*

> The artificial reintroduction of LWD into streams should be seen as a stopgap measure, to be used until a regenerated riparian zone can naturally supply timber to the stream. In most cases it will take many decades for trees planted in a totally cleared riparian zone to grow large enough to contribute useful long-term LWD.

1.1. Introduction

Large woody debris (LWD) is recognised as an important structural and ecological component of many stream environments. Woody debris provides hard surfaces for attachment and growth of aquatic plants and invertebrates, and also habitat conditions of fundamental importance for maintenance of fish populations (Harmon *et al.,* 1986; Gippel, 1995). Because many streams have been de-snagged, or denied a source of woody debris through degradation or removal of riparian timber, re-introduction of large woody debris is often an important aspect of stream rehabilitation. As well as devising riparian management strategies to ensure an ongoing supply of wood to streams, some agencies are attempting to speed the recovery of woody debris loadings by direct re-introduction of wood and wood structures into channels (Gippel, 1995).

Re-introduction of woody debris will create physical habitat, but its utilisation will depend on the existence of other factors, such as adequate water quality, fish passage, appropriate stream flows, and recolonisation opportunities. In Meadow Creek, eastern Oregon, USA, large amounts of LWD that were re-introduced to the stream were displaced during a subsequent storm event, contributing to loss of riparian soils and redistribution of stream gravels (Beschta *et al.,* 1992). In Fish Creek, north-central Oregon, despite an extensive instream habitat rehabilitation effort that included a 200% increase in the number of pieces of LWD in the channel, the numbers of anadromous fish did not increase significantly (Beschta *et al.,* 1992).

Thus, woody debris cannot be introduced in isolation from other stream rehabilitation strategies.

There is now a reasonable body of literature detailing the characteristics and loadings of woody debris in rivers, although most of the work has been done in North America (eg. Harmon *et al.,* 1986), with a few other studies from Australasia (eg. Gippel *et al.,* 1996a) and Europe (eg. Piegay, 1993). These studies provide basic information on the volumes, dimensions, characteristics and arrangement of debris found in a range of river environments. Such information can be useful at the planning stage, but implementation of a debris re-introduction program would generally require more detailed information on issues such as selection of materials, methods of anchoring (if required), how to build debris structures, and where to place debris.

Presently, there are no well-established or commonly accepted criteria for the re-establishment of debris into rivers. There is only a limited literature dealing with the methods and results of river rehabilitation projects in general, and there has been only limited research into the specific problem of debris re-introduction. Most debris management guidelines are limited to methods for the selective removal and/or realignment of debris (Bryant, 1983; Bilby, 1984; Shields and Nunnally, 1984; Gippel, 1995; Gippel *et al.,* 1996a; Gippel *et al.,* 1996b; Gippel *et al.,* 1998). Some specific guidelines for debris re-introduction have recently become available (eg. Gippel *et al.,* 1996b; Abbe *et al.*, 1997; Ontario Streams, 1998; D'Aoust, 1998; Hilderbrand *et al.,* 1998). Currently, the design of many rehabilitation projects tends to be based on a trial-and-error approach (Brookes and Shields, 1996), and the

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re-introduction of debris into rivers seems to be no exception. Monitoring and post-project evaluation of rehabilitation works is rarely performed (or if done, it is rarely reported) (see V.A. Poulin & Associates, 1991; Beschta *et al.,* 1994; and Gore and Shields, 1995 for some exceptions); this has no doubt slowed the development of guidelines.

The majority of the literature on re-introduction of debris comes from North America. Guidelines devised in North America may be inappropriate for areas with different types of trees, or streams that are geomorphologically or hydrologically different. For example, the eucalypts that line streams in south-eastern Australia are significantly denser and stronger than the riparian trees found in North America. It is more likely then that snags in Australian rivers are more stable. Additionally, the form of most eucalypts usually differs from that of North American pines and conifers in that the bulk of the crown is concentrated towards the top of the bole, and the bole generally has less taper. Furthermore, the large branches typical of a eucalyptus tree can effectively brace the snag in the bed of the river. These differences have implications for the techniques of anchoring reintroduced debris. Flows in Australian rivers are highly variable, with occasional catastrophic floods a feature of the hydrological regime (Finlayson and McMahon, 1988). Such floods have sufficient power to significantly re-arrange debris. Bed material type is probably also important in determining not only the resistance to debris movement, but also the tendency of debris to become partially embedded (and thus more stable). Thus, it is likely that many aspects of debris re-introduction technology are not directly transferable between environments.

This section of the manual reviews debris re-introduction guidelines. Some of these guidelines relate to general issues that have wide application. Others were developed from experience in specific areas, and caution is advised in attempting to transfer them to a geographically different field site.

Debris is reintroduced to rivers in four main forms:

- as individual debris elements;
- as multi-element debris structures;
- as bank revetment; and
- as in-stream structures such as current deflectors, weirs, and cover devices.

Much has been written on in-stream structures made from wood, such as crib walls, deflectors, half-logs and log weirs (eg. Swales and O'Hara, 1980; Wesche, 1985; DeBano and Heede, 1987; Charbonneau and Resh, 1992; Gore and Shields, 1995; Ontario Streams, 1998). These structures certainly increase the volume of large wood in the stream, but they are not necessarily expected to perform the same hydraulic, geomorphic and habitat functions of natural large woody debris formations. While Booth *et al.* (1996) found few analogues for these structures in undisturbed streams in the Pacific Northwest, natural log steps are a well-described feature of undisturbed headwater streams (Heede, 1972; Gurnell and Gregory, 1981; Bilby, 1981; Harmon *et al.,* 1986). The focus of this review is methods of re-introducing wood into streams with the specific objective of rehabilitating or restoring the natural (pre-disturbance) debris forms and functions. Sometimes this distinction is unclear; for example, when debris is re-introduced to provide habitat and to stabilise eroding banks. Tree revetments are an example of this type of debris re-introduction (Henderson and Shields, 1984, p. 60; Wesche, 1985, p. 154; Johnson and Stypula, 1993, p. 7–22).

Woody material can be obtained in the form of cut logs, root wads, trunks with attached rootwads or entire trees. Selection of material and anchoring technique will depend on the desired function of the debris, the expected life span of the project, the availability of materials, the costs involved, and ease of access to the river. The majority of debris re-introduction projects aim to directly enhance or restore the natural habitat values provided by wood in streams (hydraulic diversity; fish cover, resting and refuge areas; a substrate for macroinvertebrate colonisation) and/or to indirectly improve habitat by decreasing sediment discharge downstream and/or protecting banks from erosion (Skaugset *et al.,* 1994a; Richmond and Fausch 1995; Booth *et al.,* 1996).

1.2. Suitability of sites for LWD re-introduction

From an ecological perspective ultimate aim is to restore the natural load of debris into the river. In many instances this will not be achievable, either because changes of channel form do not allow it, or because sufficient quantities of suitable LWD cannot be sourced and emplaced at reasonable cost. In other cases it may be undesirable to re-instate the natural load of debris because of undesirable hydraulic effects (increased flooding), risk of localised bank erosion, navigational requirements, or excessive risk of damage to infrastructure if the debris should dislodge.

Snags are not a natural feature of all stream systems. Streams in the northern tropics, where high gradients and flows tend to flush out debris, and where high temperatures result in rapid decomposition of organic material, may contain low natural levels of wood. Other streams naturally lacking woody debris include intermittent desert streams in which vegetation is sparse and stunted. Organisms in these streams are generally adapted to alternative habitats such as those provided by boulders, macrophytes, leaf packs etc.

Most de-snagging has occurred in river systems that drain the major intensive agricultural regions of Australia. It has been a common practice—usually as part of a more general channelisation program—in most larger Victorian rivers, most coastal New South Wales rivers, the major rivers and streams of the Murray–Darling basin, almost all streams running through urban areas in southern Australia and in several rivers in south-eastern Queensland and south-western Western Australia.

Swanson *et al.* (1984) suggested that debris re-introduction is called for if debris is absent for distances of 5–10 channel widths. However, it should be recognised that debris is not naturally present in all streams. This may be due to a lack of riparian trees, but more likely due to a combination of high stream power and a channel width that exceeds tree length. In other cases debris could be buried beneath mobile sand beds. The natural distribution of LWD has been documented for many sites around the world, but a general relationship between LWD availability (proximity, volume, type and dimensions), stream power, channel width, and LWD loading has not yet been developed.

For headwater streams in British Columbia, V.A. Poulin & Associates (1991) recommended that LWD re-introduction be limited to streams with a gradient <0.03. In lowland rivers, Sear (1996) found that where bankfull stream power was below 15 W/m^2 habitat-enhancement works (which might reasonably include LWD re-instatement) are likely to fail through excessive deposition of sediment. When bankfull stream power is above 100 W/m^2 habitat enhancement works are likely to fail through excessive erosion. For lowland streams with bankfull velocities of 0.5–1.5 m/s, and depths of 1–4 m, this suggests an upper channel gradient limit of 0.02 for slow, shallow streams and 0.002 for fast, deep streams. Brookes (1990) also noted that stream rehabilitation works are generally unsuccessful where the channel confines floods greater than the 1:5 year ARI event.

1.3. How much debris to put back in?

The natural load of debris into the river can be determined by measuring the amount of debris present in relatively natural reaches of a similar river or from records in historical documents. If no information is available, a general rule for lowland rivers is to attain a debris loading of around 0.01 m^3 for every m^2 of the channel bed (Gippel *et al.,* 1996). A stream flowing through degraded riparian land will probably require re-introduction of more debris than a stream flowing through more intact riparian land. Booth *et al.* (1996) commented that debris re-introduction was particularly appropriate in urban channels, because of the severe depletion of debris, and because of the general lack of source material for natural recruitment.

1.4. Replacing individual debris elements

Placement of individual logs is the most common form of LWD re-introduction. Individual logs may be placed as:

- log steps placed perpendicular to flow in small steep streams; and

- cross-stream logs placed diagonal or perpendicular to flow.

As a general rule, the longevity of wood will be greatly enhanced if it remains fully saturated (Alvarado, 1978; Harmon *et al.,* 1986). The maximum decay rate occurs with alternate wetting and drying (Johnson and Stypula, 1993). There are practical difficulties with installation of debris in deep water. The normal practical limit is around 1.2 m depth (Ontario Streams, 1998).

1.4.1. Log steps

Fallen logs are often incorporated into the geometry of steep, forested headwater streams, to form natural log steps (Marston, 1982; DeBano and Heede, 1987). Although temporary structures, streamside forests maintain the density of log steps. Artificial re-introduction of log steps may be appropriate in channels where the riparian forest has been cleared, or in channels that have stabilised after incision.

Log steps (also termed check dams, low dams or log weirs) are used in small streams up to 5–6 m wide when deepening of pools in the range 0.15–0.3 m is desired (Wesche, 1985). Log steps are often notched in the centre. This concentrates the flow to form a waterfall, thereby dissipating energy, aerating the water, and creating a plunge pool below. Further downstream a riffle forms. Sediment accumulates above the log steps to produce gentler channel gradients. Log steps are normally placed in a step-like series in areas of steep gradient. Stable pool–riffle sequences are possible in streams with slopes up to 0.01, and where coarse bed material (coarse sand to gravel) is present (Swales and O'Hara, 1980). As well as stabilising the channel bed, log steps can provide pool habitat for fish and macroinvertebrates (Swales and O'Hara, 1980; Charbonneau and Resh, 1992; Zapzalka, 1997). Various modifications to the basic single log design are given by Wesche (1985).

Construction techniques for log steps can be found in Wesche (1985) and Charbonneau and Resh (1992): log ends should be sunk 1–2 m, or at least one-third of the channel width, into both banks; to prevent failure by undercutting; embed the base log at least 0.15 m into the substrate; rip-rap can be placed over log ends to reduce the chance of endcutting; and the minimum log size is 0.3 m diameter. Swales and O'Hara (1980) noted that while the natural pool–riffle sequence can be re-instated by placing log steps a distance of 5–7 channel widths apart, the spacing is often dictated by stream gradient, with steep streams requiring closer spacings. Montgomery *et al.* (1995) found that natural pool spacing in forested drainage basins decreased from 13 channel widths to less than one channel width with increasing debris loading. Life expectancies of 20–40 years can be achieved with durable timber that is submerged at all times (Wesche, 1985). Minimum design standards for log steps are provided in Alvarado (1978).

1.4.2. Cross-stream logs

Debris is most commonly re-introduced as a series of individual logs. There are two basic re-introduction philosophies: anchored (Ontario Streams, 1998) and unanchored (Booth *et al*, 1996). Placement of anchored individual debris might be the preferred method in areas where there is concern over the potential for negative impacts of log jams or debris accumulations. The common concerns are increased flooding, impediment to fish passage, catastrophic failure during floods that causes severe channel erosion (DeBano and Heede, 1987), or drift accumulations on bridge piers (Diehl, 1997). The need for anchoring depends to a large extent on the likelihood of debris movement, which is largely dependent on stream power, log length and channel width. Hilderbrand *et al.* (1998) found that logs longer than the bankfull channel width were significantly less likely to be displaced than logs shorter than this width. Ontario Streams (1998) found that streams wider than 7 m transported debris less than 10 m in length to sites of accumulation, while trees longer than 10 m were stable if securely anchored to the river bed or bank. Unanchored debris is placed in streams with the expectation that it will be re-orientated and relocated through natural fluvial processes (Booth *et al.,* 1996).

Cross-stream logs are normally placed in small to moderate-size streams and rivers (5–20 m wide) for the purpose of providing habitat for fish and macroinvertebrates, both directly, and indirectly through the morphological structures that are created by local hydraulic interactions. Ontario Streams (1998) warned against attempting to place debris in actively eroding streams with high bedload transport. Woody debris occurs naturally at loadings of between 0.001 and 0.1 m^3/m^2 in relatively undisturbed streams and rivers. The spacing of debris is variable, ranging from one log per kilometre to more than one log per metre in lowland rivers (Gippel *et al.,* 1996a). Ontario Streams (1998) noted that a density of 12–15 logs per 100 m was not uncommon. V.A Poulin & Associates (1991) re-introduced debris at a spacing of one structure for every two bankfull channel widths, based on Hogan's (1986) observations of debris density in small undisturbed streams in the Queen Charlotte Islands, Canada. Debris is orientated at a range of angles to the flow. In larger rivers, the debris tends to be orientated downstream to the flow, at a median angle of around 20–40° to the flow direction (Gippel, 1995). There is little information regarding the natural position of debris in the channel, but higher loadings would be expected close to the banks, as this is both the source of debris and an anchor point.

There are four main philosophies for placement of debris within the channel:

- essentially random log placement (Booth *et al.,* 1996; Hilderbrand *et al.,* 1998);
- placement based on ideas of how to manipulate habitat (V.A. Poulin & Associates, 1991; Hilderbrand *et al.,* 1998);

- placement to mimic natural analogs (Booth *et al.,* 1996); and

- placement to minimise the hydraulic impact on the stream with respect to the magnitude of the afflux generated (Gippel *et al.,* 1996b; Gippel *et al.,* 1998).

Random placement is carried out with the expectation that the debris will be relocated by subsequent high flows. Creation of specific habitat features (such as pools) through strategic debris placement is not well understood, and trials report variable results (eg. V.A. Poulin & Associates, 1991; Hilderbrand *et al.,* 1998).

For hydraulic efficiency, debris should be orientated approximately 20–40° to the flow. In terms of hydraulic considerations, there is little difference between upstream and downstream orientation, but downstream orientation is more common in nature. In lowland Australian streams the root wad generally faces upstream and the trunk downstream. (Gippel *et al.*, 1996a; Gippel *et al.,* 1996b; Gippel *et al.,* 1998). Hydraulic effects can be reduced by placing debris in zones of low velocity. Ideal locations are along the channel margin or the inside of meanders or in pools (Gippel *et al.,* 1998). Debris that occupies less than 10% of the channel cross-sectional area has only a minor effect on the water surface elevation at bankfull flows. Higher blockage ratios can cause localised flooding (Gippel *et al.,* 1996b; Gippel *et al.,* 1998).

1.4.3. Anchored logs

Individual logs can be anchored to bedrock, boulders or other stable substrate using anchor pins or cable (Ontario Streams, 1998). The minimum size of debris suitable for re-introduction is 0.3 m diameter and 3 m length (Ontario Streams, 1998). Murphy and Koski (1989) preferred logs greater than 0.6 m in diameter, explaining that smaller debris is too easily transported to form stable habitat, and longevity of debris is directly proportional to diameter. In general, the larger the river, the larger is the debris that is needed to form stable accumulations (Bisson *et al.,* 1987).

Skaugset *et al.* (1994a) found that large logs (0.7 m diameter) placed perpendicular to the flow and flush with the stream bed (termed 'spanners') were the most effective in pool formation. For habitat creation in small, steep, degraded streams, V.A. Poulin & Associates (1991) rated the single cross-stream log orientated diagonally to the flow and obliquely angled to the bed as the most efficient structure in terms of cost–benefit ratio. The most manageable and effective logs were 0.4–0.6 m in diameter and spanned the width of the channel.

Branches and root wads increase the complexity of hydraulic interactions, potentially increasing the range of habitat available (V.A. Poulin & Associates, 1991). Branches tend to trap other items of debris, so if this is undesirable, then the branches should be orientated downstream (Ontario Streams, 1998). Booth *et al.* (1996) reported that re-introduced debris with complex geometry was more effective than simple cylindrical logs in reducing sediment discharge in unstable channels.

Ontario Streams (1998) recommended the use of aircraft cable and buried T-bar posts as anchors. Their preferred configuration was to allow the log to float above the bed. Millar (1997), Slaney *et al.* (1997) and D'Aoust (1998) provide design guidelines for the mass of ballast required when anchoring debris of various diameters and lengths with boulders. For example, a single log 0.5 m in diameter and 10 m long requires 3,600 kg of ballast. The mass of ballast required is halved if one end of the log is anchored to a tree or stump on the bank (D'Aoust, 1998). V.A. Poulin & Associates (1991) used discarded logging cable to attach debris to stumps or live trees on the bank, or to 'deadmen' buried in the substrate. The deadmen were made from pieces of debris 0.2 m in diameter and 2 m in length, buried to a depth of 2 m. They also recommended burying the upstream end of the log flush with the streambed elevation, or lower, and the downstream end with half of the log below the bed or lower.

1.4.4. Unanchored logs

There are no guidelines available for re-introduction of unanchored debris. Booth *et al.* (1996) determined the size of material and the number of logs per unit length of stream on the basis of published descriptions of debris characteristics in undisturbed streams. The debris was placed in the stream with the expectation that it would be re-organised naturally when subjected to high flows. Hilderbrand *et al.* (1998) found that logs shorter than the bankfull channel width moved more frequently than logs that were longer than the channel width. Long logs moved less often than short logs, but once entrained, they tended to move further downstream (Hilderbrand *et al.,* 1998).

1.4.5. Pendants or sweepers

Pendants or sweepers are whole trees anchored by the base to a stump, steel post or deadman on the bank. Cables are used for the anchoring. The single point of attachment allows the sweeper to move up and down with flow variations. Naturally occurring sweepers (sometimes termed submerged brush shelters) are common in the upper reaches of Ontario streams (Ontario Streams, 1998). Whole trees provide a wide range of hydraulic habitat, and the branches tend to collect fine organic debris, further adding to the habitat complexity. These structures are intended to attract juvenile fish by providing dense cover and a rich food supply (Ontario Streams, 1998).

Sweepers are also used for protecting streambanks from erosion. Henderson and Shields (1984) reported successful use of sweepers (they termed them 'pendants') that were placed in an overlapping configuration, cabled to the bank and to each other. This debris was designed to withstand velocities of 1.5–2.4 m/s. In another application, sweepers 10–15 m in length were placed 10 m apart, some being angled downstream from the bank, and others placed perpendicular from the bank (Henderson and Shields, 1984).

Sweepers are versatile because they can be used in streams with widely fluctuating water levels and significant bedload transport (Ontario Streams, 1998). They can be placed on the outside of meander bends or on straight reaches. Ontario Streams (1998) recommends a minimum butt diameter of 0.15–0.40 m and minimum length of 4 m, with a high number of branches being desirable.

1.5. Multi-element debris structures

1.5.1. Clumped debris

Widely spaced individual items of debris have a much greater hydraulic effect on the flow (in terms of elevation of the water surface profile) than does a series of closely spaced logs (preferably within 1 diameter spacing) located on the bed (Gippel *et al.,* 1996b; Gippel *et al.,* 1998). Debris can be positioned close together in low clumps to produce a streamlined long profile shape. A series of closely spaced, progressively smaller logs upstream and downstream of a large log will provide a more streamlined shape (Gippel *et al.,* 1996b; Gippel *et al.,* 1998).

1.5.2. Log arches

Log arches are triangular structures comprising two logs angled diagonally to the flow, with the upstream ends cabled together in the centre of the channel and the two downstream ends anchored on opposite banks. A cross-brace can be added to the downstream end of the structure if effective anchoring cannot be achieved. The apex of the structure is excavated into the stream bed, flush with the surface of the bed, with the downstream butt ends buried halfway into the stream bed. These ends are further secured by cabling them to stumps, trees or deadmen on the banks. A deadman is buried 2 m deep into the bed to anchor the apex of the arch (V.A. Poulin & Associates, 1991).

Millar (1997), Slaney *et al.* (1997) and D'Aoust (1998) provide design guidelines for the mass of ballast required when anchoring log arches of various diameters and lengths with boulders. For example, up to 6.63 tonnes of ballast may be required to secure a structure made from logs 0.5 m diameter and 10 m in length if it is not anchored to the bank.

V.A. Poulin & Associates (1991) found that, compared with single cross-stream logs, log arches were more difficult to build, and prone to unsatisfactory performance in term of pool development. The main application of log arches is in situations where the stream is too wide to span with a single log.

1.5.3. Engineered log jams

Abbe and Montgomery (1996) showed that natural accumulations of debris in log jams in large alluvial channels could be extremely stable, with life expectancies exceeding those of many river engineering projects. Debris accumulations appear to be more common in undisturbed rivers in the Pacific Northwest area of the US than they are in lowland Australian rivers. This partly explained by the historical removal of log jams from Australian rivers, but it is also possible that individual logs in Australian streams are less prone to downstream transport due to their relatively high wood density (commonly >1,000 kg/m^3) and prominent branches that can become buried in bed sediments. However, log jams do occur in Australian streams. Early explorers of the Murray, Murrumbidgee and Darling rivers often commented on the density of snags in these rivers, with one surveyor encountering "perfect walls of timber" (Lloyd, 1988, p. 87–88). There is currently a large log jam on the Ovens River, Victoria (J. Koehn, pers. comm.), and there is a 30 km long raft of timber on the Gwydir River downstream from Moree (McCosker and Duggin, 1993).

Abbe *et al.* (1997) used the characteristics of naturally occurring stable log jams, combined with geomorphic and engineering principles, to develop design guidelines for engineered log jams (ELJs). These structures are appropriate in large lowland rivers, and are designed to provide habitat and to protect banks from erosion. ELJs are best placed next to pools on the outside bends of meanders and along the banks of deep runs (Ontario Streams, 1998).

Design of stable and functional ELJs requires consideration of the factors that apply to individual LWD elements, plus some additional factors.

- Rootwad diameter:bankfull discharge water depth > 2 (Abbe *et al.,* 1997).
- Log diameter:bankfull discharge water depth > 0.8 (Abbe *et al.,* 1997).
- Trunk length:rootwad diameter > 3 (Abbe *et al.,* 1997).
- Place the largest logs close to the bank to absorb the erosive energy of the current (Ontario Streams, 1998).

Position one or more key members parallel to the flow, with an attached rootwad facing upstream. Various forms of log jams exist. All types of log jams usually have one or more key members orientated parallel to the flow, and they invariably have an attached rootwad facing upstream (Abbe and Montgomery, 1996).

The key member should be partially buried to provide stability to the structure. Additional debris should be racked on top of the key members placed at various orientations to the flow (Abbe *et al.,* 1997).

The key member and front edge of the ELJ should be attached to logs (deadmen) that are anchored and keyed into the bank, and which extend out to the front face of the structure. These deadmen should face into the bankfull current, be spaced about 2.5 m apart, and be at least 4–5 m in length and 0.3 m in diameter (Ontario Streams, 1998).

- The length of an ELJ is site dependent, but varies from 5–30 m (Ontario Streams, 1998).
- The ELJ should not block more than 25% of the low-flow channel (Ontario Streams, 1998).
- The ELJ should taper up to the bankfull channel elevation such that it does not impede higher flows (Ontario Streams, 1998).

1.5.4. Bank revetments and protection

Tree revetments are a relatively inexpensive form of bank protection. They can also provide suitable habitat for fish (Gore and Johnson, 1980; Swales and O'Hara, 1980; Wesche, 1985).

These structures are made from whole trees cabled together and held in place with rock and/or deadman anchors buried in the bank (Swales and O'Hara, 1980; Henderson and Shields, 1984; Wesche, 1985; Johnson and Stypula, 1993). In the Tanana River, Alaska, a revetment comprising 51 groups of single and multiple trees was assembled on the bank, anchored to deadmen, and then pushed into the stream. The current carried the structure a short distance downstream and then swung it into the bank (Henderson and Shields, 1984). Trees lacking root clumps were less effective than those with root clumps, because they tended to float away from their original position.

Tree revetments are pervious, so they can trap sediment. However, because the timber is subject to wetting and drying, tree revetments have a limited life and must be replaced periodically (Johnson and Stypula, 1993). Henderson and Shields (1984) estimated an effective lifespan of 10 years for conifer revetments in Wyoming. For adequate protection of banks on large rivers, the revetments should be made from bushy trees with a diameter of approximately 0.3 m (Wesche, 1985; Johnson and Stypula, 1993). Wesche (1985) reported that a tree revetment in Oregon reduced mean water velocities near the bank by about two-thirds, and silt deposits 0.6 m deep occurred during the first year of placement.

Logs placed at an upstream angle to the flow can enhance bank stability. Placing logs at an upstream angle to the flow deflects flows at right angles to the log, away from the bank and towards the centre of the stream. A series of logs so placed can shift the thalweg away from the toe of the bank, thereby enhancing the stability of the riverbank on the outside of meander bends (Johnson and Stypula, 1993).

Logs placed at a downstream angle to the flow in shallow water can sometimes result in bank erosion immediately downstream. Placing logs at a downstream angle to the flow in shallow water can result in localised turbulence (and scour) around the end of the log, and higher velocity flow can be directed into the bank immediately downstream of the log (Johnson and Stypula, 1993).

A bank protection technique commonly used in California is to incorporate logs into rock toe constructions. Logs are combined with construction of a rock toe, such that the rear of the trunk is keyed into the bank in a trench, and the middle and outer (closest to water) parts of the trunk are incorporated into the rock toe construction. This construction technique is commonly used in King County, Seattle, Washington (Johnson and Stypula, 1993). In this area, experience has shown that bank stability is enhanced by placing the rootwad facing upstream into the flow, such that the snag is orientated at an upstream angle to the flow.

1.6. Selection and sourcing of materials

Selection of debris for re-introduction into streams is often limited by availability. Logs 6–12 m in length and 0.3–0.8 m in diameter are generally available from commercial logging operations, but they lack rootwads and branches (Booth *et al.,* 1996). ELJs can be constructed largely from logged timber, without branches or large root wads, thereby reducing sourcing and transport costs. Rootwads without significant trunks are sometimes available from land clearing operations (Booth *et al.,* 1996).

Avoid introduced species such as (in Australia) willows and poplars, as they decay rapidly and are inappropriate for invertebrate and biofilm colonisation. In North America, western red cedar (Thuja plicata) and Sitka spruce (*Picea stichensis*) have a greater longevity than cottonwood (*Populus balsamifera*) or red alder (*Alnus rubra*) (Johnson and Stypula, 1993; Abbe *et al.,* 1997). In south-eastern Australia, river red gum (*Eucalyptus camaldulensis*) has a lower decay coefficient than mountain ash (*Eucalyptus regnans*) (Bootle, 1991). Trunk diameters greater than 0.3 m are preferred, because they will have greater longevity than smaller pieces (Murphy and Koski, 1989), and they are stronger and less likely to fail structurally during large floods.

Fallen debris already present on the floodplain or in the riparian zone should not be transferred to the stream, as it performs important functions for the terrestrial environment (Harmon *et al.,* 1986). Zapzalka (1997) reported a study in which a tree-thinning experiment was conducted in six riparian areas in Oregon and Washington. Two-thirds of the conifers at each site were cut, while the other third were left as controls. The cut trees were re-introduced to the streams as woody debris. Rates of growth in both diameter and height had increased in treated areas three years after the canopy was thinned, while an increase in only diameter occurred in untreated areas (control areas). Three-year mean diameter growth was 17 mm in areas where the overstorey was removed compared with only 6 mm in the untreated areas. This study showed that releasing conifers in small clearings in riparian zones enhanced conifer survival, thus helping to contribute to a future supply of conifers to the nearby stream. This process can significantly contribute to stream rehabilitation and improve fish habitat (Zapzalka, 1997). Richmond and Fausch (1995) warn that removal of riparian trees for placement into streams can result in soil erosion.

1.7. Planning and undertaking works

Complete in-stream LWD restoration before beginning riparian restoration. It is inefficient to revegetate the riparian zone, only to destroy that work by dragging large logs over the top on their way to the stream.

Work should be done during environmentally less sensitive periods (eg. not during known periods of fish spawning) and periods that are likely to present logistical difficulties, such as high-flow months (Shields and Nunnally, 1984). House *et al.* (1989) reported that soil compaction can result from the use of heavy equipment in debris re-instatement. Rubber-tyred hydraulic cranes (Booth *et al.,* 1996), skyline yarding equipment (Skaugset *et al.,* 1994b) and helicopters (Booth *et al.,* 1996) are alternative methods of placing debris in streams. In this respect, ELJs have an advantage over scattered individual LWD elements because damage to banks during emplacement is restricted to a smaller number of locations.

Recently published Australian snag management guidelines (Gippel *et al.,* 1998) recommend that snag re-introduction proposals should be treated like any other development proposal. The proposed work could require an environmental impact evaluation and public review. This can be confirmed by the local council. As a minimum, the proposal should be prepared with a clear set of objectives, supported by hydraulic calculations.

> **Note:** Reinstating LWD to streams can have consequences for other values of the stream. *Other effects of reinstating large woody debris*, below, discusses the effect of returning snags to streams on bed and bank erosion, flood levels, and navigation.

1.8. Conclusion of LWD reinstatement techniques

Debris re-introduction is now accepted as an integral component of stream rehabilitation programs. In many cases it is the highest priority action, because of perceived high benefit–cost ratios and the rapid improvement in habitat availability that can be achieved. It should be remembered that re-introduction of debris will not necessarily result in ecological improvement in terms of increased fish abundance or diversity, because there are many other factors that could act to limit fish populations. Guidelines for re-introduction of large woody debris are scattered throughout the literature, and some are readily accessible on the Internet.

In general, the objective should be to reinstate the natural woody debris loading in a way that mimics the natural range of sizes and orientations. In some highly modified streams this may not be possible, in which case the priority might be channel stability or re-creation of lost morphological habitat features. The general rule for small streams appears to be to either place a range of debris in the channel and allow the stream to reorganise it, or install a series of individual logs obliquely spanning the channel and anchored securely on both banks. Anchoring is likely to be less of an issue in Australia than overseas, because Australian timber is more durable, dense, and inherently more stable.

Large rivers require a different approach. The risk of debris being transported from the site during large floods and possibly accumulating in undesirable downstream locations (such as bridge piers) means that debris should be securely anchored. Clumped debris is more hydraulically benign than scattered individual elements, so is the preferred configuration where flooding is a sensitive issue. Engineered log jams have several advantages over scattered individual elements. These advantages include: restriction of bank damage during emplacement to a small number of locations; log jams are a known focus of biological activity; ELJs provide bank protection, so that the requirement for rock protection can be eliminated or minimised, thereby reducing costs; ELJs are inherently stable structures; and ELJs can be constructed largely from logged timber, without branches or large root wads, thereby reducing sourcing and transport costs.

2. Other effects of reinstating large woody debris

(The following section was compiled by the editors)

Reinstating LWD brings three main secondary consequences for other users of the stream: increased bed and bank erosion; higher flood peaks and durations; and problems for navigation. The magnitude of these effects should be assessed in any plan to reinstate LWD to streams.

2.1. LWD and channel erosion

2.1.1 Some general principles of LWD and erosion

As with any object placed in a stream, there will be scour associated with placing LWD into a stream. Much of the bed scour will be considered welcome habitat. It is usually the bank erosion that is of most concern to managers.

The following discussion of LWD and channel erosion applies equally to natural logs in the flow, and logs placed artificially in the flow. LWD can both increase and decrease local bank erosion by:

- providing flow resistance in the channel that reduces average flow velocity, so reducing erosion;
- increasing flow velocity around the snag, thereby directly increasing bank scour;
- deflecting flow away from the banks, thereby directly decreasing bank scour;
- directly protecting the banks and reducing erosion; and
- increasing local bed depth and consequently increasing local bank erosion by slumping.

Whether a given piece of LWD will increase or decrease erosion depends on: the orientation and size of the obstruction; the velocity and depth of flow; and the character of the bed and bank material. Most of these variables are in some way controlled by the size of the stream. As a result, LWD tends to have less effect on large streams that have resistant banks.

Not all erosion is bad. Scour of the bed, and undercutting of the banks, is essential for producing the 'hydraulic diversity' required for habitat in a healthy stream. Natural streams are lined with undercut banks.

Trees usually fall into a river during floods. By the time erosion around a fallen tree is noticeable, there is a good chance the bank erosion from the LWD is almost complete. It is probably reasonable to assume that the erosion around LWD follows a negative exponential curve. This means that, if the same-sized flood occurred on a given stream twice in a row, the second flood would cause much less erosion around the same piece of LWD than did the first flood. Put another way, the flow velocity or duration of the second flood would probably need to be much greater to generate the same amount of erosion as occurred in the first flood.

As a rough guide, erosion around an obstruction will usually remove an amount of material equivalent to no more than one or two times the projected area of the obstruction (that is, the area of the obstruction as seen from the front). This is because the erosion is unlikely to proceed once the cross-section has re-established its original velocity profile. For example, if a log has a projected area of 5 m^2, then the erosion around the log is much more likely to remove a total of 5–10 m^2 of the cross-section, than say 50 m^2.

2.1.2. Flow deflection by logs

Flows passing over a log will be redirected across the top of the log, roughly at right angles to it (Figure 52). This effect has been shown by research on deflectors (Hey, 1994), and on bendway weirs (Derrick, 1997). Spur-dikes directed upstream have been found to be more effective in protecting streambanks than those in other orientations because of this redirection (Kehe, 1984). The redirection tends to decrease as the log becomes more parallel to the flow and is at a maximum at an angle of about 45° to the direction of flow. The strength and direction of the redirection around logs is poorly understood, and is the subject of research.

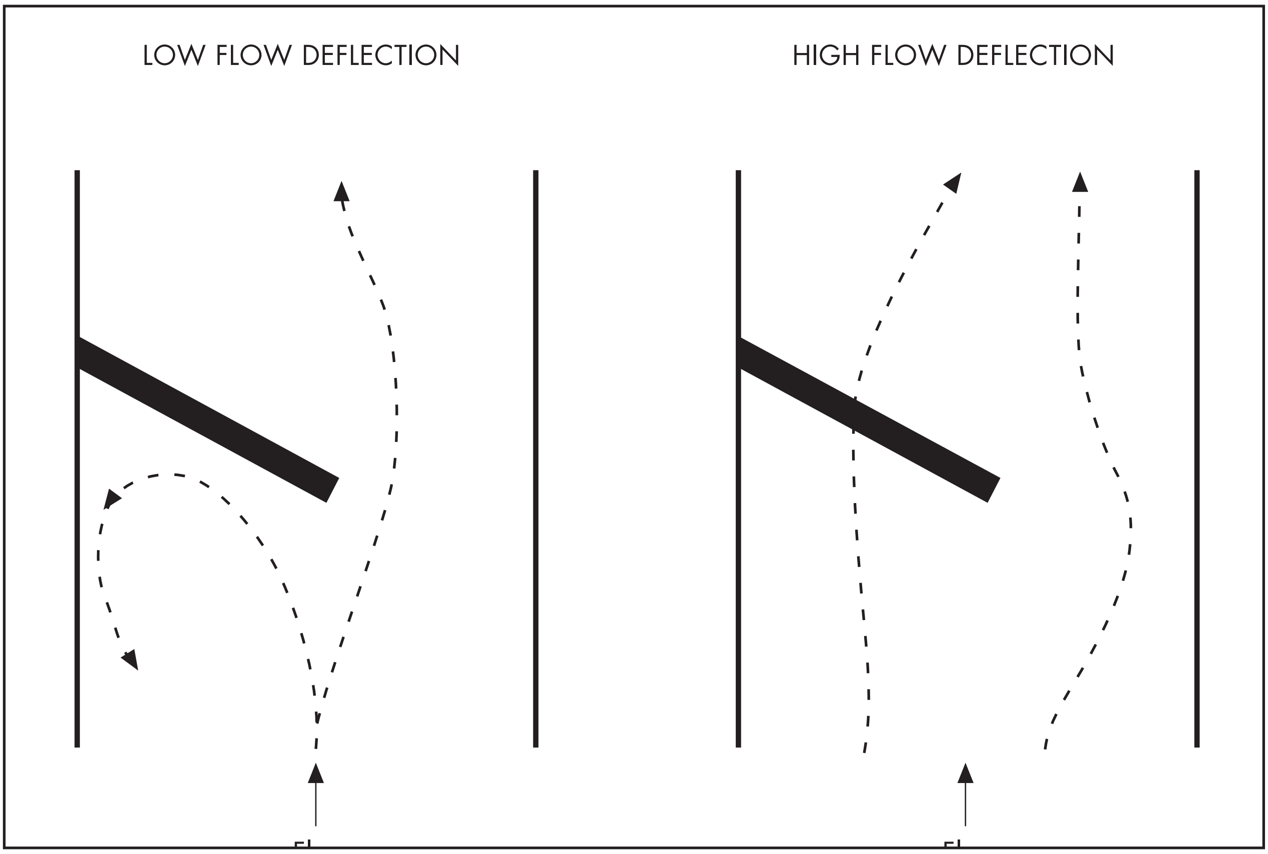

Figure 52. Deflection of flow across a snag at high and low flows.

It is important to always think about the effect of a snag at a range of flows. It is possible that at low flows a snag will deflect flows in the opposite direction to that at high flows.

This deflection angle means that the common perception that a log orientated with its tip pointing upstream will cause more scour on the opposite bank (ie. by deflecting flow across the channel) will seldom be true. In fact, at high flows it is likely that a log orientated upstream will deflect flow away from the opposite bank. Scour of the adjacent bank is usually caused by the following three mechanisms which are not strictly a function of flow deflection:

- high-velocity flow over the top of the log, and under the log, at high flows;
- scour of the scallop left in the bank when the tree and its rootball fell into the channel; and
- deepening of the bed around the log leading to bank failure because of the greater bank height.

The amount of flow deflection produced by debris in a channel is often over-estimated because of what appear to be 'deflection-lines' flowing across the surface of the water, away from the end of a log. These lines of flow often extend right across the channel. In fact, these surface flows do not reflect the true deflection around the log within the water column. This has been confirmed in recent flume experiments on groynes (Dyer *et al.,* 1995) which show that water is deflected only a small amount across the channel.

There is an infinite variety of snag sizes and orientations, producing a similar variety of erosion. The variables include the relative size of the snag to the stream, the length and diameter of the snag, and its vertical and horizontal orientation. It is important to note that the effect of a snag on a bend will differ from that of the same snag in a straight reach because of the effect of secondary circulation in the bend.

2.1.3. Size of the river and erosion from LWD

As a general rule, in most Australian streams, the effect of LWD on erosion decreases with the size of the channel. This can be demonstrated by considering the general planform of the channel. Although LWD is often randomly distributed in larger stream channels, and often at high natural densities, larger channels retain their general meandering characteristics. That is, the planform is not controlled by the LWD, which is at most a secondary impact on erosion processes. The same is not true of LWD in smaller streams. There is much literature (mostly from North America) that demonstrates how LWD accumulations control the morphology of small headwater streams by producing large jams and accumulations of debris.

2.1.4. Some guidelines for managing erosion from snags

- LWD can be located so as to reduce bank erosion.
- When placing LWD into a stream, the erosion effect depends upon the size of the debris relative to the stream, and the position in the stream. If the projected area of the piece is less than 10% of the cross-sectional area, it is unlikely to cause anything but minor local erosion.
- Several pieces of LWD placed close together (as described above), with one end attached to the bank, will behave like partial-width bank protection (see Partial width bank erosion control, above). This means that they will tend to protect the banks from erosion.
- Estimate the maximum erosion that could be expected before 'managing' a snag. As a crude rule of thumb, the cross-sectional area of erosion around a snag will be ±100% of the 'projected-area' of the obstruction.
- There will almost always be bed scour at the tip of a log, and on the downstream side of the log. The amount of erosion will increase the more the log interferes with the flow.

In general the total amount of erosion caused by snags tends to be small and localised.

2.2. Effects of LWD on height and duration of flooding

As usual, the most cost-effective approach to rehabilitating the LWD in our streams is not to remove the natural LWD that remains in the streams. There is still pressure from various groups to remove LWD from streams in order to reduce flooding and bank erosion. LWD blocks the channel, increases hydraulic roughness, and so can influence the capacity of a channel. These issues are discussed in Gippel *et al.* (1992), Gippel (1995) and Gippel *et al.* (1996b).

LWRRDC has also produced snag guidelines. Here we will provide a little more detail from the above publications. The hydraulic effects of removing LWD can be considered as the inverse of putting the timber back into the stream.

Considering how much desnagging has taken place in Australia, it is surprising how little evaluation there has been of the effectiveness of the work. The little evaluation that there is suggests that removing major blockages can reduce flood levels, but most often because the snags stabilise the channel. When the snags are removed the bed deepens and the channel widens. Small streams will be more affected by desnagging than large ones.

2.2.1. Flooding following the de-snagging of large streams

The following examples illustrate the effect of desnagging large streams.

One of the major desnagging exercises in recent decades has been the removal of some 25,000 large river red gum snags from the Murray River between Hume Weir and Yarrawonga in order to increase irrigation flow conveyance (cost about $3 million) (MDBC, 1988). Evaluation of the work has suggested a 10% increase in conveyance, but this is questioned by other analyses (Gippel *et al.,* 1992) which suggest no measurable effect.

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

Gippel *et al.* (1996b) also modelled the effect of LWD in the Lower Thomson River, Victoria and found that 96 items of woody debris in the channel did not produce a measurable effect on the height of bankfull flow.

Thus, removing major debris accumulations can increase channel conveyance, but at high flow the effect would be trivial in most cases. However, it is also important to note that stream channels can deepen and widen following de-snagging, in part because the snags protect the channel from erosion. This increase in capacity can lead to substantial increases in channel capacity.

It is important to note that, if flood conveyance is increased in a reach following de-snagging, then the reach downstream will probably experience an increase in flooding. For example, on the Wimmera River, north-western Victoria, a short reach of stream was bulldozed clean of all vegetation and snags over a length of about 2,000 m, and the channel enlarged. The works had the desired effect of reducing the flood duration on six adjacent properties, but the stream management agency are now assessing applications from landholders immediately downstream of the treated reach (whose properties are now being more flooded) to desnag their reach of river. The process will continue until all of the LWD is removed from the stream. Clearly, it is better not to start the process.

Recall (from *How changing the channel can affect flooding,* in Natural channel design, this Volume) that de-snagging will have absolutely no effect if it is carried-out in the backwater of a larger downstream flow obstruction, such as a bridge.

2.2.2. Effect of removing individual logs

Recent research has shown that removing single logs from a stream will have little effect on flood stage (Gippel *et al.,* 1996b). This will not be true if the tree is very large in relation to the channel. A rule of thumb is that a log is not likely to have a measurable hydraulic effect if it does not occupy more than 10% of the area of any given cross-section. Ten percent actually represents a quite high density of timber.

For example, in a 30 m wide channel, 2 m deep, a log 20 m long and 1 m in diameter (ie. blocking one third of the channel area), in a flow of 1.5 m/s, causes a 5% increase in water surface elevation (100 mm). This is a surprisingly small effect when you picture the relative size of the log.

Three hydraulically independent items of debris angled at 20–30° produce a combined afflux about the same as a single log of the same dimensions, orientated perpendicular to the flow (Gippel *et al.,* 1996b). Another way of saying this is that the flood effect of a log is proportional to the projected area that the log presents to the flow, so three logs at 20° have the same area as one log going right across the channel (Figure 53).

Several pieces of debris in line will not produce any more afflux than a single piece, so long as each piece is located within two times the diameters of the next piece upstream. Figure 54 shows that up to six pieces can be placed in a line. In general, any piece of debris will add little extra afflux if it is placed within four diameters of the next piece upstream.

The higher the flow velocity, the greater the impact of LWD on flood stage. Thus, placing debris away from the centre line of the channel (on channel edges and point-bars) will improve channel capacity, but this could also lead to scour of the channel thalweg.

Gippel *et al.* (1996b) describes a methodology for predicting the afflux associated with given pieces of debris in a stream. This can be used to predict how much flood benefit you will get by removing LWD. A more sophisticated approach to predicting the flood impact of LWD is provided in Shields and Gippel (1995).

2.3. Navigation

A large proportion of the snags in our lowland streams were removed in order to provide boat access. Returning snags to streams will affect navigation for some boats. It is particularly important to consider speed-boats, water skiers, and canoeists. Hitting a log can be fatal for water-skiers, as can being stuck under a log for canoeists.

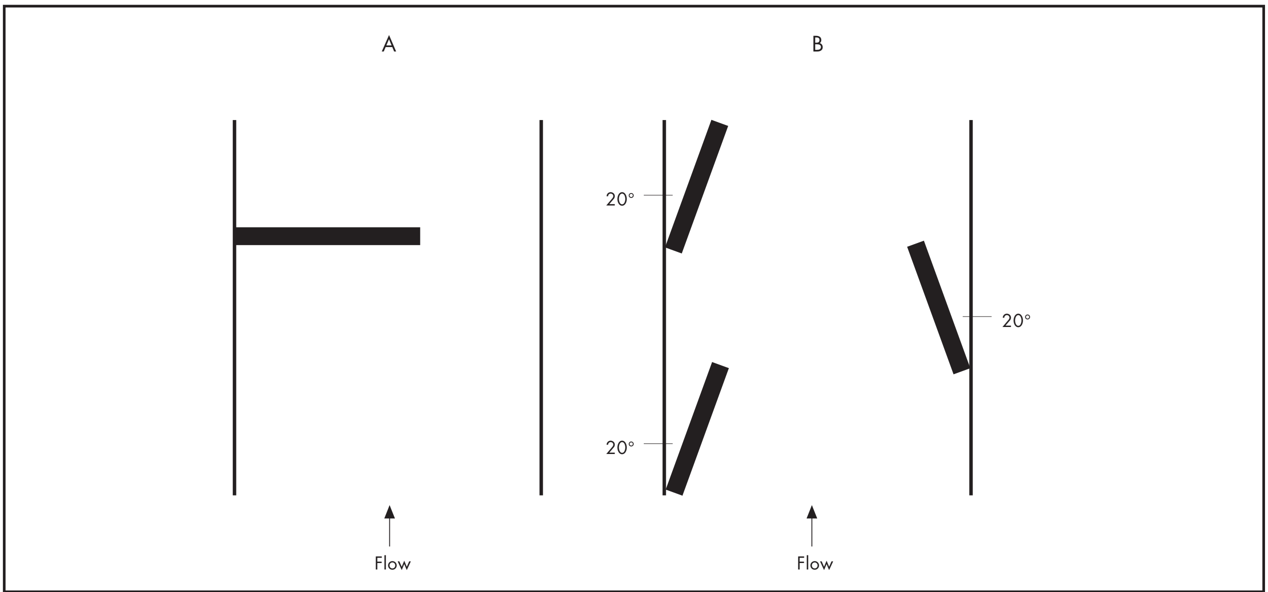

Figure 53. The effect of woody debris on flood levels depends on the logs' projected area to the flow. The three angled logs have the same effect on flood levels as the single log.

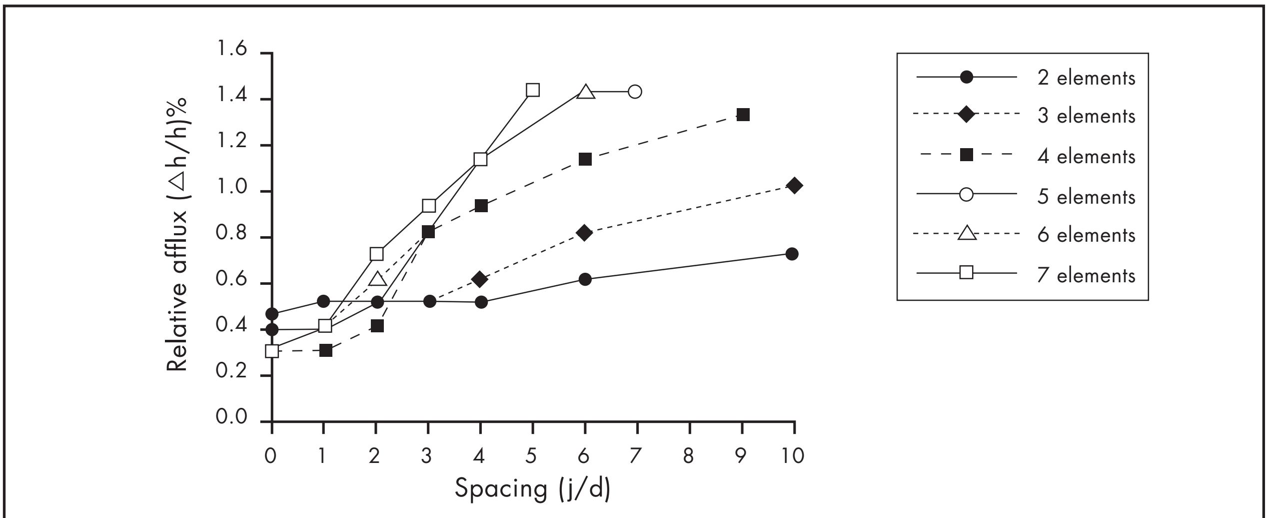

Figure 54. The rise in water surface level (afflux) caused by cylinders positioned next to each other in a line. The change in water surface level depends on the spacing of the cylinders (from Gippel *et al.,* 1996b). Reproduced with permission from John Wiley & Sons Ltd.

SAND AND GRAVEL EXTRACTION AS A REHABILITATION TOOL

Key points about sand and gravel extraction for rehabilitation

- Sand and gravel extraction from stream beds will usually damage natural values of the stream. It is only in rare circumstances that extraction can contribute to the rehabilitation of streams. Outside of these circumstances, instream extraction should be prohibited.
- Extraction may be beneficial where streams have been aggraded (that is filled progressively for at least 5 years) with slugs of sediment that have come from human disturbance. Even in these circumstances, extraction should be contemplated only with professional advice.
- Sediment should be extracted only from reaches in which the aggrading sediment has come from outside of the reach (ie. the sediment has not come from erosion of the bed or banks within the reach), and the channel has not adjusted to the influx of sediment by eroding.
- Annual bedload transport rates cannot be used as a measure of an environmentally benign extraction rate. However, they are a useful starting point for assessing the effects of extraction.
- A very fast extraction rate could lead to rapid erosion of the banks. A slower rate allows the banks to batter back gradually, and grass can become established.

Mining sand and gravel from stream beds is one of the two major extractive industries reliant on rivers. The other is water extraction. Sand and gravel from streams are sought after by industry because the sediment is usually well-sorted, clean and easy to extract. At least two million cubic metres of sand and gravel are extracted from non-tidal Australian streams each year, with the majority coming from streams in northern New South Wales and southern Queensland (Rutherfurd, in press). Extraction rates from non-tidal streams are generally declining, except in Queensland. Extraction from Australian streams must be considered in the light of an increasing amount of research that is identifying the low natural rates of bedload transport in our streams compared with streams in the northern hemisphere (Hean and Nanson, 1987).

Sand can be extracted by:

- dragline (where sand is extracted with a large bucket that is dragged across the bed);
- bulldozer (where sediment is pushed-up from the dry bed of streams); or
- suction dredge (where the sand is hydraulically sucked from the bed).

It is usually stockpiled in large heaps near the stream banks (see Figure 55).

In most cases, sediment extraction causes some damage to stream systems, although in rare circumstances it can be beneficial to the rehabilitation of the stream. In this section we are interested not in the economic value of extracted sediment, but in the potential environmental benefits of extraction. We call this 'environmental extraction'. This section of the manual describes the environmental impacts of sand and gravel extraction, and the rare situations when extraction can be encouraged on environmental grounds.

Figure 55. A sand extraction operation on the Mary River in Queensland.

Despite many claims to the contrary, the commercial extraction of sand and gravel from streams only rarely provides environmental benefits to the stream. From the perspective of rehabilitation, the precautionary principle should apply to future extraction. That is, unless it can be shown that the extraction will cause no environmental harm, it should not be allowed. Because almost all extraction must be licensed by State governments (even from privately owned streams), there is a good opportunity for regulation of extraction from streams.

Extracting sand and gravel from stream beds has the potential to severely damage streams and should be contemplated only with professional advice.

1. Erosion effects of extraction

Extraction leads to bed degradation both up and downstream of an extraction hole. The process is well described by Galay (1983), Pickup (1975) and Lee *et al.* (1993) and is summarised in the following three points and in Figure 56.

1. The hole will begin to fill with sediment coming from upstream (the normal bedload of the channel). The proportion of the bedload sediment trapped in the hole will depend upon how large the hole is relative to the stream (ie. the trap efficiency of the hole).

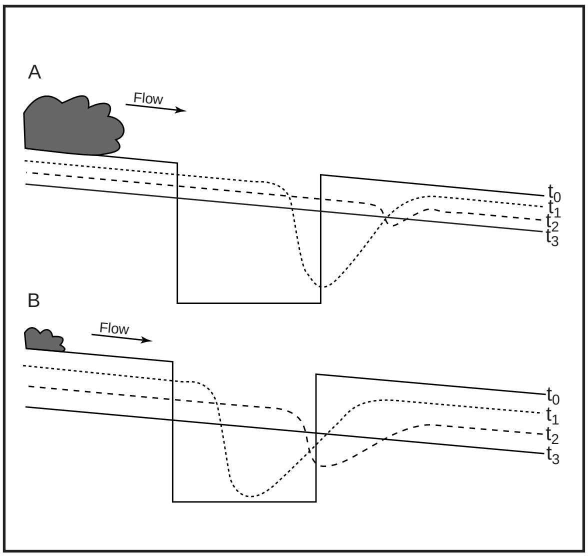

Figure 56. Schematic effects of extracting sediment from a stream bed. In A, where there is a large sediment load, the pit migrates downstream, but overall bed lowering is small. In B, where the sediment load is small, the pit fills slowly, and the bed lowers considerably.

2. Because bedload is trapped in the hole, the flow picks sediment up again **downstream** of the hole, thus leading to bed erosion downstream of the hole. The downstream erosion zone moves progressively downstream until the bed slope is reduced to the point where erosion stops.

3. If there is no downstream hydraulic control (such as a weir, constriction etc.), then the scour downstream of the hole will produce an increase in water surface slope that will then trigger **upstream** progressing erosion. The knick-point of erosion will then progress upstream until there is a smooth bed profile up and downstream of the hole. The bed will now be lowered by the same volume that has been removed from the hole.

The final effect of an extraction hole is to generally lower the bed by the same amount as was removed from the bed.

Most studies of extraction from Australian streams have demonstrated that commercial extraction rates far exceed the annual bedload transport rate. This can result in a general lowering and destabilisation of the bed, which can lead to destabilisation of the banks.

Thus, the physical impact of the extraction depends upon the bedload transport rate of the stream relative to the size of the hole. If the volume of extraction is large relative to the bedload (ie. the sediment moving across the bed) then the relative volume of erosion will also be large.

2. Secondary effects of extraction

Extraction has numerous secondary physical effects that have biological consequences. Here are some of them.

- Up and downstream bed degradation. There are many spectacular examples of bridge and culvert failures following over-extraction (eg. Galay, 1983; Kondolf, 1994).

- Bed degradation can lead to bank erosion. In one creek, the same contractor who had the commercial licence to remove sand from a stream, won the contract to cart the rock needed to stabilise the banks that were eroding as a result of over-extraction.

- Coarsening of the bed following bed degradation—the eroded bed can develop an armour layer of gravels that may be larger than the armour elsewhere in the channel. This can affect fish spawning because the particles become too large for fish to move for egg laying (Kondolf, 1994).

- Extraction can produce pools in the bed that are large relative to the average pool depth. These pools can become stagnant at low flows, with low levels of dissolved oxygen (MacDonald, 1988) and, because the pools capture suspended sediment, high nutrient loads. In lowland Australian streams, deep pools could also become saline (McGuckin *et al.,* 1991).

- Degradation of the stream bed following extraction can drop local watertable levels (this may be good or bad depending on the circumstance, eg. it may drain important wetlands, or may lower a saline watertable).

- In tidal reaches, bed lowering following extraction can push the salt-wedge further upstream and alter the tidal range and velocities (eg. in the Tweed estuary (Erskine, 1990a) in northern New South Wales/southern Queensland).

- The extraction process itself may cause many environmental problems, including damage to the riparian zone by stockpiles and tracks. The extraction can also release plumes of suspended sediment to the stream.

Extraction has direct and indirect biological impacts. These issues are canvassed in detail in a review of the cumulative biological effects in Victoria of small-scale eductor dredging (ie. small suction dredges) (Parliament of Victoria, 1994). This review concluded that the effects warranted maintenance of the ban on eductor dredging in the State.

3. Using extraction to manage sediment slugs

Many Australian streams are aggrading as a result of slugs of sediment moving through them. These slugs can be sand or gravel, and they can originate from many sources: mining, bank erosion, gully erosion, or (less commonly) catchment erosion (Figure 57) (sand slugs are described in more detail in *Sediment slugs*, in Common stream problems, this Volume). The slug migrates down the channel as a wave, and its passing at a point is seen in a rapid rise followed by a slower fall in bed level. Sediment slugs can trigger major changes of channel form as they pass, and they invariably cause ecological damage.

Figure 57. Sand aggrading the Lachlan River (New South Wales) originating from historical gully and sheet erosion.

Extracting a slug of sediment can protect downstream reaches from damage, and accelerate the recovery of the aggrading reach.

Sediment slugs can safely be extracted under the following circumstances.

- If the extraction takes only the aggraded material and does not cut into the 'original' cross-section.
- If the sediment (either sand or gravel) has 'invaded' the reach to be treated (ie. the sediment is not the result of erosion within the reach).

It is unwise to extract sediment slugs in the following situations.

- If the sediment slug is a natural phenomenon (eg. from natural erosion during floods).
- If the slug has originated from within the reach (ie. from widening or incision of the channel), then extraction could trigger new erosion. For example, widening of the Goulburn River (New South Wales) during the 1955 floods released a pulse of sand into the stream that aggraded the bed and formed benches (Erskine, 1994). In this case, the benches were essential sources of sediment for the recovery of the channel after the flood.
- If the reach in question has already adjusted to the higher sediment yield (eg. it has increased in width, or formed a sinuous channel with stable benches) then extraction could trigger further instability of the new equilibrium channel.
- Where rapid extraction will destabilise the stream (eg. rapid deepening could lead to increased bank slumping in some streams). The rate of extraction has to be slow enough to allow the stream to stabilise.

4. How do I know that the bed is aggrading?

The New South Wales Department of Water Resources (DWR, 1992, p. 26) also suggests that extraction from the stream bed should be allowed only where there is "objective evidence of recent bed aggradation". A 'sustainable' extraction rate must remove only the material that is stored in a reach (ie. the difference between reach input and output). This storage occurs:

- as bed aggradation;
- as growth of a bench within the channel (horizontal depositional surfaces below the floodplain level—see Figure 58); or
- as growth of a point bar (upward and outward).

The concept of sediment storage is entirely a function of time. That is, most sediment will eventually make its way through the system over many thousands of years. We would suggest that a reasonable definition of storage over 'management' time is:

Figure 58. A bench deposited on the Murray River. Note that it is a flat surface below the bankfull level.

> *...a persistent increase in the mean bed, bench or bar elevation over at least five years, including at least one large flood.*

This definition attempts to distinguish between seasonal or short-term fluctuations in the bed (better defined as 'scour') and persistent aggradation. Methods for identifying bed aggradation in a reach are described below.

Cross-section surveys

- Repeated cross-section surveys. It is important when comparing cross-sections to determine that it is aggradation and not seasonal scour that is being observed. This depends upon when, and how many cross-sections are surveyed. For example, in a particular stream seasonal scour may occur during winter flows, and deposition during spring flows. If the cross-sections from winter (scoured bed) are compared with those from spring, the bed of this stream will appear to be degrading.

- Cross-sections used for bridge designs are often good records because they usually show the height and structure of the bed when the bridge was constructed, providing reference points for the changes occurring. Bear in mind that scour may be higher close to the bridge.

- Specific gauge records can provide a long-term record of bed changes. This is a measure of the stage (that is water surface height) of a particular water discharge over time. This stage can be taken from successive discharge measurements at gauging stations. If the stage of the same discharge consistently rises, then the bed could be aggrading. These curves should be interpreted with caution because there are many processes that can alter the stage of a river, not just bed height (eg. width, roughness).

The morphology of the channel itself may give clues. For example, a tightly meandering channel with a uniform channel depth (ie. pools filled in) would be unusual in natural streams and could suggest aggradation.

Anecdotal evidence

There are many sources of anecdotal information that may be useful in diagnosing aggradation. For example:

- farmers may relate that they have been progressively shortening their pump take-off pipes over the years as the bed aggrades; and

- it is very common for landholders to recount that they used to, for instance, "stand on a horse's back to collect swallows eggs under this bridge forty years ago, now you can't even crawl under the bridge", or "we used to swim and fish in a large hole at that bend, that you can now walk across". It is important to attempt to corroborate such stories with other evidence because human memory is not always reliable.

5. Where to extract from?

Sediment can usually be taken from three sites: the active low-flow channel bed, the point bar (above and below low water), and from benches. Each site has advantages and disadvantages.

- Benches should not be extracted, because a proportion of sediment slugs is often deposited in benches that can then stabilise. Thus, these benches are an important part of the recovery of an aggraded stream and should not be disturbed.

- 'Skimming' from a point-bar (ie. removing the point bar above low water) will lead to downstream erosion, and might also lead to local erosion of the point-bar itself upstream of the extraction area. But point-bar extraction usually will not lead to general upstream degradation in the reach. At flows around bankfull, sediment will move across the channel from the concave bank, and replace the volume of sediment extracted from the bar. Clear water will then scour sediment from the next downstream 'crossing' (ie. riffle) and possibly from the next point-bar downstream.

- Extraction of large volumes from below the low water-level can be done from point-bars or from the active channel. Extracting from the point bar will reduce the continual plumes of sediment moving downstream.

- Extracting at the apex of bends, rather than at inflection points, could encourage the development of pools that remain clear of sand. Secondary circulation at the bends might be sufficient to keep the pool free of sand once extraction has stopped.

Whichever type of site you extract from, it is usually best to target the front of the sand wave as it moves downstream (ie. the downstream end) rather than the tail. Extracting from the front of the slug will prevent sediment moving downstream into unaffected reaches.

6. How much to extract?

It is useful to have a rough idea of the bed-load transport rate of a reach in any discussion of extraction. The bed-load is the coarser fraction of the load that moves by jumping, rolling, or sliding along the bottom. For example, if you know that a stream only carries 'Z' m^3 of sediment a year, then it is easy to evaluate an extraction proposal for 10 x Z m^3/year. Estimating bed-load is a difficult problem. Fluctuations in bed level are not always a good indication of bed-load transport rates. There are problems defining what bed-load is, let alone measuring it.

6.1. Measuring bed-load

There are four ways of estimating bed-load transport rates.

1. **Direct measurement.** There has been very little measurement of bed-load transport rates in Australian rivers. There are numerous ways to measure bed-load, but the most common is to place a device on the bed of the stream that will capture the passing bed-load. The instrument most often used is a Helley-Smith sampler designed by the United States Geological Survey. The most thorough bed-load sampling program in Australia is being carried out with these samplers in Queensland rivers (see Wong (1994) for details of the equipment used). Wong estimates that it costs roughly $30,000 to set up the equipment needed for routine sampling on one large river. It need not be so expensive on a small stream, but measurements must be made frequently and over a long period to be useful.

2. **Estimation using equations.** There are numerous equations available for estimating bed-load transport rates. The equations will give you an answer, but the problem is to validate the accuracy of the answer. In general, bed-load estimates from equations are an imprecise tool and should not be used without expert interpretation. Different models can provide results that vary by hundreds of percent and are a poor basis for decision-making. This is particularly so because the equations estimate the potential bed-load transport. This may not be realised if there is not enough supply, as is often the case in Australia (Hean and Nanson, 1987).

3. **Approximation as a function of suspended load.** In the absence of any other measure, a crude way to estimate bed-load is as a proportion of suspended load. Many streams in Australia have at least an approximate record of suspended sediment concentrations because these are much easier to measure than bed-load. Bed-load is 'normally less than 10% of the total solids load, although in non-alluvial mountain streams it may reach 70%' (Richards, 1982, p.106). A value of 10% is often quoted in textbooks. In alluvial rivers, a rule-of-thumb is that the more similar the bed load and suspended load in particle size, the higher the bed load as a proportion of the total load. Lane and Borland (1951) estimated that bed-load in a sandbed stream, with a suspended sediment concentration less than 1,000 mg/L, could be between 25% and 100% of the suspended load. The method is to:

    - create a rating curve that relates suspended load to water discharge;
    - estimate annual suspended load from the duration of flows with particular sediment concentrations; and
    - estimate bed-load as a percentage of suspended load.

You can expect errors of ±200% with this method, but it may be better than nothing.

4. **Deposition in a sediment sink.** The best way to estimate bed-load is to measure the volume of load entering some type of sink. Examples are:

    - sediment volume entering a reservoir in a given time (difficult to do in a large reservoir). Bed-load will normally fall out close to the upstream end of the weir pool. The trap efficiency depends on the size of the reservoir relative to the discharge, which can be estimated using the method of Heinemann (1981).
    - Another method is to estimate bed-load from how long it takes to fill an extraction hole below a bed-control structure of some sort (rock bar or weir). This works because the extraction hole cannot trigger upstream progressing degradation. The methods relies on the bed-load being able to move easily across the obstruction, and on the hole that it is entering being large relative to the stream width.

7. Standard rules of any extraction operation

The following issues should be considered before beginning sand and gravel extraction in any stream. Some of these guidelines are discussed in the New South Wales policy on extraction from non-tidal watercourses (DWR, 1992).

- If there are assets up or downstream of the extraction site (eg. bridges, culverts, pipe-crossings), then they could be threatened if the bed degrades. Bed degradation may cause bank erosion and thus also threaten assets such as buildings and roads.

- A good extraction site is one with up and downstream hardpoints, such as rock bars, that can limit degradation.

- Sediment should not normally be extracted below low-flow water level (ie. it should not be 'skimmed' from bars and from seasonally dry beds), except where the reach is affected by a sand slug (as discussed above). Even when undertaken above low-flow water level, sediment skimming can damage the ecology of the stream by producing a broad, shallow, low-flow channel that has little habitat potential (Kondolf, 1994).

- If the bed of the stream is armoured, then extraction of that armour layer could trigger major deepening. This is because the finer material exposed below the armour is much more easily eroded than the armour layer itself. An armour layer often denotes a dominance of transport capacity over sediment supply. Whether armour layers should be extracted depends upon how frequently they are mobilised. For example, the flows released from Eildon Weir in the Goulburn River in Victoria are insufficient to transport the sediments comprising the armour layer in the stream (Erskine and Terrazzolo, 1996). Extracting the armour layer could trigger substantial bed degradation because the sediments beneath the armour layer will then be easily moved by the flows. If, on the other hand, the armour layer is moved each year or so in any case, extraction will have less impact on degradation rates. Note that even a patchy armour layer can dramatically reduce bed-load transport.

- Where there is evidence of overall channel enlargement (ie. substantial bed and bank erosion), then extraction should not be allowed. Extraction in these circumstances can jeopardise efforts to rehabilitate streams. For example, many millions of dollars were spent 'training' the Hunter River in the 1960s and 70s in order to accelerate the recovery of the channel after catastrophic widening and erosion in the 1950s. Much of this recovery was driven by deposition of sediment in training fences. This process cannot have been assisted by the commercial extraction of hundreds of thousands of tonnes of sediment from the channel.

- Extraction increases turbidity in the stream, most severely during periods of low flow, at the very time when it is usually easiest to extract. The effect can be minimised by not extracting from the active channel.

8. Using extraction to fund stream rehabilitation

Royalties are often paid to State authorities for extracted sediment. In Queensland the royalty was little over a dollar per cubic metre (1995) for extraction from boundary water courses. A similar royalty applies in Victoria. Considering that around 28 million cubic metres of sediment has been extracted from non-tidal Queensland streams between 1950 and 1994 (Queensland Department of Primary Industries Year Books), the royalties are not trivial.

In a few places, royalties from extraction have been used to pay for stream rehabilitation works. In the Glenelg River in Victoria, an extra 'environmental levy' of about a dollar per cubic metre, was placed on the extractors to pay for rehabilitation, surveys and other costs. On the Nambucca River in northern New South Wales, extraction royalties helped to pay for 48 log sills placed in the stream. It has been suggested that the extraction contributed to the later failure of some of these structures. Although this assertion has not been proven, it does highlight the dangers of using extraction to raise revenue.

Nevertheless, if properly managed, extraction from appropriate sites can be a useful way of removing damaging sediment from a stream and raising revenue. This assumes, of course, that the administrative structure in the State is flexible enough to return the royalties to the stream.

9. Examples of rehabilitation extraction

Sand slugs in the Tambo River

Gold mining in the catchment of the Tambo River, Victoria in the 1890s produced a pulse of sand that moved into the lower river within a decade, and then substantially slowed its progress (Erskine *et al.*, 1990). The front of the sand slug is progressing slowly (10s–100s of metres per year) toward the estuary of the river (Figure 59). The estuary is renowned as a breeding area for the Australian bass (a fish).

At one time the Ports and Harbours Authority attempted to simultaneously solve two problems by taking sand from the Tambo sand-slug and placing it on the beaches of the nearby Lake King (Gippsland Lakes), which were eroding. Unfortunately, the sand was too fine and washed off the beaches. If the strategy had worked, it would have been a neat example of rehabilitation.

The Tambo slug is ideal for 'environmental extraction' because:

- the sand has come from outside the reach in question;

Figure 59. The front of the sand slug in the Tambo River (see arrow) (the water is about 5 m deep downstream of the front of the slug).

- the bed has been aggraded for more than five years (in fact, for nearly a century);
- the reach of the Tambo that has filled with sand has not adjusted to the slug of sand (it has simply aggraded without widening); and
- the further downstream migration of the sand is set to cause further environmental problems (threatening a native fish species).

Sand slugs in the Glenelg River, western Victoria

Catchment and gully erosion in the catchment of the Glenelg River last century released slugs of sand into first the tributaries, then the trunk stream of the river. An estimated 4–8 million m^3 of sediment is stored in the system. The sand is considered the major environmental threat to the river (Ian Drummond and Associates *et al.*, 1992).

The sand is moving only slowly (ie. about 0.1% to 0.05% of the total storage per year) through the system and one option for management is its commercial extraction. There is a good demand for quartz sand in the region. A management plan was developed for the catchment that identifies how much sand should be removed from particular reaches (Rutherfurd and Budahazy, 1996). The sand in the catchment is actually made up of several discrete slugs that were identified by probing with a 5 m steel probe. The clay bed of the river could be identified easily below the sand.

The bed-load transport rate in the trunk and tributary streams was estimated by various methods. These rates were used to identify the minimum rate of extraction required to protect downstream reaches.

Extraction was encouraged from the front end of particular slugs in order to protect remnant reaches of stream that have not yet been damaged by the creeping sand (ie. extract upstream of these reaches to intercept the sand). In smaller streams the rate of extraction was restricted because of the bank erosion that would be caused by a rapid fall in the level of sand.

We conclude this section by reiterating that there are so many physical and biological problems associated with extraction of sand or gravel from stream beds that the practice should be discouraged. Nevertheless, in some circumstances, such as where a stream bed is rapidly aggrading with a pulse (or slug) of sediment, extraction might deliver environmental benefits.

INTERVENTION IN THE RIPARIAN ZONE

- Vegetation management
- Exotic weed infested streams
- Willow infested streams
- Managing stock access to streams

VEGETATION MANAGEMENT

Revegetation is the most common stream rehabilitation technique used across the country. There is a huge amount of specific local guidance available for revegetation, and there is no point reproducing that here, apart from a few specific points. There is also little point discussing which plants to use because they tend to be so specific to local regions, and even to specific points in a catchment (eg. see the New South Wales Department of Water Resources species lists for catchments in north-eastern New South Wales).

One of the aims of this manual is to cover those aspects of stream rehabilitation that are not covered in detail elsewhere, and to give wider exposure to ideas or techniques that have national application. In the context of revegetation, we have identified the following issues as fitting those criteria.

- Limits to the role of vegetation in stabilising streams (where it will work and where it won't).
- Where on a stream bank should vegetation be planted for maximum benefits?
- In-channel vegetation (ie. information on vegetation that grows low down on the banks or on the channel bed).
- Direct seeding methods.
- Some tricks for successful vegetation establishment.

Please note: the management of riparian vegetation is covered in more detail in LWRRDC's Riparian Zone Management Manual. See details at www.river.gov.au

1. The role of vegetation in stabilising stream banks

Everybody appreciates that vegetation is central to the rehabilitation of Australian streams. What is less clear is what species to plant and where they will be successful. There are situations (usually on large streams) where vegetation alone will not control erosion, and structural measures (eg. rip-rap, rock-chutes) will be required. To know what those situations are, we need to know something about the erosion processes that we want to control. The National Riparian Zone Guidelines give a detailed account of the role of vegetation in bank erosion, which we will summarise here. Again, the key is to match the vegetation to the erosion process, after first identifying the most important erosion process that is occurring. Often the erosion process that looks the most important at a casual glance, is the product of some underlying process that it not so obvious.

There are three classes of stream erosion:

1. **Sub-aerial erosion.** Caused by processes unrelated to flow in the stream (eg. rill erosion, stock trampling, ice-plucking).
2. **Fluvial scour.** The action of water eroding individual particles. Scour increases with flow velocity and shear stress (a product of depth and slope) and tends to be highest at the outside of meander bends.
3. **Mass wasting/gravity failure.** Large sections of the bank collapse into the stream.

Each of these processes operates on all stream banks, but their importance varies at different points in a catchment. Sub-aerial processes tend to be most important in smaller streams, fluvial scour tends to be most important in the middle reaches of a stream, and mass failures tend to dominate in the lower reaches of a stream where the banks become sufficiently high. Despite the many processes that can operate on a stream bank, it is fluvial scour at the bank toe that ultimately controls the rate of bank erosion. This is because all other erosion processes (sub-aerial and mass failures) tend to *decrease* the bank slope, and so tend to 'self stabilise'. For example, the material that slumps off the bank in mass failure will pile up at the toe and eventually reduce the bank slope sufficiently to prevent further slumps. However, if fluvial scour removes the collapsed material, then the banks remain steep and unstable. Thus, it is the fluvial scour at the bank toe that keeps the banks unstable (Thorne, 1982).

> For bank erosion and vegetation the key questions to ask are: What is the dominant erosion process? Can it be controlled using the vegetation that I have at my disposal? Often these questions come down to whether you can establish vegetation on the bank face, and whether you can get roots close to the bank toe.

1.1. How vegetation stabilises banks

Vegetation reduces erosion in the following ways:

1. **Sub-aerial erosion.** Vegetation growing on the bank, or hanging over the bank, protects the bank from erosion due to rain-splash and most sub-aerial processes.

2. **Fluvial scour.** Vegetation growing on a bank face dramatically reduces the flow velocity close to the bank, and directly reduces scour (Thorne and Furbish, 1995). The vegetation also directly strengthens bank material, making it harder to remove from the bank face.

3. **Mass failure.** The most important role of vegetation in mass failure is to reinforce the failure plane (ie. where roots pass through the failure plane). Vegetation has other effects on mass failure, such as altering bank hydrology, but these tend to be less important than root reinforcement. For example, people are often concerned about the effects of the added weight of a tree on the bank. This is very seldom a problem. In fact, the weight of the tree will often reduce mass failure, especially if it is planted low on the bank face.

1.2. Where to plant vegetation on the bank

> The simple rule for planting vegetation for bank stability is to get it as close as possible to the low- water level, and to have as much of it as possible.

If you have identified that a specific erosion process is dominant then adopt the more specific rules that follow:

1. **Sub-aerial erosion.** Any vegetation on the bank face, or hanging over the bank face is suitable.

2. **Fluvial scour.** Again, any vegetation on the bank face is best. Particularly good are macrophytes that will grow close to the toe (see *In-channel vegetation: macrophytes and emergent plants* below). Vegetation on the bank top is unlikely to do much for this process, except in large floods when it slows the overbank flow.

3. **Mass failure.** Roots need to cross the failure plane to be effective. The failure plane is the fracture line where the slump block breaks away from the bank. You can estimate the depth of the failure plane by looking at typical failure blocks along the reach, and by looking for tension cracks on top of the bank. The failure plane will be either steeper than the bank face, or will parallel the face. The best place to plant trees to control mass failure is close to the bank toe. The next best place is close to the potential failure plane, on top of the bank. Shallow-rooted species on the bank face are useful for controlling shallow slips.

1.3. Limits to the role of vegetation

Vegetation is not the answer to all stream erosion problems. It has its limitations and in that regard the following three points need to be kept in mind.

1. Before European settlement, even with a full cover of native vegetation, streams eroded their banks, and underwent major changes of channel form and position. The evidence for such changes is preserved as ancient channels and other features on our floodplains. Thus, vegetation alone will not eliminate bank erosion, if that is your goal. In fact some of the erosion associated with vegetation, such as undercutting, is thought to be desirable fish habitat.

2. Clearing of vegetation, and other European modifications, have greatly increased the 'power' of our streams. That is, over the last 150 years many of our streams have deepened and enlarged so that they now carry a higher proportion of water in the channel than on the floodplain. This fundamental transformation of our streams cannot be reversed by simply returning vegetation to the stream. In many cases, the forces now operating in our transformed channels are too great for vegetation to modify.

3. Similarly, there are many situations where vegetation alone cannot provide enough strength to protect assets from stream erosion. Drawing on many years of experience in using vegetation for stabilising slopes and streams, Gray and Sotir (1996), engineers working in the northern hemisphere, conclude that a prerequisite for success in high intensity erosion situations is having a stable base on which vegetation can grow. In many cases, the toe of a bank must be stabilised with rock, gabions, or some other engineering structure. It is also important to note that Gray and Sotir reached this conclusion after working with much stronger and more responsive vegetation than is available to us. That is, almost without exception, the bio-engineering designs used in the northern hemisphere use willow, poplar and alder cuttings as the central feature of their designs. The cuttings are 'woven' into the engineering structure and then grow quickly, producing a true bio-engineered structure (see *Longitudinal bank protection*, in Intervention in the channel, this Volume). Since we are no longer using willows in most rehabilitation work in Australia, and since few of our native vegetation species will sprout from cuttings, we face an even harder job in incorporating vegetation into engineering designs than do our international colleagues.

1.4. How do I know if vegetation will stabilise my bank?

There are situations where vegetation cannot be established close enough to the active erosion zone to reduce erosion. See Figure 60 for an example of this. Further examples are:

- saline streams;
- streams with long-duration high flows (eg. the Murray, Tumut, and Mitta Mitta rivers have months of high, regulated irrigation flow levels);
- where the toe substrate will not support vegetation (eg. where the toe is coarse gravel);
- where the toe of the bank is too steep for vegetation to establish;
- where flow velocities are too high to allow establishment (eg. many gullies); and
- where the rate of toe scour is so rapid that it precludes establishment.

Figure 60. The roots of the trees growing on the banks of this gully do not penetrate deeply enough to stabilise the toe of the bank.

Sometimes it is possible to deduce that vegetation alone will not stabilise a bank. If the bank was originally vegetated, but the vegetation has been eroded away, this gives a good indication that revegetation may not be very successful. Similarly, reaches of stream where vegetation is growing on the inflection point of bends, but not right at the bend apex, are often seen (Figure 61). This is a good indication that the erosion is too vigorous at the bend for vegetation to establish.

In these situations, two approaches can be taken.

1. Artificially strengthen the toe (with any of the methods described in *Longitudinal bank protection*, in Intervention in the channel, this Volume). Then you can use the suite of 'bio-engineering' techniques described above to vegetate above the stable toe, which can often be restricted to one-third of the bank height.
2. Establish a 'sacrificial zone' that is revegetated with fast-growing species that will slow the erosion sufficiently for the larger, slower-growing species to establish further back from the bank top (Figure 61).

1.5. Vegetation and the size of a stream

The size of stream that can be stabilised by vegetation depends, to a great extent, on the root systems of the species used for the work. There has been little research on the root characteristics of Australian vegetation, but some broad generalisations follow.

The root systems of trees are highly variable—as variable as the above-ground parts—and difficult to characterise. Although they can penetrate to great depth and extend a long way from the trunk, for the purposes of bank stability applications the roots of large trees can be thought of as having limits of about 3 m deep and a lateral extent equal

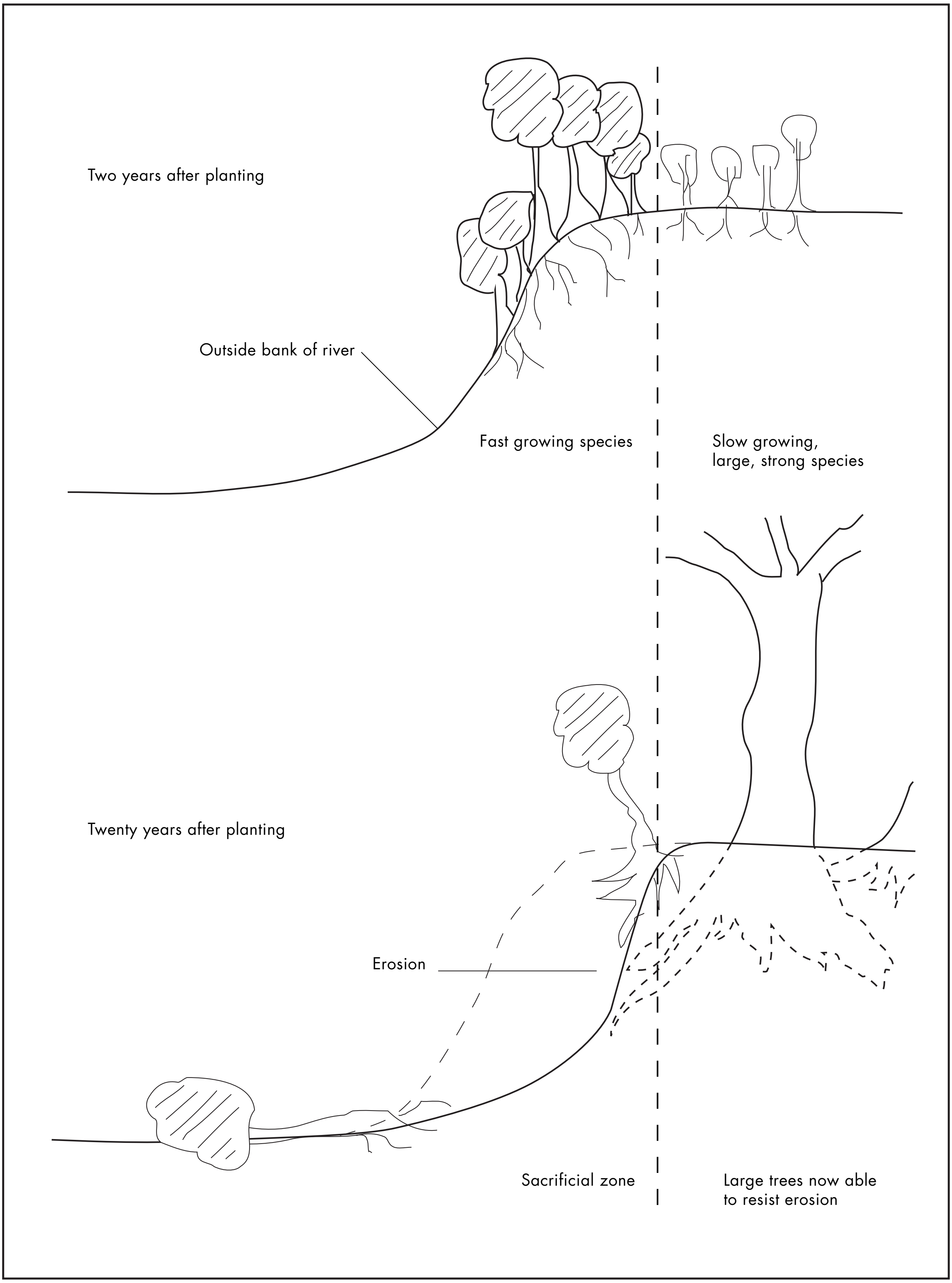

Figure 61. Fast- growing plants are grown in the 'sacrificial zone' in order to slow down the erosion and give the larger, slow-growing species a chance to establish further back. By the time the erosion has reached these slower-growing trees, they will be large enough to stabilise the bank.

to about that of the crown. The mass of roots is contained within a central 'rootball' or 'rootplate' in some species (or where the growing depth is restricted by a high watertable). As a general rule of thumb, the rootball can be considered to be about five times the diameter of the trunk. From the rootball, individual roots spread out into the surrounding soil with root density declining sharply with distance from the trunk and with depth below the surface. Most of the roots outside the rootball are found in the upper 0.5–1.0 m of soil, within the dripline of the tree.

The rootball/plate of most Australian tree species does not usually extend below the summer low-water level of a stream (ie. below the top of the summer watertable), although individual roots can extend deeper.

In general, trees alone can stabilise banks up to 3 m high if they are growing on top of the bank, and perhaps higher if they also grow down the bank face. It is common to see streams undercutting below the rootplate of trees. If the undercut is less than, say, a quarter of the bank height then the undercut will probably contribute to bank stability. This is because as the face of the undercut moves further and further back below the roots, the velocity of the flow against the back of the undercut declines. This means that a bank that is undercut below a strong root plate can be considered a stable bank (Figure 62). In this way, tree roots can reduce scour to a deeper depth than their rootplates, as well as providing excellent habitat. Undercuts are to be encouraged (see Figure 63).

Figure 63. Undercutting of the bank in Babinda Creek in far north Queensland.

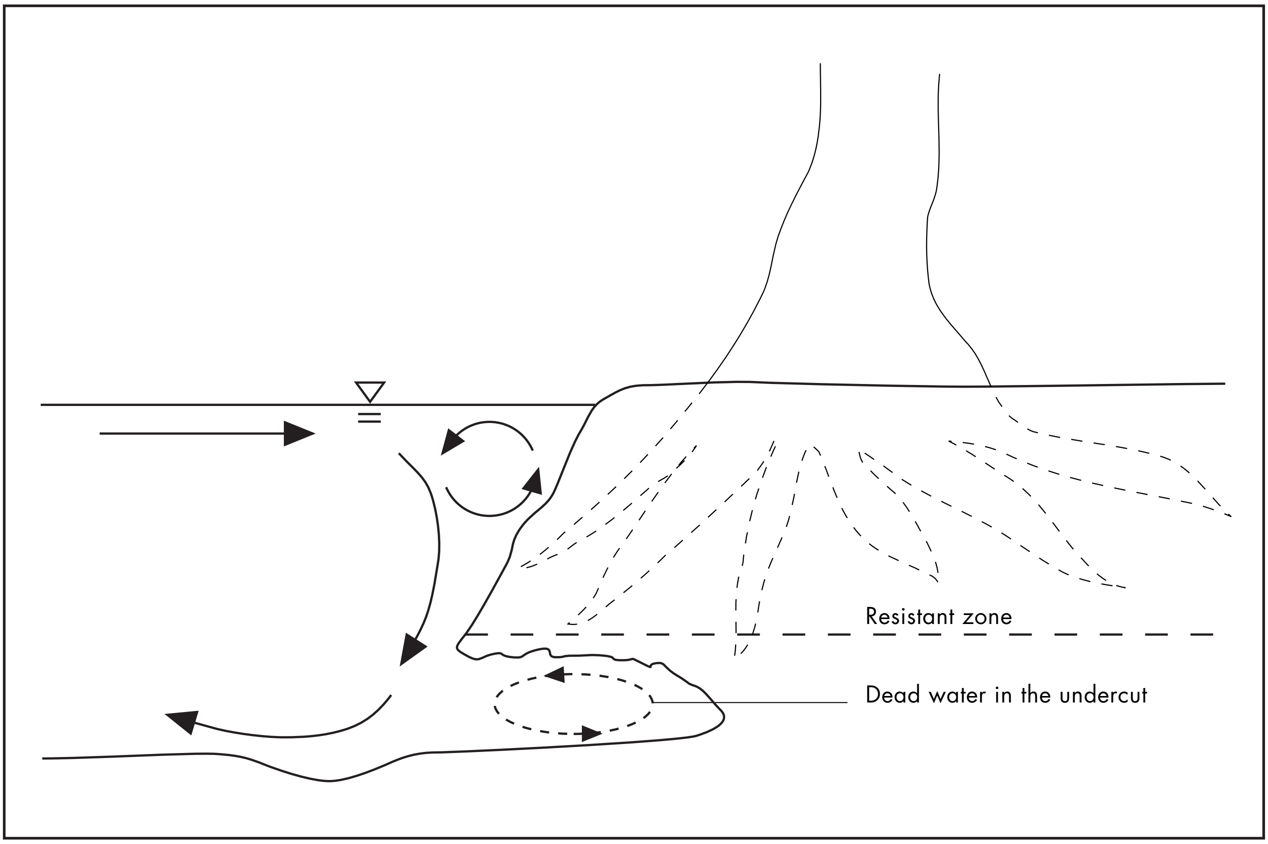

Figure 62. Undercutting below the root zone leads to a stable bank toe, as well as providing important habitat. If the height of the undercut is too great, then the undercutting will continue.

2. In-channel vegetation: macrophytes and emergent plants

*by Judy Frankenberg **

2.1. Some common reed species and their value for bank stability

Reed-beds are particularly useful where wave action from boat traffic is responsible for bank attack, because they absorb wave energy and act as a buffer. A reed-bed 2 m wide can absorb about two-thirds of the wave energy generated by wash from pleasure craft (Bonham, 1980). In addition, emergent macrophytes restrict the near-bank flow velocity and provide some reinforcement to the bank surface through their shallow root mat. Frankenberg *et al.* (1996) credited reduced erosion rates at some sites on the Murray River, near Albury–Wodonga, to the presence of *Phragmites* spp.

There are many emergent macrophyte species in Australia. The following are three common ones.

Phragmites australis (common reed) is endemic across southern Australia (eg. Figure 64) and is probably the best reed for bank protection because it grows right at the margin of streams, from 2 m depth, up the face of the bank. The characteristics of this reed are described in more detail below.

Typha spp. (cumbungi) will grow only in deep silty sediments below the water margin, and so is good for bed stabilisation, but it won't protect the bank from flow. It tends to grow in low-velocity streams, and only down the middle of the channel, deflecting the water against the bank. *Phragmites* will also do this if the banks are heavily grazed. Cumbungi is good for protecting against wave action in lakes, though it is not as resistant to scour as *Phragmites*. Cumbungi is also less drought-resistant, and needs longer flooding (though *Typha domingensis* is more drought-resistant than *T. orientalis*).

Figure 64. *Phragmites* reeds in the Mitchell River, Victoria.

Lomandra longifolia is a common species along the margins of coastal streams in northern New South Wales, eg. the Clarence River. It is resistant to scour but does not grow below the water line, so provides mid-bank protection from floods.

Phragmites is one of the most important reeds for bank erosion control. Some notes on its use follow.

2.2 Suggestions for using *Phragmites* spp. for bank protection

Phragmites australis, the common reed, is native to temperate eastern Australia, north as far as Mackay, and west to South Australia. *Phragmites karka*, another species with similar characteristics, occurs in northern Australia. The extent of the reed has been dramatically reduced by grazing. *Phragmites* is potentially very useful for bank erosion control for three reasons.

1. It is rhizomatous (ie. it grows from roots as well as from seed), and develops a long-lived network of underground stems (rhizomes) that can travel for several metres, producing a mat of surface roots.

2. It can grow to a depth of 2 m into the water, depending on the flow, and protect the bank at the soil–water interface. It will also grow up the bank, some distance from the water edge, providing protection from flood flows.

3. It provides valuable aquatic and riparian habitat, and makes an important contribution to the sediment and nutrient-trapping function of riparian vegetation.

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2.3. Where *Phragmites* spp. are appropriate

Phragmites can control erosion on bends that are not too steep for it to establish, and performs best where the erosion is caused by wave action. It is particularly appropriate on medium to large streams, where it will not choke the channel, but where the banks are not vertical. Phragmites can survive moderate rates of scour, but is unsuitable as the only form of protection in a severely eroding site. It is not recommended for small or aggrading streams where flooding due to loss or channel capacity is likely to be a problem.

Phragmites can also be very effective in stabilising the floor of gullies, and in accelerating the natural recovery of a stable channel within a gully. The reed will trap sediment and raise the floor level significantly, provided some access to moisture is available year round.

Phragmites can retard flow and increase flooding, although it tends to lie flat in high flows which may actually reduce resistance. Dense stands, however, do trap a large amount of sediment, and this can affect flood levels.

2.4. Planting position on the bank

Emergent macrophytes such as sedges, rushes and reeds grow on the margins of the mean water level and readily colonise wet areas where terrestrial plants are hard to establish. Emergent macrophytes generally will not survive in water which that is more than 0.5 m deep for long periods. They flourish in conditions of low velocity (about 0.2 m/s) but will withstand short periods of inundation and high velocity when the stream is in flood (Coppin and Richards, 1990).

The planting position depends on the flow regime of the stream. *Phragmites* should be planted at the level which is least likely to dry out, or be deeply flooded, for a few months after planting. Therefore, on a stream with a maximum winter–spring flow, planting should be high on the bank in autumn, in anticipation of a water level rise, and lower on the bank in spring or summer, when the water level is likely to fall. The leafy stems will die if submerged for more than 10–15 days, and rhizomes must be sufficiently developed to support new growth.

Phragmites is very palatable to stock, so control of grazing is essential for establishment and persistence.

Banks should be fenced a sufficient distance from the stream to allow spread of the *Phragmites* up the bank, so as to obtain maximum stabilising effect. Shading by associated tree and shrub planting will prevent complete domination of the riparian zone.

2.5. Rate of establishment

The time needed to establish dense reed beds will depend on the site. On high-nutrient soils, mature stands will develop within a few years. On lower fertility sites, growth will be slower and reeds will not be so tall and dense. On these sites up to 10 years may be necessary for maximum development. Density of planting will also have some influence. On high-nutrient sites, or where reeds are fertilised at planting, large plants 1 m apart will close up within 2 years. On poorer sites, planting at 50 cm or 30 cm spacings may be warranted.

2.6. Establishing *Phragmites*

Phragmites can be grown from seed (for details contact the author for a copy of the relevant pamphlet) or directly transplanted. For direct transplanting, the reed can be dug up from one site with an excavator, put into a truck and simply replanted at the chosen site. The plant clump can be divided before planting to give a wider spread of plants. Future growth will fill the gaps between plants (Figure 65).

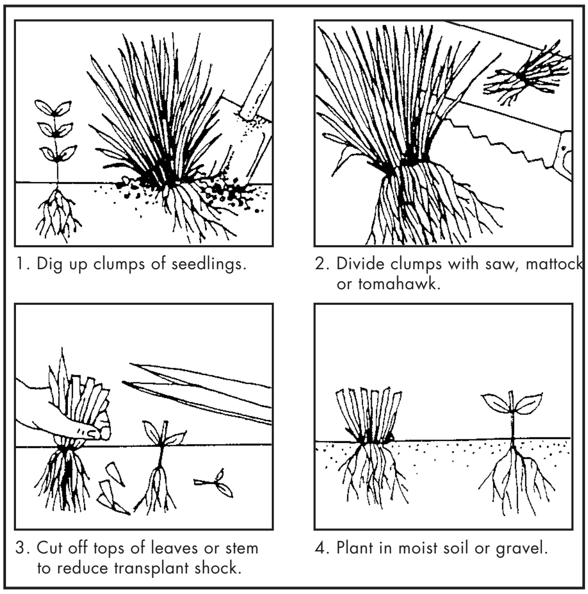

Figure 65. A method for establishing emergent vegetation (from Raine *et al.*, 1997).

3. Some tips for revegetation

3.1. Revegetating the littoral zone

The zone of the banks that is almost always permanently moist in cohesive bank streams (just above normal flow levels) is often steep and difficult to access for revegetation. The Lake Wellington Rivers Authority (LWRA) in Gippsland, Victoria has been revegetating this section of the bank. LWRA staff have been planting swamp paperbark (*Melaleuca ericifolia*) seedlings on the La Trobe River by travelling downstream by boat, pulling alongside existing vegetation areas and planting the seedlings by pushing them into the moist part of the bank by hand. The location of the seedlings near existing vegetation makes sure they are sheltered from high velocity flows and from trampling by cattle.

3.2. Tips for tubestock planting near streams

Standard tubestock planting should be carried out when the soil is moist and there is no danger of frost. The hole should be about twice the width of the pot and there should be a slight depression around the plant to retain water. When planting in coarse gravels, tubestock are likely to be subject to water stress because the water retention of gravel is poor. For coarse substrate, backfill the hole with fine soil (preferably rich in organic matter).

An artificial bench is usually constructed in the rehabilitation of over-wide gravel bed streams. The experience of the New South Wales Department of Land and Water Conservation (DLWC) has been that if these artificial benches are limited to around 10 cm above the low water depth, tubestock are less likely to suffer from water stress (Allan Raine, pers. comm.).

3.3. Long-stemmed tubestock

An important extension to tubestock planting is the experimental work on deep planting of long-stemmed tubestock currently being trialed by the New South Wales DLWC. One of the limitations of any revegetation program is that the germination of seeds or survival of seedlings is strongly affected by the soil moisture conditions. Many tubestock planting trials have failed in the few years just after planting through lack of follow-up watering. This problem is common on streams, particularly in sands and gravels which drain freely. DLWC is currently trialing the deep planting of tubestock grown in long tubes. The roots of the longer stemmed plants are closer to permanent water and thus have a better chance of tolerating low surface moisture conditions on gravel bars.

The tubestock are planted using a water jet lance (sand), or percussion jet for gravel streams (see Figure 66). Trials have so far indicated that long stem tubestock have higher survival and growth rates, better survive competition from weeds, and are less likely to be uprooted by scour during floods (Hicks *et al.,* 1999). The limit for the application of long- stemmed tube stock is finding nurseries that can provide the plants. Details of how to jet the long-stemmed tube-stock into the gravels, are described in Hicks *et al.* (1999). Contact the Muswellbrook Office of DLWC for details of these trials and addresses for nurseries.

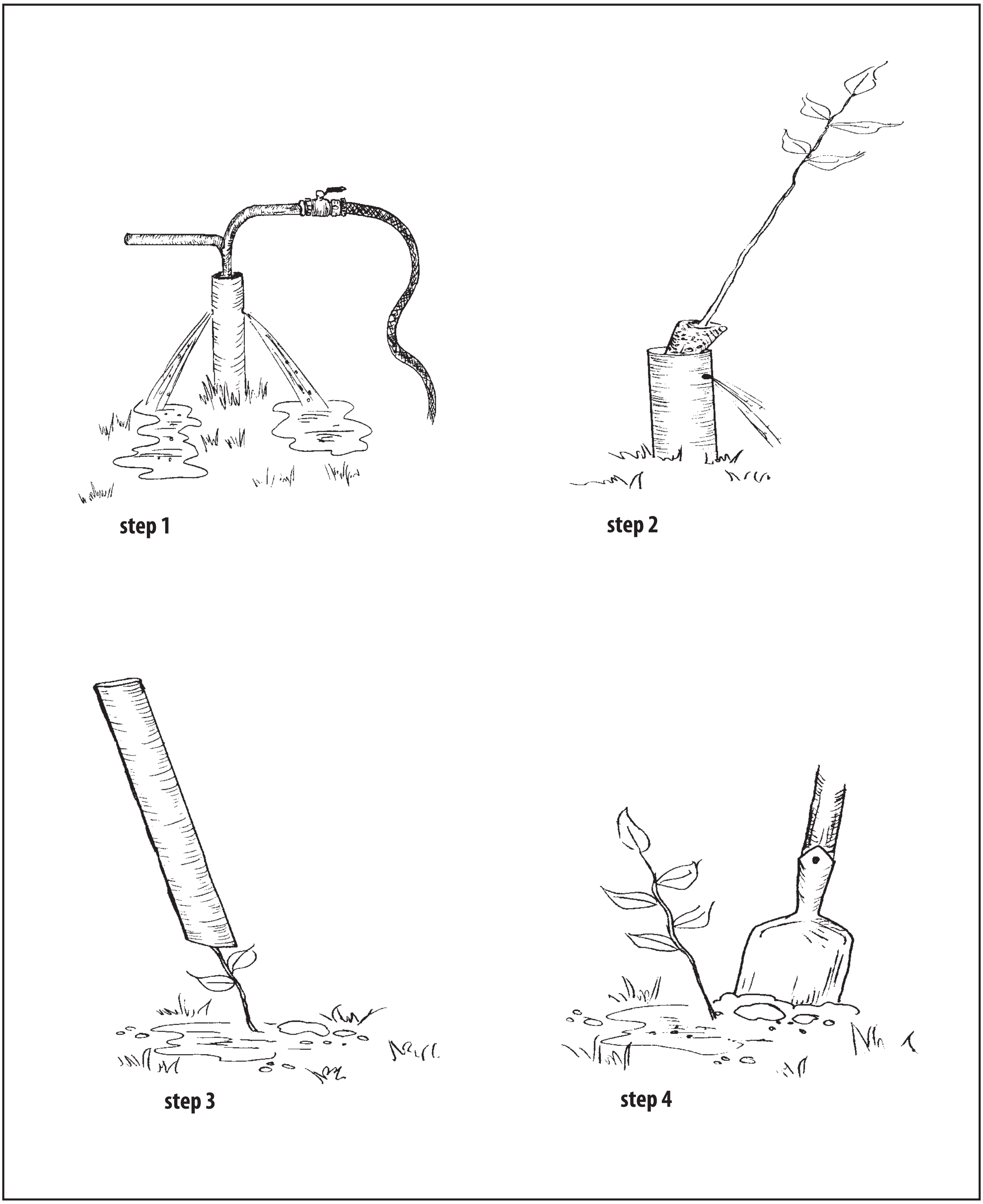

Figure 66. The method for planting long-stemmed tube stock (from Hicks *et al.*, 1999). *Step 1* – The jet is placed inside a PVC pipe and the pressure of the water used to drill a hole in the soil to a depth of 0.6– to 1 metre. Holes in the top of the pipe allow water to escape. It should be noted that the PVC pipe is not necessary in cohesive soils such as silts and clay-loams. *Step 2* – The jet is removed from the pipe and the long-stemmed plant (remove tube) is placed in the PVC pipe. If necessary a stick or rod is used to push the plant to the base of the planting hole. In most cases, 70–90% of the plant length is placed in the hole. In cohesive soils the plant is gently placed directly into the hole. *Step 3* – The PVC pipe is removed from the hole, leaving only the long-stemmed seedling. Care must be taken to ensure that the plant stays in the hole while the pipe is removed. *Step 4* – The hole is filled in around the plant. It is important to ensure that the entire hole is filled with soil. Air pockets will retard growth and discourage root development from the nodes. (Reproduced with permission from the Cooperative Research Centre for Catchment Hydrology.)

4. Direct-seeding methods

By Jim Burston and Wayne Brown†*

The factors for success in direct seeding are:

- site preparation;
- time of sowing;
- seed viability/species selection; and
- maintenance of the site.

The broad principles of direct seeding have been the topic of a number of books (Dalton, 1993, Venning 1988), a national conference (Greening Australia Ltd, 1990) and other extension material.

4.1. What are the advantages of direct seeding compared to tubestock?

1. Plant density: an average germination, using a seed mix of 1 kg/ha, will deliver approximately 4,000–6,000 seedlings/ha (Dalton, 1993; M. Campbell, pers. comm.). Compare this to tubestock, using a 3 m by 3 m spacing, which produces less fewer than 1,000 seedlings/ha.

2. Cost: site preparation and fencing costs are the same for either technique. However, direct seeding will require approximately 1 kg of seed mix (approximate price of $170/kg), whereas tube stock at $0.50 per seedling (@ 1,000/ha) will cost $500.

3. Species diversity: most sites in South Australia are sowing, on average, 20–25 species and at some sites the range is 35–45. This level of diversity is not feasible using tubestock plantings.

4. Randomness: most tubestock planting tends to be done on a rigid adherence to a 3 m by 3 m format. This leads to a regular, pine-plantation-like appearance quite unlike the variability of the natural landscape. The results of direct seeding more closely approximate the natural landscape.

5. Growth rates: many first-time direct seeders are disappointed with the early results as compared with tubestock planting. Although direct-seeded seedlings might seem to grow more slowly, experience in South Australia indicates that, by year 2, the height of these seedlings surpasses that of tubestock. In the ensuing years the difference in performance widens.

6. Time: for the average site, one hectare (= 3 linear km of sowing) of direct seeding will take approximately 20 minutes with the mechanical seeder. How long would it take you to plant 1,000 tubestock trees?

4.2. Site preparation

Undoubtedly the most important factor in a successful revegetation program based on direct seeding is weed control (both herbaceous and woody). The vast majority of revegetation projects fail due to poor weed control. Good weed control starts with understanding the weed spectrum at your revegetation site. Depending upon the weed spectrum (eg. couch, kikuyu, phalaris, cocksfoot, gorse, blackberry) weed control may need to be initiated up to 24 months before sowing. This is particularly important if the weed spectrum includes aggressive summer-growing plants. Good weed control means a complete kill of all weeds. Weed control ensures adequate soil moisture for plants to grow through the summer months. The experience from hundreds of revegetation sites across South Australia is that, unless weed control is excellent, direct seeding will fail. In fact, if you don't control your weeds, don't bother with direct seeding.

Control of most herbaceous weeds is generally achieved through the application of a knockdown herbicide (eg. glyphosate 360 g/L, @ 1–2 L/ha). For best results, two applications should be made: the first at 1–2 months before sowing, and the second 1 week before sowing. Some broadleaf weeds (eg. strawberry clover, prickly lettuce, wire-weed) can be controlled with herbicides such as MCPA®, DiCamba®, and Ally®. Extreme care should be taken to ensure that no herbicide enters the stream.

Some practitioners have encouraged the use of residual herbicides to achieve satisfactory weed control. However,

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unless the soils to which these herbicides are applied have a high clay content, there is a risk of herbicide leaching into the zone where the seeds have been laid (and elsewhere for that matter).

For best growth, it is desirable to remove weed competition for a distance of 1.5 m from the seedlings. This will ensure the seedlings have access to sufficient soil moisture and nutrients. Good weed control will render fertiliser application unnecessary.

Weed control with herbicides generally takes the form of blanket, strip or spot spraying. When revegetating watercourses, it is desirable to allow weeds to grow to a height of approximately 150 mm before spraying. As the weeds die, they will form a mulch and protect the soil from erosion (but not necessarily flood events). Sowing in spring will also reduce the chance of the site being damaged by a major flood (in southern Australia) and severe frosts. On steeper slopes, or where access may be difficult, strip or spot spraying is appropriate.

Grading and cultivation are two other methods of weed control. Both techniques have serious pitfalls. They physically remove the seed bank that is stored in the top few centimetres of the soil profile, exposing the site to erosion in heavy rainfall events, and may change the weed spectrum. Many hard-coated seeds can survive in the soil for many years (eg. seeds of *Acacia* spp. may survive up to 120 years). Any potential for natural regeneration from the seed bank to complement the direct seeding is lost if site preparation involves grading or cultivation.

4.3. Seed treatment/seed viability/seeding rates

Many individuals tend to be obsessed with seeding rates and have devised all sorts of formulas to determine the 'correct' rate. Our view is that much of this concern is unwarranted. The most important factor is to ensure that there is an adequate floristic (ie. wattles, banksias, bottlebrushes, gum trees, tea-trees etc.) and structural diversity (ie. trees, shrubs, grasses) within the seed mix. The approach to revegetation in South Australia has been to encourage and develop the seed-collecting skills of landholders. Germination tests are unnecessary if emphasis is placed on collecting fertile seed, which is an easy task.

Most hard-coated seeds (eg. *Acacia* spp.) will require some form of treatment (ie. scarification) before sowing. The easiest method is to place the seeds in very hot water for a short time; for further details see Bonney (no date). This can be done a few days before sowing.

4.4. Sow at the right time

Sowing should be timed to coincide with optimal conditions of soil moisture and temperature. In southern Australia, where sites receive rainfall of >450 mm pa, the optimal time is spring (ie. August–October, depending upon average annual rainfall). In fact, direct seeding is arguably more successful in years of slightly below average annual rainfall, due to less opportunity for weed growth. In regions receiving <450 mm, May–June is generally the preferred time of sowing (ie. after the break of the season). In particularly dry years, or where a late break to the season is encountered, it may not be possible to undertake direct seeding.

4.5. Methods of direct seeding

The depth to which seeds are sown will have a major bearing on the success of direct seeding. It is important that seed has good contact with the soil. Ideal burial depth can vary according to the amount of light required by the seed. A general rule of thumb is to sow seed at a depth that is twice its diameter (Dalton, 1993).

Most direct seeding is done using machines that resemble up-market '1080' rabbit-bait layers. This simple 'farmer friendly' technology is central to the widespread adoption of direct seeding in South Australia.

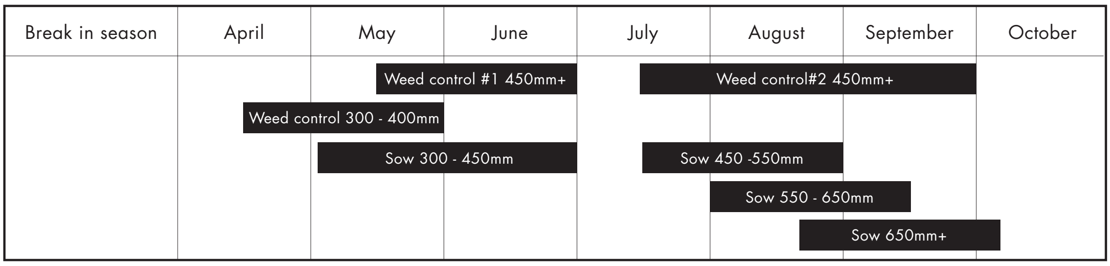
All direct-seeding machinery currently used in South Australia performs the following tasks:

- removal of soil and trash (ie. generally the top 1–2 cm of the soil profile);
- preparation of a level seedbed for sowing with standard (or modified) agricultural seedling implements;
- ensuring that germination takes place in mineral soil; and
- pressing the seed into the soil in order to minimise consumption by ants (Dalton, 1993).

Where access is limited, machines can be attached to 4WD motorbikes. Where access can be achieved only on foot, hand seeding is the answer. The procedures for hand seeding are outlined in Figure 67.

1. TIMING

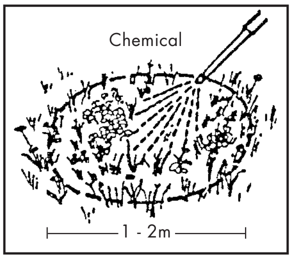
Select the weed control and sowing period corresponding to the average rainfall in your area.
This technique is not recommended for areas that receive less than 300mm of rainfall annually.
Sandy sites in 450mm+ areas should be sown early.



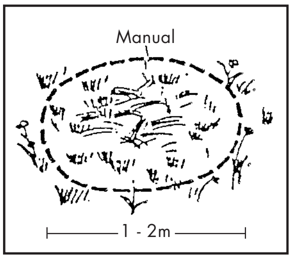
Seed must always be sown into a moist seedbed. Area subject to waterlogging should be sown in spring.
Summer active weeds should be managed the year prior to sowing, and at the time of sowing.

2. WEED CONTROL

Good weed control is essential for seedling survival.
Control can be either chemical or manual.



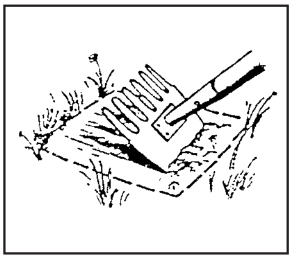
Control weeds for a circle of 1 to 2 meters diameter.



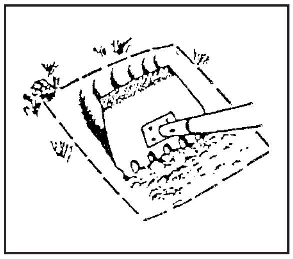
Remove all weeds but leave litter trash to protect the soil.

3. PREPARE THE SOWING SITE

Preparation of the sowing site can be done about one to three weeks after spraying.

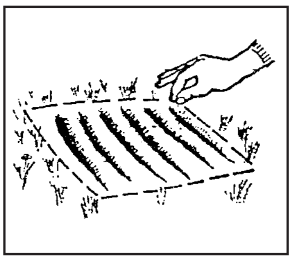


Scrape to remove dead weeds and trash (30 x 30 cm area).



Rake to prepare sedbed.

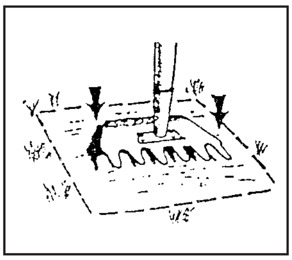
4. SOW



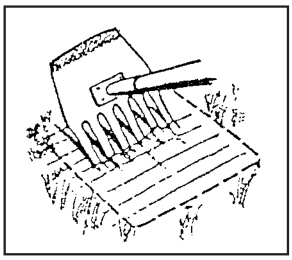
A pinch is plenty (10 to 20 seeds)

Sow only one species per site.

5.PROTECT THE SEED



Tamp the surface for fine seed, for example eucalypts, tea tree or firm seed into soil with your shoe.



Rake then tamp for large seed, for example wattle, sheoak.

Ideally, bury the seed to a depth of once or twice its size.

Figure 67. Direct seeding of native plants by hand (from Primary Industries (SA) Fact Sheet 7/95/97).

In the agricultural regions of South Australia, there are only two soil types which present problems for direct seeding: alkaline, black, cracking clays (these sites were originally native grasslands); and deep, non-wetting sands in low rainfall areas (ie. less than 350 mm pa).

In the past two years, the success rate of direct seeding onto non-wetting sands has been dramatically improved with the use of wetting agents at the time of sowing, seed treatment before sowing and advances in seeding machinery. Successful germination on cracking clay has been achieved, but most seedlings die as the soil cracks upon drying.

4.6. Use of local species

For the past decade there has been a concerted effort to use indigenous species for revegetation. The reasons are many, including:

- maintaining landscape character;
- conserving biodiversity;
- avoiding genetic pollution of remnant vegetation; and
- longevity of local species.

South Australia is littered with sites that have been planted with 'exotic' native species (ie. Australian species that are not indigenous to that area). Unsurprisingly, most of these sites have failed in the longer term (ie. 15–20 years) and now require a second revegetation effort. Species selection can vary within a few hundred metres, owing to a change in aspect, soil type, geology or any number of other factors. Thus, species lists have to be very site specific.

In South Australia, several landholders (including the author) have planted river oak (*Casuarina cunninghamiana*) along their watercourses. We do not recommend this species because it appears to have a habit similar to willows: its roots protrude into the channel, thereby reducing its capacity. This is of particular concern on the smaller watercourses (ie. < 4th order).

4.7. Maintenance

Young seedlings are vulnerable to defoliation from pests such as red-legged earth mite and lucerne flea. In some circumstances, it may be necessary to add an insecticide (eg. Le Mat®) to the herbicide solution. It is essential that extreme caution be exercised when applying insecticides near watercourses, regardless of the concentration.

It is highly desirable to provide young plants the opportunity to grow through a second summer in a weed-free environment. This can be achieved by spraying the site with a knockdown herbicide, at a reduced rate (ie. glyphosate 360 g/L @ 0.5 L/ ha), during late winter (ie. late July–early August). This approach may cause minor tip-burning to some species, but it is quite safe. At this time, the young native plants are relatively dormant as compared with introduced grasses and broadleaf weeds. Most native plants will be physically shielded from the herbicide by the growth of herbaceous weeds.

Some individuals may become concerned that direct seeding can create a situation of 'too many seedlings', and express a desire to 'thin-out' the site. Over time, nature will ensure self-thinning, leaving only the strongest individuals.

4.8. Conclusion

River engineers build erosion control structures mindful of the fact that vegetation is a vital tool in attaining a stable watercourse. However, the revegetation component is the weak link in the chain. Most revegetation is undertaken using an outdated technology — tubestock planting. There has been nearly a decade of successful use of direct seeding for broad-acre revegetation. The technique is dependent upon good weed control, sowing at the right time and using viable seed. Most importantly, the method is cheap and farmer friendly.

STREAMS INFESTED BY EXOTIC WEEDS

1. Managing exotic vegetation

Australian streams have been invaded by numerous exotic plant species, from large trees (eg. camphor laurel and willows), to riparian understorey (eg. blackberry), to water weeds (eg. water hyacinth) (eg. see Figure 68 and 69). In addition, there are native species that have greatly increased their range and become nuisance plants in that area (eg. cumbungi). Controlling these riparian and emergent species is often a key activity in stream rehabilitation. We cannot cover all the species in detail because they tend to be region-specific. Instead, a general review is provided. A detailed discussion of willows (*Salix* spp.), which are one of the most important weeds, is covered in *Willow infested streams*, below.

As always, the best strategy is prevention, and small infestations of exotic vegetation should be attacked with vigour before they spread.

1.1. General exotic vegetation issues

Exotic vegetation includes not only non-native species but also native plants that are not indigenous to the region. These plants may out-compete the local native vegetation. An example of this is *Acacia bailleyana* (Cootamundra wattle) which is indigenous to southern New South Wales but has been used in gardens and for revegetation programs throughout Australia. This plant has become an environmental weed, out-competing native vegetation and producing monocultures of wattle.

Figure 68. Camphor laurel trees growing on the banks of the Nambucca River, northern New South Wales.

The general treatment options for exotic vegetation are labour intensive, and normally entail a combination of hand removal and poisoning (usually with a glyphosate herbicide). Herbicides should be used with caution around water. A particular concern is their impact on amphibians, which breath through their skin and are thus very sensitive to chemicals used in and around streams!

There have been many stream management documents produced on how to manage exotic vegetation; procedures vary from species to species. Most stream management organisations have a wealth of experience in eradicating weeds. Table 1 gives a summary of some fact sheets that are available.

Figure 69. 'Parra' grass infestation in a tributary to the Johnstone River, Far North Queensland.

2. Management of exotic weeds

Table 1. Common riparian weed species across Australia, and where you can get information on how to control them. (for full references see *Bibliography of technical information*; Miscellaneous planning tools, this Volume).

Plant(s)	Title of publication	Contact organisation	Description
Gorse, blackberry, briar rose and any other woody weeds	Woody Weed Control along Water Courses	SA DENR[1]	
Common bullrush (two species—narrow-leafed cumbungi (*Typha domingensis*), and broad-leafed cumbungi (*Typha orientalis*)	Control of Cumbungi	Qld DNR[2]	Emergent native which grows up to 4 m in still or slow-flowing water up to 2 m deep. The plant has a strong and extensive root system and is very useful for erosion control and as habitat for waterbirds and amphibians, but in isolated situations it can congest streams (particularly an issue in irrigation systems), restricting flow and trapping sediment. *Typha* should only be removed where it is having an unacceptable impact on the hydraulic conditions of the stream.
Water hyacinth (*Eichhornia crassipes*)	Control of Water Hyacinth: the worst aquatic weed in the world	Qld DNR	Free-floating aquatic plant found in still or slow-flowing water. The weed is extremely quick to choke watercourses, and reduce oxygen and light levels in the stream.
Salvinia (*Salvinia molesta*)	Control of Salvinia	Qld DNR	Floating aquatic fern (from Brazil) found in still or slow-flowing water. Grows into dense mats, choking streams and reducing the oxygen and light levels in the stream.
Cats claw creeper *(Macfadyena unguis-cati)* Madeira vine (*Anredera cordifolia*)	Control of Exotic Vines	Qld DNR	Found in northern NSW and southern Qld.
Willows, ash and poplars	Exotic Trees along Watercourses	SA DENR Mount Lofty Ranges Catchment Program	Large exotic trees, can infest streams.
Camphor laurel (*Cinnamomum camphora*)	Camphor Laurel Control	B Hungerford, NSW DLWC: (unpublished) Available through Murwillumbah district office of DLWC	Large exotic trees that that are prolific in coastal regions of northern NSW and southern Qld.

[1]SA DENR = South Australian Department of Environmental and Natural Resources

[2]Qld DNR = Queensland Department of Natural Resources

WILLOW-INFESTED STREAMS

1. Introduction

Willows thrive in the cold-water streams of south-eastern Australia and are found from northern New South Wales, through to eastern Victoria, Tasmania and South Australia. In general, willows do better in the colder regions. For example, the willows used in many stream stabilisation works in northern New South Wales rivers through the 1950–70s are experiencing dieback and there is no succession of vegetation to maintain the bank stability at the site once the willows have died. By contrast, in Gippsland, Victoria, willows are spreading by seed and completely choking many of the smaller waterways (Cremer *et al.,* 1995). The attitude towards willow eradication varies from State to State in response to these differences in virility. In South Australia, it is felt that willows should be eradicated from streams, while in northern New South Wales, where willows die younger and are less likely to spread, a more moderate stance is taken. Here the role of willows in stabilising streams is acknowledged.

Willows are very easy to propagate, grow rapidly and vigorously resist erosion. Some native tree and reed species share some of these features, but few have them all (although see *Vegetation management*, above, for a discussion of using long-stemmed native tubestock instead of willows). Banks planted out with willows are at least 80% more resistant to fluvial scour than grassed banks, and 30% more resistant than a dense stand of native vegetation (Table 2). A dense stand of willows can increase the shear strength of soils by up to 100% (Waldron, 1977). However, there are numerous bends in Australian streams where the toe of the bank is so steep, and the erosion rate so high, that even willows cannot establish themselves.

Table 2. Tractive stress rating of various vegetated materials.

Bank material	Tractive stress (N/m^2)
Bare banks	1 to 10
Grass (turf)	15
Dense native vegetation	about 50
Willow revetment	70
Rockfill bank protection (average diameter 0.4 m)	150

(From Bavarian literature reviewed by Walter Hader, NSW Department of Land and Water Conservation)

Despite their advantages in erosion control, in many parts of south-eastern Australia, the disadvantages of willows (outlined below) outweigh their benefits. As a result there are major willow eradication programs under way in the Mt Lofty Ranges near Adelaide, and in the catchments around Melbourne. The Lake Wellington Rivers Authority in Gippsland, Victoria, for example, spent about 70% of its 1997 operating budget removing willows.

2. The effects of willows on streams

2.1. Biological consequences of willows versus native riparian vegetation.

*By Martin Read**

Stream-side willows have the following serious disadvantages.

1. **The thick canopy creates denser shade than most native species.** Romer (1994), cited in Frankenberg (1995), stated that ground beneath a willow canopy received 38% of the incident sunlight, compared with 53% beneath a red-gum dominated riparian zone. The low light levels suppress growth of instream algae and macrophytes, as well as other riparian vegetation. This

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reduces terrestrial and aquatic habitat, and severely alters the food supply in the stream. The suppression of algal growth may sound attractive in streams with a nutrient problem. However, algae in moderate levels are an important food source in streams. The variation in shading from dense canopy (summer) (Figure 70) to no shading (winter) affects the temperature regime of the water and cover value of the trees for instream biota.

Figure 70. Willows on the Onkaparinga River, South Australia. Note the dense shade under the thick foliage.

2. **The timing of leaf fall.** Leaves and other debris from riparian vegetation can form a major part of the aquatic food chain. Australian native trees tend to drop a continuous supply of leaf litter, providing a constant food source for the instream biota. Willows, on the other hand, produce much larger quantities of litter in a much more variable supply (Figure 71). This may be reflected by a higher abundance of 'shredders'—macroinvertebrates that use leaves for food. In faster-flowing streams, the mass leaf fall is dispersed and may have relatively little effect. However, in streams which have low flows, or are constricted by willows, the accumulation of leaves will degrade stream habitat and may lower the dissolved oxygen levels as they decompose.

3. **They provide poor-quality food.** The leaves and wood that are deposited in the river system by willows are not of the type that our riparian and instream biota have evolved to depend on. The leaves represent an abundant food source but break down rapidly, so are available for a short time. As well as representing a less variable supply, native litter breaks down more slowly, providing a constant food source for the instream biota.

4. **They provide low-quality LWD.** Many native riparian canopy species naturally shed branches of all sizes. There is also a large annual input of bark. Native wood is dense, and large snags can remain in the channel for a long time. The characteristics of native wood allow hollows and branches to become refugia and spawning sites for native fish. By contrast, willows do not shed branches readily. When this does occur, branches have a tendency to take root and form new trees. Their lightness allows them to be transported downstream. They also rot more rapidly than native species, they do not shed bark and the rotting wood does not form hollows or irregularities that can be used by aquatic fauna. Recent research by the author suggests that a much higher number and diversity of macroinvertebrates were found on native wood than willow wood.

5. **They spread like rabbits.** Originally only one gender of each willow species was introduced to Australia, so the entire population of any species was thought be either male or female, and natural seed production should not be possible. Thus, it was believed, willows would grow only where cuttings had been intentionally placed or by the rooting of accidentally detached branches. Recent research has shown that this is not the case, and that there are at least a dozen species of willow that not only produce viable seed, but have produced seedling populations ranging from a few dozen to half a million (Cremer *et al.,* 1995). Spread of willows downstream through vegetative reproduction has also been more of a problem than expected, especially with those species which easily fragment.

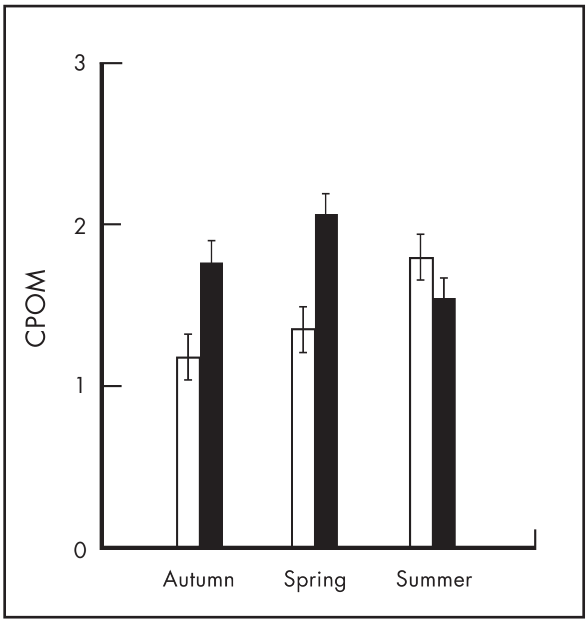

Figure 71. Differences in standing stocks of coarse particulate organic matter (CPOM) in native (light bars) and willow (shaded bars) reaches in each season. Vertical lines represent the standard error of the mean.

In conclusion, willow infestations lead to a decrease in the diversity and abundance of stream biota through:

- the reduction of habitat diversity through shading-out of native macrophytes and riparian vegetation, introduction of inferior LWD, and smothering the habitat with dead leaves;

- the reduction of food quality and diversity through shading which reduces algal growth, the changed nature and timing of litter inputs into the stream; and

- reduction in water quality when mass decomposition of leaves in autumn leads to reduced dissolved oxygen levels.

> Having described the benefits of native vegetation over willows, it is important to emphasise that even willows are better for the stream than no vegetation. So, it is important not to remove willows unless you are going to replace then with indigenous native vegetation.

2.2. Willows and stream size

The effect of willows on stream erosion varies dramatically with the size of a stream, and with the character of channel change in the stream.

2.2.1. Small, degraded streams

Small streams (up to 10 m width) can be totally blocked by willows. It is very common to see small channels whose form has been destroyed by willows, with the main channel consisting of an anastomosing network of smaller channels through willow roots and trunks. Substantial erosion can be expected when willows are removed from this type of stream, as the deposited sediment is stripped out. Willows in these small streams might be stopping major headcuts from moving further upstream.

2.2.2. Larger streams

In larger streams, where the bed of the river is aggrading (building up) over time, willows can invade and block the channel floor. Sediment will build up around the willows; removing them will produce a pulse of sediment (sand or gravel) that migrates down the channel. It will also lead to faster migration of sediment slugs through the stream system. Willows can effectively constrict channels that have been aggraded by large pulses of sediment. For example, willows have constricted the lower Bega River in southern New South Wales by hundreds of metres over the last decades (Brooks, 1994). Removing such willows could again destabilise the channel.

Where willows invade the bed of any stream they dramatically reduce channel flow capacity and encourage more water to invade the floodplain. At best, mid-channel willows will tend to deflect flow into the banks and widen the channel. At worst, they can lead to wholesale changes of stream course. Willows have been implicated in changes of channel position in South Australia, Victoria and New South Wales.

In large degrading streams (that is, where the bed is progressively eroding) willows can play an important role in stabilising banks. An increase in channel depth often leads to bank instability, and this can be controlled by willows. Where the stream is deep and large, willows cannot invade the bed, but they may still densely colonise the banks. There is no question that willows growing on the bank face of large streams dramatically reduce bank erosion rates. Willows reduce near-bank velocities and directly protect the bank face from scour.

3. Managing willows

With contributions from David Outhet, Jim Burston† , Jason Carter§, and Ross Scott¶.*

While willows have great potential in stream stabilisation works, it is better, wherever possible, to avoid using them. This policy rests on the golden rule of stream rehabilitation: "it costs 10 to 100 times more to reverse our past mistakes than it did to make them". The removal of willows is a challenging problem due to the vigour of their growth, and their propensity to grow from limbs or twigs falling to the ground. The following section illustrates how some Australian stream managers are tackling the removal of willows. The removal itself is only part of the plan. Before any willows are removed, a long-term stream rehabilitation strategy should be adopted, including a revegetation technique, stream fencing, and maintenance review. Successful revegetation after removing willows is very important. Without it, the removal will most likely reduce the stability and environmental value of the stream, rather than improve it.

> Before any willows are removed, decide (and budget) on how to revegetate, fence off the stream, and who is going to do the extensive follow-up maintenance. A controlled number of willows on a stream bank is better for the stream than no vegetation at all!

3.1. When should managers consider leaving willows?

There are a few situations where willows may substantially improve the ecological recovery of stream systems, and improve the long-term stability.

- In a retard field, willows grown between the retards are very successful at trapping the fine sediment that is essential for growing native plants. In gravel-bed streams, without willows or some other vegetation type, the dominant sediment deposited behind the retards is gravel or coarse sand. It may be difficult to trap finer material. Willows tend to be better than native tree species in trapping this sediment. To an extent this may be because there has been little work on using natives in this situation, so it is not yet known which species are appropriate. When the fine sediment has accumulated, the willows should be progressively replaced by natives.

- Willows might be retained on aggressively eroding outside bends where further erosion would result in the loss of native riparian vegetation and other assets on the stream bank. Native vegetation can be planted behind the willows to progressively replace them.

- Where there are no other trees in the riverine corridor, existing willows on the banks are better than nothing for providing shade, windbreaks, biological diversity, nutrients to the aquatic ecosystem and nesting sites/cover for birds.

- Willows can protect and conserve ecologically important stands of remnant native plants from the erosive power of the river in places where the flow energy is too high for native plants alone (usually where the river is degrading due to human impact).

- Willows may be an important part of the natural heritage of a town or of a reach of rural river (eg. there is resistance to removing weeping willows along the upper Murrumbidgee River because the willows are considered to be part of the cultural landscape).

> A monoculture of willows on the banks is better than a grassed and grazed riparian zone.
>
> Willows need to be tightly managed to prevent their unwanted spread from any location where they have been retained. Willows are rapacious colonisers.

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3.2. Prioritise willow removal efforts

This section is a compilation of contributions from the above authors.

Willows have so extensively invaded our waterways, that to maximise the value of removing them we need to prioritise our actions. Priorities for willow removal are as follows.

1. **Very high.** Remove or replace all the willows identified as the species and hybrids that are supplying seed or large amounts of branches and twigs to the river. This removes the prime cause of many problems. Most willow species in New South Wales can produce seed and branches, but *Salix nigra* is the worst offender for seeding, and *Salix fragilis* is the worst offender for production of branches and twigs. Note that special training is needed to identify willow species and hybrids (general guidance is provided in Cremer *et al*. 1995). Willow seeds are transported by wind as well as streamflow, and willows producing seed germinating on streambanks may be located up to 30 km away (Cremer *et al.,* 1995).

2. **High.** Remove willows in river beds and on bars that are obstructing and diverting flow. This will have immediate physical benefits.

3. **Medium.** Replace willows on alluvial banks on straight reaches of rivers in equilibrium. This will have no physical benefit, but has a long-term ecosystem benefit.

4. **Low.** Replace willows on alluvial banks on all outside bends and on straight reaches of degrading rivers. This will be costly and time-consuming, with no physical benefit and a risk of starting accelerated erosion, but will have a long-term ecosystem benefit.

3.3. How you manage willows depends on where they are

Management of willows depends on the location of the willows and the behaviour of the river at the site. River behaviour is determined from a geomorphic analysis of field, survey and historical information. If you are unable to recognise the indicators of flow energy level, equilibrium, aggradation and degradation, consult a river behaviour specialist.

3.3.1 Removing willows from small streams

Willows are very effective at halting headcuts or knickpoints in smaller streams (up to, say, 10 m width). Willows can often be holding several metres of head-cuts in their roots over a few kilometres of stream. There are many examples of major erosion following willow removal as these head-cuts migrate upstream. Removing the willows without planning for consequent bed erosion would be foolish.

3.3.2 Managing willows in larger streams

The general rule with willows in larger streams appears to be that they should be removed wherever possible, so long as removal does not trigger major erosion, and so long as they will be replaced quickly with native vegetation. It will take only about 3–4 years for dead willows to rot away in streams. Native riparian species are ecologically better than willows, but willows are better than nothing.

3.3.3 Willows on channel beds and bars, and on bedrock banks

Willows in these situations can be completely removed (roots included) in one operation provided that:

- the trees in the bed are not controlling bed degradation (if they are preventing degradation, install bed control structures before willow removal); and

- there are other trees along the stream to provide shade etc. (if not, establish native plant communities on adjacent land and wait at least 10 years for them to mature before removing the willows).

If clearing is to be done on a long length of channel that has aggraded because of the build-up of sediment around the willows, the operation should be done in segments of no more than one kilometre per year. If too much sediment is released at once, it may choke the river channel downstream with a sediment slug. Alternatively, the sand and gravel can be removed from the river at the same time as the willows and sold to help pay for the cost of the operation. Rehabilitation of a section of the Fish River at Bathurst, New South Wales, provides an example of this. Here, the full cost of the willow removal is covered by the sale of the sand and gravel that had deposited in the river over many years. Note that in such schemes supervisors must ensure that the river bed is not lowered below its pre-aggradation equilibrium level (see *Sand and gravel extraction as a rehabilitation tool*, in Intervention in the channel, this Volume).

3.3.4. Willows on alluvial banks on equilibrium or aggrading inside bends and straight reaches

Willows can be removed (roots retained) in one operation provided that:

- replacement native trees/shrubs are planted immediately and maintained until well established;
- the roots are retained to hold the banks until the replacement trees mature;
- there are other trees along the stream to provide shade etc. (if not, establish native plant communities on adjacent land and wait at least 10 years for them to mature before removing the willows); and
- the willows are immediately replaced with permanent structural erosion controls in locations where flow energies are too high for native plants to survive.

3.3.5. Willows on alluvial banks on all outside bends and on straight, degrading reaches

Willows can be phased out according to Figure 72 provided that:

- they are killed in strips of three phases along the bank with an interval of at least 5 years between them to allow the replacement trees/shrubs to become well established (see diagram). This reduces the length of bank exposed to erosion;
- the roots are retained to hold the banks until the replacement trees mature; and
- in locations where flow energies are too high for native plants to survive, the willows are replaced only after the installation of permanent structural erosion controls (this can be done to the whole site at once).

3.3.6. Willow removal at other sites

At sites where the above-mentioned provisos cannot be met (eg. outside bend, high flow energy, no money for structural erosion control) the willows must be maintained to prevent the loss of their erosion control effects, native vegetation protection and other benefits. When maintaining willows adopt the following principles:

- poison and/or remove all individuals of willow species and hybrids in the area that are known to be producing seed or large amounts of broken twigs/branches and replace with non-seeding non-fragile species (following strategies and methods described above);
- lop frequently to prevent the willows from growing into large trees, or replace with shrub species;
- when lopping, ensure that even the smallest broken pieces are removed from the area;
- dispose of cuttings by feeding to stock or burning;
- replace dead or dying plants with cuttings from non-seeding, non-fragile species; and
- monitor the willows annually to determine when they need lopping and if any are starting to produce seed.

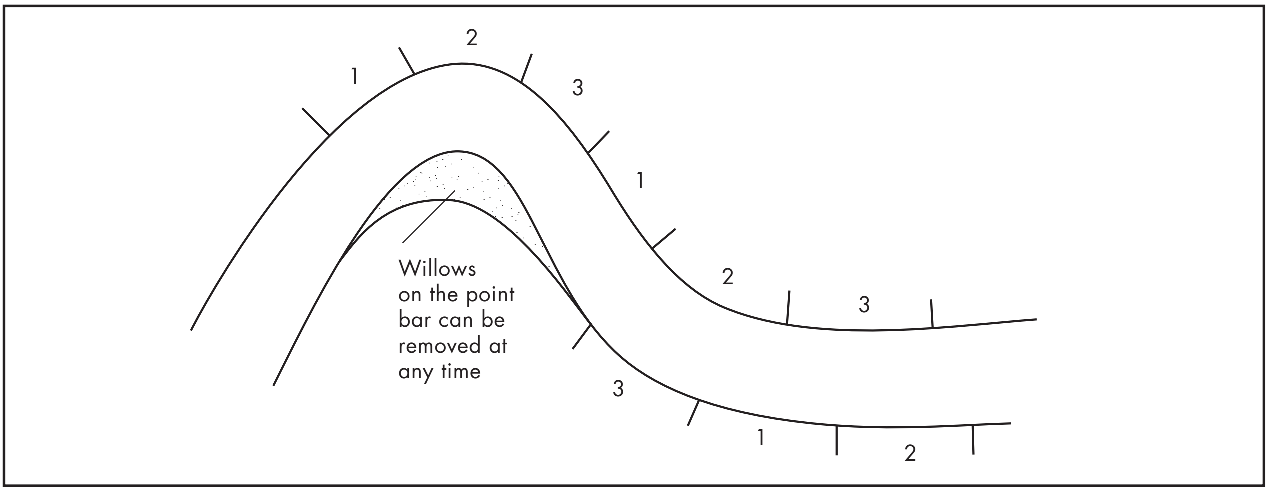

Figure 72. Phasing willows out of meander bends. The numbers represent the three phases of willow removal (figure from David Outhet).

3.4. Removing willows

There are four approaches to destroying willows: roots'n'all; poison and leave; chop and kill; and poison and cut.

3.4.1. Roots'n'all

Willows are removed roots and all, using an excavator. This is the most extreme method of removal, and is likely to be the least beneficial to the stream because the substrate is disturbed as the roots are removed and the protective root mat is not left in place while native vegetation becomes established. This method can be used in small, choked streams where the willows are in the middle of the channel, causing local flow diversion and channel erosion, or in bedrock streams where the willow roots are not stabilising the stream.

3.4.2 Poison and leave

Willows are poisoned by frill cut or stem injection (Figure 77), the trees are left intact to die and the limbs to fall and rot of their own accord. This is the cheapest willow removal method, but the stand of dead timber will be a safety hazard if the area is accessed by the public. The poor aesthetic value and rather dramatic vision of a stand of dead trees is also undesirable in highly visible areas, like up and downstream of road crossings or in public access areas. If a number of dead willows fall into the stream at the same time this may have a dramatic effect on flow conveyance. So for willow-congested streams that have nearby land uses sensitive to the effects of flooding, it may be desirable to remove willow limbs (using either the chop and poison or kill and cut method) to prevent them congesting the channel. An example of where the poison-and-leave technique is being successfully used is the La Trobe River and streams in north-eastern Victoria. Groups of willows (say up to 10 trees in a group) are treated by getting to the sites by boat and stem injecting or frill cutting the whole group of trees every 12–18 months until no new shoots are sent out.

3.4.3 Chop and poison

Willow limbs (everything above ground level) are removed with a chainsaw during the growing season, and the cut surface is sprayed or painted with poison to kill the roots and prevent the willow from re-shooting. This type of removal maintains the roots for erosion control until replanted vegetation along the stream bank is well enough established for effective erosion control. This is the most common method of willow control in Victoria and South Australia. The main concern with this approach is the dropping of viable twigs into the stream and onto the stream bank while lopping the willow. This problem can be reduced by cutting down the willow during warm, dry summer periods when the cut material will desiccate and die, at least on the stream banks.

Willow removal by the Lake Wellington Rivers Authority, Victoria

The Lake Wellington Rivers Authority (LWRA) manages the catchments in the central Gippsland area of south-eastern Victoria, including the Avon, Macalister, Thomson, and La Trobe rivers (and tributaries) which discharge into Lake Wellington (the westernmost of the Gippsland lakes). Many of the streams within this catchment are either choked with willows, or possess reaches which have a willow monoculture; other streams have pockets of willows between native riparian vegetation.

Choked and willow-lined streams

Willows are removed from choked and willow-lined streams using the cut and kill method. The following procedure was adopted by LWRA in1996.

1. Willows are cut at ground level by highly skilled chainsaw operators (the multiple trunks of willows make working with a chainsaw a hazardous business).

2. The willow stumps are painted with neat 'Roundup Bi-Active' within 20 seconds of cutting.

3. An excavator with a 'thumb' attachment is used to lift willows out of the stream and stockpile them (Figure 73).

4. The stream bank is 'stick picked' to remove any twigs or branches that can germinate.

5. Currently, the stockpiles are burnt but alternative uses for the timber are being investigated.

6. A reconnaissance visit to the site is planned for 12–18 months after initial removal to poison any new willow growth.

Figure 73. A stockpile of willows removed from the banks of the Latrobe River, Victoria.

The long-term plan for these major willow-removal exercises is to re-establish valuable riparian corridors, by eventually fencing out stock and revegetating the area with native vegetation. Figure 74 shows an example of a willow-infested stream (Traralgon Creek, near the Loy Yang mine and power station) which has had the willows removed (cut and kill method), and native species replanted.

In cases where the willow limbs are removed, they can be felled with a chainsaw and are best stockpiled using an excavator with a gripping arm or 'thumb' (Figure 75).

Figure 74. Hand-planted seedlings on Traralgon Creek (Victoria) following willow removal.

Figure 75. Gripping arm or 'thumb' attached to bucket used for willow removal on the La Trobe River, Victoria.

3.4.4. Kill and cut

The willows are poisoned by frill cut or stem injection and the limbs are cut down once the tree is dead. This approach has a distinct advantage over the cut and poison method because it limits the potential for spread of viable twigs during the lopping process in that only dead willow is handled, but removal of the dead wood may be dangerous because of its brittleness. A thick stand of willows may be a mass of intertwined branches which makes lopping even green timber dangerous. With some species of willow the increase in danger while lopping dead, brittle timber will be an unacceptable risk.

Another limitation of the kill and cut technique is that it takes at least two treatments and two growing seasons to kill the willows, hence revegetation is not started (or growing is not effective) until the third growing season after the initial poisoning. It is essential during willow removal that the soil-stabilising function of the willow roots overlaps as much as possible with the revegetation of the bank. If willow roots last only 3–4 years before rotting away, then the roots of the willows killed in the first year will last for only about one year after revegetation commences (Figure 76 compares chop and poison and kill and cut methods).

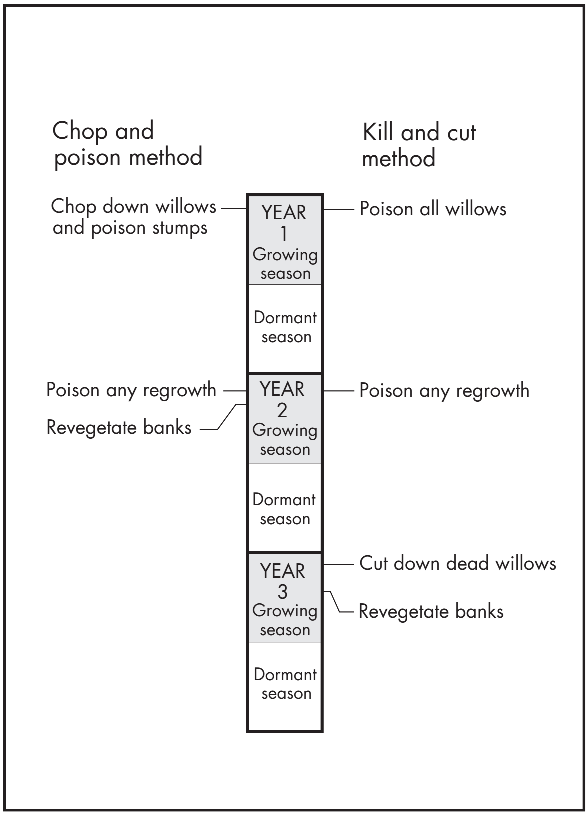

Figure 76. Chop and poison and kill and cut methods compared.

3.5. Notes on poisoning

Other than physical removal of the whole tree (including the root system, which is not recommended), all techniques use poison to kill the willows. Adherence to the following instructions will enhance the effectiveness of poisoning.

1. Poisoning willows should be done during the growing season (October–April), and is most effective in early autumn, before the leaves change colour, because this is when the plants are taking sap down to their roots.

2. Use a glyphosate herbicide such as 'Roundup Bi-Active' (usually used neat for stem injections, though some operators feel it works better diluted to speed uptake).

3. Apply poison by painting directly onto a cut stump, or stem injection (not leaf overspray). Stem injection involves using a small axe to cut into the sapwood (or drill) as per Figure 77, and form a ring of cuts or holes at about 5–10 cm intervals around the limb. The cuts should be made near the base of the limb (DNRE, no date).

4. Apply about 2 mL of herbicide to each cut into the sapwood (DNRE, no date). Herbicide can be applied using a squirt bottle or sheep drench gun.

5. Inspect the treated willows during the following growing season, and repeat the poisoning on willows which have not died (leaves or buds present) and those which were missed during the earlier run.

> Overspraying the leaf mass should not be used to poison willows near water courses.

3.6. Upstream or downstream

There is some debate about whether willow removal should proceed upstream or downstream through a stand of trees. When willows are cut down, debris invariably falls into the stream and is washed downstream, where it may establish a new willow stand. Some groups advocate starting from the downstream end and progressively removing willows upstream. This avoids the need to constantly remove debris from the tree you are about to remove. Instead, you can set up a net (fell a willow across the channel) to catch the willow debris from a whole reach and periodically remove the debris from the net. Others say that removing willows downstream is a better practice because you pick out the broken willow twigs as you go so there is reduced potential for viable twigs to become established on areas that have been cleared of willows.

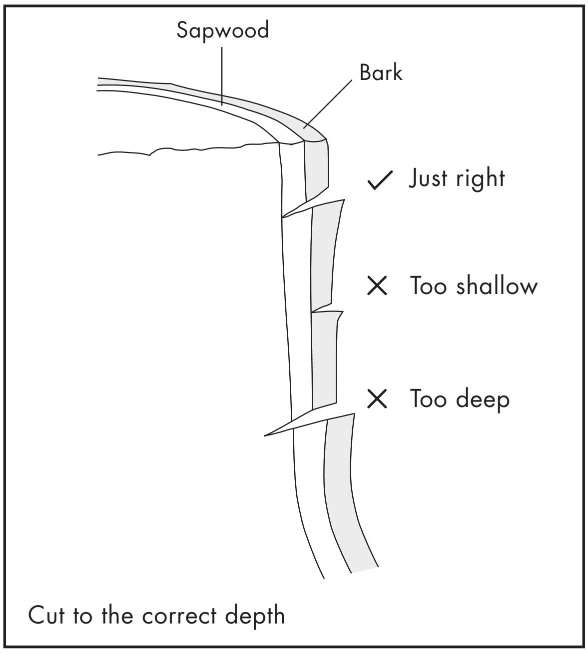

Figure 77. The appropriate depth of cut in the frill cut or stem injection technique (from DNRE, no date).

MANAGING STOCK ACCESS TO STREAMS

1. Fencing the riparian corridor

In developing this manual, catchment managers from around the country were canvassed for their views on information requirements in stream rehabilitation. Many of the responses highlighted the local problems of erosion through streamside degradation. For example, Steve Gallagher (Catchment coordinator, Pitt Water Catchment Strategy, Clarence, Tasmania) said he needed to know "how to best fence off streamside vegetation in flood prone areas. While electric fences are mobile, even these get washed away during floods". Catherine Travers, (Border Rivers Catchment Coordinating Committee, Goondiwindi, Queensland), said she required information on "combined management requirements for fencing of riparian zones".

Stock control through fencing is the most direct and effective method of riparian zone protection. There are many different types of fencing available. The two basic options are conventional and electric fencing, which are compared in Tables 2 and 3. Alternative designs for flood gates, and cheap gates for electric fences, are well covered in manufacturers' brochures and publications such as Nicholas and Mack (1996) and Tungkillo and Harrogate Landcare Groups (no date).

Table 2. A comparison of the advantages and disadvantages of conventional and electric fences.

	Conventional	Electric
Advantages	• Relatively little day-to-day maintenance. • Not reliant on external power source. • Still function when overgrown. • Familiar to most people. • Long materials life.	• Inexpensive to construct and repair. • Quick to construct and repair. • Particularly useful for flood gates. • Curves do not need corner assemblies. • Variety of options available for permanent and 'wash away' flood gates. • Animals can escape from fire and flood. • Gates can be inexpensive and simple.
Disadvantages	• Can be costly to purchase materials. • Labour-intensive to install. • Time-consuming to repair.	• Requires regular checking to ensure proper function. • Electric supply must be available (mains, battery or solar).

Table 3. A comparison of the cost per kilometre of fence for conventional and electric fences (compiled from Nicholas and Mack, 1996; and Tungkillo and Harrogate Landcare Groups, no date).

	CONVENTIONAL	1) Star picket and 5-strand barb[1]		2) Star picket and 5-strand plain[1]		3) Wooden post and ringlock[2]		ELECTRIC 4) Permanent, 5-strand[3]		
Item	**$ / item**	**No/km**	**$**	**No/km**	**$**	**No/km**	**$**	**$/item**	**No/km**	**$**
Strainers	19	5	95	5	95	5	95	21.25	2	42.50
Stays	11	8	88	8	88	8	88	13.80	4	55.2
Droppers	2	100	200	100	200	136	200	2.35	75	176.25
Star pickets	4.20	96	403.2	96	403.2	–	–	–	–	–

Table 3 (cont'd). A comparison of the cost per kilometre of fence for conventional and electric fences (compiled from Nicholas and Mack, 1996; and Tungkillo and Harrogate Landcare Groups, no date).

	CONVENTIONAL							ELECTRIC		
		1) Star picket and 5-strand barb[1]		2) Star picket and 5-strand plain[1]		3) Wooden post and ringlock[2]		4) Permanent, 5-strand[3]		
Item	**$ / item**	**No/km**	**$**	**No/km**	**$**	**No/km**	**$**	**$/item**	**No/km**	**$**
Timber posts	8	–	–	–	–	64	512	6.10	25	152.50
Plain wire 300	45	–	–	10 @ 500 m	450	–	–	90	3.3 @ 1,500 m	
Ringlock	70	–	–	–	–	10 @ 50 m	700	–	–	–
Barbed wire	45	10 @ 500 m	450	–	–	–	–	–	–	–
Insulators		–	–	–	–	–	–	0.80	50	40.00
Clamps		–	–	–	–	–	–	0.62	4	2.48
Porcelain insulators		–	–	–	–	–	–	1.13	2	2.26
Cut-out switch		–	–	–	–	–	–	8.50	1	8.50
Total cost /km		**$1,236**		**$1,236**		**$1,595**		**$779.70**		

Fence cost based on

1	2	3
5 strainers/km (approx. 1 per 200 m along creek)	5 strainers/km (approx. 1 per 200 m along creek)	2 strainers / km (one each 500 m)
2 stays per strainer	2 stays per strainer	2 stays per strainer
star pickets every 10 m	wooden posts every 15 m	wooden posts (1.8 × 100–125 mm creo posts)
droppers between each post (every 10 m)	two droppers between each post	posts 40 m apart with droppers at 10m intervals

2. Alternative stock watering

The major concern for many landholders is the issue of alternative water access options once a stream has been removed from the paddock. There are several manuals/guidelines about placing watering points, and manufacturers can provide advice on placing the different pumping alternatives. The most important issue for many landholders is to know which alternative offstream watering option is best for them, based on cost, water supply volume and physical requirements like pump capacity. The following summary table which has been adapted from Nicholas and Mack (1996) may be useful for this (Table 4).

Table 4. Offstream watering options for stock (from Nicholas and Mack, 1996).

Option	Advantages	Disadvantages	Example	Delivery head (m)	Daily volume (L)	Stocking capacity Sheep	Cattle	Capital cost ($)	Running cost
Stock access to stream watering points .	Cheap to provide.	Does not solve all problems of stock access, only limits the extent Relies on cross stream fencing. Requires stable banks inside bend and moderate velocities.	Fenced access to stable point bar.			@ 9 L/d	@ 45 L/d	Low	High maintenance

Table 4 (cont'd). Offstream watering options for stock (from Nicholas and Mack, 1996).

Option	Advantages	Disadvantages	Example	Delivery head (m)	Daily volume (L)	Stocking capacity Sheep	Cattle	Capital cost ($)	Running cost
Electric pump	Can operate from time, pressure or float switch. Low maintenance. Quiet. Low capital cost. Easy access to sales and service.	Requires access to mains power. Ongoing operational costs.	1,100 watt 240 V centrifuge.	20	9,000 L/hr	1,000	200	400	Mains power cost.
Petrol or diesel pump	Can be installed virtually anywhere.	Usually requires manual starting. Ongoing fuel costs. Ongoing engine maintenance costs.	5HP petrol centrifugal.	20	23,400	2,600	520	500	Fuel, plus high engine maintenance.
Solar pump	Versatile. Low maintenance Self starting . No running costs. Best output during summer when water is required.	High capital costs. Requires clear access to sun.	2 panel floating solar pump.	20	450	50	10	1,750	Low maintenance.
			2 panel solar helical rotor.	20	24,00	267	53	3,300	Low maintenance.
			4 panel tracking solar helical rotor.	20	9,000	1,000	200	6,840	Low maintenance.
Nose pump	Cheap to run. Delivers only water required by stock.	Suitable for small stock numbers only.	Nose pump.	5	1,000	111	22	450	Low maintenance.
Air displacement pump	Allows low-cost use of mains power up to 15 km from mains. Copes with sand. Self priming, self starting. Can operate as an automatic pressure pump. Operates efficiently over a wide range of volumes.	May require long runs of air or electric lines. Relatively high capital costs.	Air displacement.	20	9,000 L/hr	1,000	200	4,000	Electricity plus low maintenance.

Table 4 (cont'd). Offstream watering options for stock (from Nicholas and Mack, 1996).

Option	Advantages	Disadvantages	Example	Delivery head (m)	Daily volume (L)	Stocking capacity Sheep	Cattle	Capital cost ($)	Running cost
Water ram pump	No running costs. Can operate continuously. Few moving parts. New designs can use very low creek flows and heads.	Requires flowing water.	Glockemann 110 (1.4 m drop 1.2 L/s).	20	2,200	244	49	1,350	Low maintenance.
			Glockemann 220 (0.8 m drop, 3.5 L/s).	20	4,130	459	92	1,750	Low maintenance.
Wind pump	No running costs.	Requires reliable winds or alternative backup.	8 ft diameter windmill.	25	1,200	133	27	3,600	Low maintenance.

GLOSSARY

Please note: This is not an exhaustive glossary of technical terms used in this manual. There are many cases where a word is defined the first, and only time that it is used. Thus, we have endeavoured to provide definitions for words that are used several times in the text. (Some definitions here were modified from the Index of Stream Condition glossary provided by Lindsay White.)

Where a word is **bold** it means that it is defined elsewhere in the Glossary. Also note that SRM is an abbreviation for Stream Rehabilitation Manual and shorthand for A Rehabilitation Manual for Australian Streams, Volume 2, ie. this Volume.

Term	Definition
Aesthetic change	Has a **stream** become more or less attractive over time?
Aesthetics	Defined in the **SRM** as how attractive a **stream** looks to people.
Afflux	The increase in water surface elevation above an obstruction in a **stream** (a measure of the **backwater** influence of an obstruction)
Aggradation	A progressive build-up of the channel floor with sediment over several years. Distinguished from the rise and fall of the **stream** bed during a single **flood** which is called **scour** and deposition.
Algae	'Plant-like' **organisms** that use various chlorophyll compounds to convert sunlight and instream **nutrients** into energy stores. This group includes many of the algae that contribute to the thin layer of slime (**periphyton**) often found on rocks (predominantly diatoms), as well as the macroalgae which grow in long strands.
Amplitude	The width of a meander belt.
Anabranch	A secondary channel of a **stream** that leaves and then rejoins the **trunk stream**. The two channels are separated by stable, vegetated islands that divide flow at **discharges** nearly to bankfull.
Anastomosing	Multiple branching **stream** channel (strictly, **anastomosing** is a subset of **anabranching streams** restricted to fine-grained, low-gradient, organic rich systems).
ARI	**Average** recurrence interval (or **return period**) is the **average** length of time between two **floods** of a given size or larger.
Armour	A coarse layer of **gravel** overlaying finer material on a **stream** bed.
Armouring	Development of a coarse layer of **gravel** over finer sediments on a **stream** bed.
Artificial barrier	An unnatural obstacle in a **stream** (eg. a dam wall, weir, **culvert**) that affects (halts or delays) fish **migration**.
Assets	Some features that are of **value**. These can be human **assets** such as bridges or land, or they can be **natural assets** such as **organisms**. See **natural assets**.

Attraction flow	The flow in a fishway that serves to attract fish to the entrance of the fishway.
AUSRIVAS	An evaluation package which gives an indication of **stream condition** by comparing the observed aquatic **macroinvertebrate taxa** at a site to the **taxa** that were predicted to occur at the site in the absence of environmental **stress**.
Average	The number found by dividing the sum of all the quantities by the number of the quantities.
Avulsion	Sudden abandonment of one channel of a river on a **floodplain** for a new channel.
BACI design	Describes a type of experimental design standing for **B**efore–**A**fter–**C**alibration–**I**ntervention.
Backwater	This is the **pool** of slower water that develops upstream of a any flow obstruction, eg. a piece of **LWD**, or a dam.
Bacteria	Single-celled **organisms** that are associated with the decay of **organic matter**.
Bag limits	The number of fish a recreational fisherman is allowed to take from a **stream** and keep.
Bank	The relatively steep part of a **stream** channel cross-section, generally considered as being above the usual water level.
Bankfull	The junction between the **floodplain** and the **channel**. This point is often difficult to define in the field, especially where there are **benches** in the channel.
Bar	A local depositional feature within a **stream** channel. The most common types are mid-channel **bars** that form within the channel and point-**bars** that form on the inside of bends of meandering **streams**.
Base level	The lowest point to which a **stream** runs. These can be local **base levels** (such as a small lake), or the final **base level**, the sea.
Basin	In Australia, usually refers to a large **catchment** made up of several **catchments** that are large in their own right. For example, the Murray–Darling Basin.
Basket-case **reach**	A **stream reach** that is in very poor **condition**. Often the lowest priority for **rehabilitation**.
Batter	The slope of a **bank**. Often used to describe changing the bank slope.
Bed **stability**	**Bed stability** is when the **average** elevation of the **stream** bed does not change much through time. **Aggradation or degradation** are the two forms of bed instability.
Bedforms	**Dunes** and other shapes moulded in the bed of the river, usually in sand.
Bedload	The portion of the sediment load that moves along the floor of the channel.
Benches	Flat deposits of sediment that accumulate along **streams**, above the **average** water level, but below the bankfull point.

Bend apex	The point of a meander bend that has the most curvature. The head of a bend.
Billabong	A section of **cutoff stream** channel (eg. an oxbow lake) usually on a **floodplain**. The **cutoff** channel will progressively fill with sediment over time. Most are only connected to the river during **floods**. Adjacent to a lowland **reach** that is typically filled with water and only connected laterally to the river when flooding occurs.
Biodiversity	A word used to describe biological heterogeneity. It covers the number of **species** of plants and animals present, as well as how different they are from one another.
Bio-engineering	Incorporating vegetation into engineering structures (eg. willows into **bank** rip-rap).
Biofilm	The mixture of benthic **algae**, **bacteria** and fungi which forms a film on submerged surfaces. This layer is the food source for many **macroinvertebrates**. Also known as **periphyton**.
Bio-indicators	Using the health or **diversity** of **organisms** in a **stream** as a measure of the health of the **stream** (especially in relation to pollution).
Biological **monitoring**	The **monitoring** of **organisms**.
Biomass	A measure of the weight of a selected group of **organisms** (eg. algal **biomass**, **macroinvertebrate biomass**) usually expressed as weight per square metre of streambed.
Biota	Plants and animals.
Buffer strips	(see **buffer-zone**)
Buffer-zone	Usually refers to a strip of **riparian** vegetation that separates a **stream** from a potentially damaging land use.
Catchment	The area of land drained by a river and its tributaries.
Catchment management	Actions to manage the human impact on a **catchment** with the intention of protecting the **natural values** of the **catchment**, whilst protecting its productive potential.
Chain-of-ponds	A type of **natural stream morphology** once common in humid Australia, but now largely destroyed. Characterised by prominent ponds separated by densely vegetated zones.
Channelisation	Engineering actions designed to increase the capacity of a channel to carry **flood** waters (typically include **desnagging**, straightening, and deepening).
Clay	Sediment smaller than about 4 microns in diameter.
Clear-water release	Release of a flow, usually from a reservoir, that carries less sediment than the water is capable of transporting. This usually leads to bed and **bank erosion**.
Clear-water **scour**	The **stream** channel **erosion** that is produced by a **clear-water release**.
Cobbles	**Gravels** larger than about 60 mm in diameter (about the size of a fist).

Collectors	Animals that collect detrital material for consumption.
Colonisation	In biological terms, an expansion in the **habitat** occupied by **organisms** by moving into new areas.
Community	An ecological term which collectively describes all the **species** occurring at a location.
Complexity	Structural **diversity**. A measure of how complicated something is.
Condition	State, quality relative to some standard.
Confinement	The width of the active **floodplain** of a **stream**. Narrow **floodplains** can be confined by **terraces** or rock walls.
Connectivity	The physical connection between places. In a **stream**, refers to connection along a **stream's** length (longitudinal **connectivity**), and between the **stream** and its **floodplain** (lateral **connectivity**).
Control (for evaluation)	(**Evaluation**) This is a sampling site or **reach** which is the same as the **rehabilitation** site in every way, except that it is not rehabilitated. The control site is compared with the **rehabilitation** site as a way of checking that any changes are a result of the **rehabilitation**, rather than some other unconnected event affecting the whole **stream**.
Control (hydraulic)	The point in a **stream** (such as a constriction or weir) that controls the upstream water level.
Conveyance	The amount of **discharge** that a **stream** can carry.
Cover	To do with vegetation density, the spread over the ground surface within the streamside zone when viewed from above. Also to do with instream **cover**. For biologists, **cover** can also mean **cover** for fish and other animals in a stream.
Crash grazing	A short burst of grazing in a protected area.
Created **assets**	In the **SRM** these are defined as **assets** that have been created by human **disturbance** and should be preserved even though they might not resemble the **'natural' condition** (eg. artificially stocked population of a rare fish).
Critical flow	Flow with a **Froude number** of 1.
Culverts	Pipes or other structures used to pass water under roads and other crossings.
Cumbungi	Otherwise known as bulrush. A common, tall rush in slow moving waters (Typha spp.).
Cutoffs	(Meander **cutoffs**) Where the **stream** cuts through the neck of a meander bend.
Cyanobacteria	A group of photosynthetic **bacteria**, also known as blue-green **algae**. Many **species** are found in water, and a few produce toxins that can kill ih sufficiently high concentrations.
Decomposers	**Organisms** such as **bacteria** and fungi which break down **organic matter** chemically.

Degradation	**Degradation** has a broad meaning of reduction in quality, and a specific meaning in **geomorphology** of general lowering of a **stream** bed, usually over a period of years, by **erosional** processes.
Degraded **assets**	In the **SRM**, this has the specific meaning of a **natural asset** that has been damaged by human impact so that it no longer has the qualities of the original asset.
Desnagging	Removing **large woody debris** from the bed of **streams**, to increase **conveyance.**
Dessication	Drying out.
Detritivores	Animals that consume **detritus**.
Detritus	Decaying **organic matter** (predominantly leaves and other vegetable matter).
Direct seeding	A method of revegetation where seed is spread directly onto the prepared ground rather than being germinated in nurseries and grown as **tubestock**.
Discharge	The amount of water flowing in a **stream**.
Discontinuous gully	A gully that is not continuous. Incised sections of gully are separated by zones of deposition where there is little incision.
Dispersal	The movement of animals or plants from their established range into new areas. The main types of **dispersal** in **streams** are **drift**, aerial **dispersal** and **migration**.
Dissolved oxygen	Oxygen that is dissolved in water and is therefore available for use by aquatic plants and animals.
Disturbance	A process that pushes a **stream** or its elements away from an **equilibrium** state. This can be a short-lived push (a **pulse disturbance**) or a more permanent push (a **press disturbance**).
Diversity	A measure of how varied something is. An ecological **community** with greater **diversity**, will have a large range of **species** within it.
DLWC	The Department of Land and Water Conservation in New South Wales.
Drift	A mechanism which allows the downstream **migration** of **organisms**. They simply let go of the **substrate** and **drift** with the flow.
Drowned out	An obstacle to flow (eg. a weir) is **drowned out** if the water surface elevation immediately downstream of the obstacle is approximately equal to the water surface elevation immediately upstream, and there is no sudden change in the water surface between the two points.
Dune	A bedform formed in sand in the bed of a **stream**, usually in the order of tens of centimetres high and long.
Duration	The length of time over which something operates. In **hydrology**, usually refers to the amount (or percentage) of time that a flow is exceeded.

Dynamic **equilibrium**	Oscillations around a gradually changing mean state in a system (eg. a change in the composition of **macroinvertebrate** communities as shading reduces water temperature).
Ecology	The study of **organisms** and how they interact with each other and their physical surroundings.
Ecosystem	The sum of everything pertaining to **ecology** at a location. This includes physical **habitats** and **organisms**.
Effluent	The point at which flow leaves one channel to flow in an **anabranch**.
Electrical conductivity	A measure of salinity. The higher the **electrical conductivity** of a **stream** the greater the salinity.
Electrofishing	A method of fishing which uses electric currents to stun fish.
Emergent **macrophytes**	Aquatic plants, such as rushes and **cumbungi**, that are rooted below the water but also extend above the water.
Environmental **flow regime**	A pattern of flows released from a dam or other regulating structure that are designed to enhance the environmental **condition** of a **stream** given other demands placed on water from the **stream**.
EPA	Environmental Protection Authority
Ephemeral **stream**	A **stream** which flows intermittently, ie. it is often dry.
Equilibrium	The **condition** of a **stream** (whether physical or biological) is stable in relation to the inputs into the system.
Erosion	Modification of the channel boundary by entrainment and removal of sediment.
Estuary	The portion of the mouth of a river that is affected by tides (and hence also salinity).
Eutrophication	A process which involves the overgrowth of **algae** and **macrophytes** in a water body due to excessive **nutrient** loads.
Evaluation	In the **SRM**, an assessment of the effectiveness of a **strategy**. Usually based on **monitoring** of some sort, but different from **monitoring** in that **evaluation** involves an assessment of success or failure, not just its description.
Evaluation plan	(**Evaluation**) The detailed plan of how you do your experiment—what you measure, when, how often etc.
Evolution of **habitat**	Progressive changes in **habitat** in a **natural stream** (eg. progressive filling of a cut-off meander bend).
Execution	How the **rehabilitation strategy** is carried out in practice.
Exotic plants and animals	**Species** of plants or animals that are not naturally found in an area (ie. not indigenous to the area). Carp, trout and tilapia are examples of **exotic** fish **species**, and willows are an example of an **exotic** plant. Note that a native Australian **species** is an **exotic** when introduced outside its **natural** range.

Exponential	A constantly doubling number sequence (eg. 2,4,8,16….).
Extraction	Artificial removal of sand or **gravel** from a **stream**.
Failure plane	The surface around which mass-failure occurs on a **stream bank** (often identified by a tension crack).
Fatal **problems**	**Fatal problems** in a **stream** are so severe that they threaten the viability of the **organisms** living a **stream**, eventually leading to extinction. There may be no point working on other **problems** until these ones are fixed.
Feasibility	An assessment of whether a **strategy** can really be carried out. See also **terminal unfeasibility**.
Feral animals	Animals introduced into Australia from another country and declared to be **feral** by government (ie. they must be destroyed by law) (eg. foxes, cats, rabbits, carp).
Filamentous **algae**	**Algae** that grow in long thin strands.
Filter feeders	A form of collector, which uses net-like structures to extract passing detrital material from the **stream**.
Fish passage	The movement of fish around an obstacle.
Flood	A flow in a **stream** that exceeds the normal channel capacity and goes over the **banks** onto the **floodplain**.
Flood frequency	How often the **stream** goes over its **banks**. Usually expressed as the probability that the flow will exceed some size in a single year (thus the 1-in-100 year **flood** would have a 1% probability of being equalled in any one year. See also **ARI** and **return period**.
Flood runner or chute	A channel that only flows during **floods** (may be an **anabranch**, but it may be smaller).
Floodouts	A zone of deposition at the downstream end of a gully or other source of increased sediment transport.
Floodplain	A flat area adjacent to a **stream** that is covered by **floods** every year or two. Note the distinction from a **bench** (which is flooded much more often) and a **terrace** (which is only very rarely flooded).
Flow regime	The typical, predictable pattern of flows experienced by a **stream** over many seasons and years. The set of flows considered to be responsible for the character of the **stream** system.
Flow regulation	Changes to the timing and volume of flow brought about by dams, diversions or other interference in a river.
Food web	The structure used by ecologists to represent the links between **organisms** within the **stream**. It is based upon the order in which various **organisms** consume one another.
Frequency	How often something occurs.

Froude number	Ratio of inertial to gravitational forces in a flow. The speed of a small wave on the water surface relative to the velocity of the water as a whole.
Gabions	Baskets of **grave**l or rocks enclosed by wire used for protecting **stream** bed and **banks**.
Gauge	A device for continuously measuring the **stage** of water in a **stream**.
Gauging structure	A structure in a **stream** that is used to measure the volume of flow. The structure that is normally found in a **stream** is a concrete weir or sill.
Geodiversity	The number of discrete landform types in a **region**.
Geographical information system	A computer program that manages spatial data in layers. Abbreviated to **GIS**.
Geomorphology	**Geomorphology** is the study of the Earth's landforms including their origin and structure. Fluvial **geomorphology** is the subset that deals with **streams**.
GIS	See **Geographical information system**.
Goal	The end-point that you are working towards in your **rehabilitation**. May be defined in terms of the original **condition** of a **stream**.
Grade control structure	A structure built in the bed of a **stream** to limit **erosion** of the bed. Can be built of rock, concrete or wood. Operates by reducing velocity, by encouraging vegetation, and by introducing a hard point in the bed.
Gravel	All sediment particles greater than 2 mm in diameter (includes the sub-classes of granule, pebbles, **cobbles** and boulders in the Wentworth particle size scale).
Groynes	Solid deflection structures in a **stream** (partial-width structures) that extend to close to the **bank** top.
Habitat	Loosely defined as a set of physical **conditions** in which an organism can live.
Head cut	Also called a **knickpoint**. A very steep section of **stream** bed that migrates upstream if not held by a bed control. Downstream of a **head cut** is normally incised and unstable.
Headwaters	The most upstream, steepest, portions of a **catchment** that deliver most water to a **stream** system.
Heavy metals	Metals with an atomic number greater than 20 (eg. mercury and copper). As pollutants, they are persistent and can be harmful to a range of aquatic **organisms**.
Herbaceous weed	Any weed that does not develop a woody stem.
Herbivores	Animals which consume plant (and **algal**) material.
Hydraulic geometry	A set of power functions that relate changes in the width, flow depth, and velocity of a channel to changes in **discharge**.

Hydraulic radius	The ratio of the cross-sectional area of a channel to the wetted perimeter (ie. the length of the boundary that is in contact with the water).
Hydraulics	The study of the physical effects of the passage of water (as opposed to **hydrology** which is concerned with the amount of water moving around).
Hydrology	The science that considers the distribution of water over the land (as opposed to **hydraulics** that considers the physical effects of the water in its passage).
Impeded **recovery**	**Recovery** of a **stream** or its components that is constrained by one or a few press or **pulse disturbances** (eg. cattle grazing or point-source pollution).
Incised **stream**	A **stream** that has eroded its bed and **banks** such that it has a very low **flood frequency**. In other words, the channel cross–sectional area is obviously too large for its **catchment** area.
Inflection point	The point in a **stream** bend where one bend ends and the next one begins (often occurs at a **riffle**).
Integrity	The **condition** of a system relative to its original **condition**.
Interstitial spaces	The gaps between the particles that make up the **stream** bed. These spaces are important **habitat** for many **macroinvertebrates**.
Invertebrates	Animals without backbones.
Junction	The point at which two **streams** join.
Knickpoint	Oversteepened point of **erosion** in a **stream** bed. May be a small waterfall. Also called a **headcut**.
Large woody debris	A dead tree, or portion of a tree, that has fallen into a **stream**. Usually considered to be greater than 0.1 m in diameter, and over a metre long. Also called **snags** or **LWD**.
Larva	A stage in the **life cycle** of some aquatic **invertebrates**. Larvae generally do not resemble the adult form and undergo a pupal stage before becoming an adult.
Larval fish	Fish that have just hatched. They are often very different in form to their parents.
Lateral barriers	A barrier restricting water and material flow between a **stream** and its **floodplain** (artificial levees would be an example).
Levee	A high-point next to a **stream bank** that is higher than the **average** height of the surrounding **floodplain**. May be formed **naturally** or artificially.
Life cycle	A cycle which links the various forms of an organism from egg to adult.
Limiting **problems**/variables /requirements	This is a resource that is required by an organism to survive, but that is most lacking from the **stream**. The limiting requirement limits the ability of a population to recover from **disturbance**.

Linked problems	**Problems** that are linked so that there is less point fixing one unless you can fix the other. So, successfully fixing one **problem** depends on fixing another **problem** first.
Longitudinal barriers	Barriers along a **stream**'s length that disrupt the movement of water and material (eg. carbon) along the **stream**.
Longitudinal continuity	A measure of the continuity of the movement of water and material along a **stream**. Continuity may be reduced by **natural** or **artificial barriers** (eg. willow jams, concrete dams, diversion channels, pumps).
Lowland **reaches**	Lowlands are broad alluvial or coastal **floodplains**.
LWD	**Large woody debris**.
Macrocrustaceans	Crustaceans such as shrimp and crayfish which are large enough to be seen without a hand lens.
Macroinvertebrate	An invertebrate (animal without a backbone) that is visible to the naked eye.
Macrophyte	A water plant. It may be either floating or rooted. Also, see **emergent macrophyte**.
Manning's 'n'	The **roughness** coefficient in the Manning's velocity equation. A crude measure of the resistance to flow in a channel, but is likely to contain all of the uncertainties in a velocity prediction or measurement.
Mannings equation	An empirical equation (ie. based on experiments rather than theory) used to estimate the velocity, and hence **discharge**, of a flow.
Mass wasting/failure	Gravity failure of a slope (including a **stream bank**) as a single block.
Median	The middle number of a series. If the sequence has an even number of values, the **median** is the **average** of the two middle values.
Megalitre	One million litres (divide by 86.4 to convert to cubic metres per second).
Migration (of animals)	Recurring long distance travel by an organism. Many fish **species** migrate up and down rivers to complete different parts of their **life cycle**.
Migration (of meander bends)	**Erosion** of the outside (concave) **bank** of a river such that the river progressively moves across or down the valley.
Modified **catchment**	A **catchment** that has been altered by human impact. The most common impacts include altered land use and **flow regime**, and the introduction of **exotic** plants and animals.
Monitoring	Gathering information about something in a **stream rehabilitation** project. May involve measuring or simply observing change. An essential component of **evaluation**.
Morphology	The shape of something.
Natural	Defined here as pre-European **condition**, including the rates and types of **disturbance** that took place.

Natural assets	Defined in the **SRM** as features of a **stream** that are in close to **natural** (ie. pre-European) **condition**. Examples would be an endangered fish **species**, well preserved **riparian** vegetation, or a whole **reach** that retains many of the original features.
Natural flows	The flow that would have existed if present rainfall patterns fell on **catchments** before European settlement.
Natural Heritage Trust	Money provided for environmental work by the Federal Government following the part-sale of Telstra. At least tens of millions of dollars are being directed to **stream rehabilitation** activities. Also known as NHT.
Nitrogen	One of the main **nutrients**.
Non-point source	(or diffuse source). Pollution that is contributed from numerous small sources as opposed to a single **point-source**.
Nutrients	Chemicals (usually refers to **nitrogen** and **phosphorus**) that are essential for plant and animal growth.
Nymphs	A stage in the **life cycle** of some aquatic insects. **Nymphs** have a similar form to the adult insect, but lack wings.
Objectives	A clear, measurable statement of what a manager aims to achieve in a project. These are the specific aims of a **rehabilitation** project, and are the small steps on the path to achieving your **goals**.
Off-channel watering	Stock watering point provided away from the **stream banks**, eg. water may be pumped to troughs in a paddock.
Organic matter	Carbon-based matter of organic origin. This includes vegetable matter as well as the bodies of dead animals.
Organisms	Plants, animals, fungi and **bacteria**. Things that live.
Overstorey	**Woody plants** greater than 5 m tall, usually with a single stem (eg. eucalypts, banksias, acacias, and willows).
Parish plans	Survey plans made by government of a 'Parish' at first settlement, showing the settlement blocks. An historical source.
Perching (at **culverts**)	A small waterfall formed by a man-made obstruction that forms a barrier to **fish passage**.
Perennial flow	Flowing all year.
Periphyton	A thin layer of **algae, bacteria** and fungi which grows on **stream substrates**.
Permanent **stream**	A **stream** that flows for all of most years.

Permeable **groynes**	(More correctly **'retards'**) **Groynes** constructed of material that allows water to pass around them (eg. logs, train tracks), as opposed to solid **groynes** made of rock or concrete.
pH	A measure of the concentration of the acidity or alkalinity of the water (hydrogen ions in water).
Phosphorus	One of the main **nutrients**.
Phragmites reeds	Also known as 'common reeds' (Phragmites australis). Occur in slow moving water.
Pilot study	A small project designed to check the **feasibility** of a method or technique before launching into a major project.
Planform	The shape of a **stream** as seen from the air.
Planktonic **algae**	**Algae** that float free in the water.
Point bar	A sandy deposit on the inside of a meander bend.
Point source	A pollution source that can be pinpointed.
Pool	The deepest point of a **stream** bed. **Pools** usually occur at the outside of **stream** bends and may be separated by shallower areas called **riffles**.
Press **disturbance**	A long-term **disturbance**.
Problem	In the **SRM**, a '**problem**' is defined strictly as any process or attribute that threatens a **natural asset** or causes it to be damaged, or to no longer be in its **natural condition**.
Producers	**Organisms** that can use **nutrients** to generate energy. This includes plants, **algae** and **bacteria**.
Prograde	Slowly move into, usually used in the sense of sand gradually moving into a lake or other water body.
Pulse **disturbance**	A short-lived **disturbance**.
Q	The symbol for **discharge**.
QDNR	Queensland Department of Natural Resources.
Radius of curvature	The radius of a circle that fits into a meander bend.
Rating	A non-dimensional number for an indicator that is evaluated by converting raw data (eg. **total phosphorus** concentrations or observations on site) using a **rating** table.
Reach	A length of **stream**, typically 5 to 30 km long, which is relatively homogenous with regard to the **hydrology**, physical form, water quality and aquatic life.

Reach priority categories	The nine (9) priority categories that **reaches** can be assigned to in setting priorities for **stream rehabilitation** in the **SRM**.
Reality check	A point in the **stream rehabilitation** planning procedure when you decide if you should go back to an earlier step.
Recolonisation	The return of a species or community to an area after some form of **disturbance**.
Recovery	Return of a **stream** system to some state that is considered desirable (usually the **natural** state) following **disturbance**.
Recovery pathway	The stages through which a system passes as it gradually recovers.
Regeneration	Vegetation that has grown from **natural** sources of seed or from vegetative growth, without being artificially planted.
Regime channel	A **stream** channel that is 'in **regime**' neither **degrades** or **aggrades** over time.
Region	A loose term relating to a tract of country with broadly similar characteristics (eg. the dry tropics is a **region**).
Regional conservation **value**	An **asset** that is rare within a **region** (as opposed to an **asset** that is rare within a **catchment** but not within a **region**—which would be classified as having local conservation **value**).
Regulated **stream**	**Stream** flows controlled by releases from a dam, or by some other artificial control.
Rehabilitation	The return of as much as possible of the original, pre-European characteristics of a **stream**, including the physical structure and **stability**, water quality, **flow regime**, and the suite of **organisms** in the **stream**. The **organisms** present in the **stream** are a good measure, in most cases, of the health of the **stream**, and thus whether it is being rehabilitated. Ideally, improvements introduced to the **stream** should be self-sustaining.
Rejuvenation	An increase in **stream erosion** following a fall in the **base level**. The **rejuvenation** can proceed as a 'wave' up the tributaries of a **stream** system.
Remediation	Attempts to improve the **condition** of a **stream** may produce a **stream** that is very different from the **natural stream**, but nonetheless improved. **Remediation** is often an appropriate **goal** in urban **stream rehabilitation**.
Replication	(**Evaluation**) This is repeat sampling to identify the inherent variability in the system. You can have replicates on many scales—replicate rivers to see if the results can be applied to different **streams**; replicate study sites within a river to see if all **reaches** react in the same way; replicate **samples** over time, to measure the temporal variability; and replicate sub-samples within a **sample**, to measure spatial variability. Thus, when you **sample**, you might take 10 **samples** from the **reach** instead of one, or 10 **samples** from 10 **streams** at the same time.

Replication	Copying the original state.
Resilience	The ability of a **community** or system to return to **equilibrium** after a **disturbance**.
Restoration	Replicating the original state of a **stream** in regard to water quality, structure and **stability**, **flow regime**, and plant and animal communities.
Retards	Permeable partial-width structures that only extend to a small percentage of the **bank** height.
Return period (of **floods**)	(More correctly '**average** recurrence interval' or **ARI**) The **average** time in years between two **floods** of a given size or larger.
Revetment	Artificial bank protection, eg. rip-rap.
Riffle	The high point in the bed of the **stream** between two **pools** (it is often covered in **gravel** or coarser material and experiences rapid, turbulent low flows).
Riparian	Pertaining to the **banks** of a river (usually more broadly defined as a strip of land tens of metres wide along the **banks** of **stream**).
Ripples	**Bedforms** that are smaller than **dunes** (usually centimetres in height).
Root wads	The root balls of trees placed in **streams**. This is usually done by driving the trunk into the **bank**.
Roughness	A general measure of the hydraulic resistance caused by obstructions to flow (often measured by the 'n' coefficient in the **Manning's equation**).
Saline **pools**	Where salt seeps into a deep hole in the **stream** bed, and it can accumulate in the bottom of the hole (saline water is denser than freshwater), with salinities often approaching that of seawater. **Saline pools** are common in **streams** in northern and western Victoria.
Salmonids	A family of fish from the Northern Hemisphere. This family includes trout and salmon. There are no native Australian **salmonids**.
Sample	(**Evaluation**) A measurement of some sort. It could be anything from the **average** depth of **erosion** at a site, as measured by **erosion** pins, to a measure of water quality, or a survey of the invertebrate population present at a site.
Sediment slug	A wave of sand or **gravel** that moves down a **stream** channel (usually introduced into the **stream** in a pulse by mining, gullying, major **floods** or other extreme events).
Scaling	A **template reach** may be found in a different part of the **catchment** than the **target reach**. The dimensions of the **template reach** that are related to the position of the **reach** in the **catchment** (eg. sediment size, slope, channel size) need to be adjusted to reflect the dimensions that would be expected in the **target reach**, given the position and different **condition** of the **target reach** in the **catchment** (eg. you will probably need to design a larger channel in a cleared **catchment** than in a forested one).

Scour	The short-term **erosion** of a **stream** bed (ie. the bed **scours** and then fills to about the same level, unless it is **degrading** or **aggrading**).
Scour chains	Chains inserted vertically into the sand or **gravel** of a **stream** bed in order to measure the amount of **scour** and **fill** taking place during a **flood**.
Scrapers	Animals which consume the **periphyton** which grows on the surface of rocks, plants and coarser **organic matter**.
Seasonality (of flows)	A difference in flows between seasons of the year.
Secondary circulation	A flow velocity across the channel that leads to spiralling currents along the channel. The circulation is associated with channel bends and is responsible for **erosion** of meander bends.
Secondary effects	Consequences of a **rehabilitation strategy** that are not related to the **goal** or objective of the **strategy**. Thus, an increase in **flood duration** is a secondary effect of adding **LWD** to a **stream**, when the primary effect that was intended was an increase in **habitat diversity**.
Sediment trap	A structure across a **stream** that creates a **backwater** in order to trap sediment.
Seeding willows	Willows usually reproduce by vegetative growth from cuttings. Some fertile willows can reproduce by producing seed.
Segment	A long portion of **stream** (consisting of several **reaches**) that is defined by the general geological character of the **catchment** (eg. changes in bedrock, faults, long **reaches** with similar slope etc.).
Shear **stress**	The force applied to the bed of a **stream** by the depth of water (roughly increases with the depth of water and the slope).
Sheet **erosion**	**Erosion** of the surface of a paddock or other portion of the **catchment** as a thin layer of soil.
Shredders	Animals that reduce coarse **organic matter** to smaller particles while feeding upon it.
SIGNAL index	An indicator in the Aquatic Life Sub-index that measures effect of pollution on aquatic **biota**. **SIGNAL** is an acronym for Stream Invertebrate Grade Number-**Average** Level.
Silt	Particles bigger than **clay** (say 4 microns) and smaller than sand (about 0.06 mm).
Sinuosity	The 'wiggliness' of a **stream** (measured as the length of the river measured along the **thalweg** divided by the valley length measured down the middle of the meander belt).
Skimming	Removing sand or **gravel** from point-**bars** above the **averag**e water level in the river.
Slug	See **sediment slug**.
Sluglettes	Small **slugs** of sand that are deposited in certain **reaches** of the Glenelg River. The sluglette usually occupies a **riffle** area above a **pool**. See **sediment slug**.

Snags	**Large woody debris**, but generally referring to the larger logs in a **stream**.
Spawning	Depositing or releasing eggs/sperm (usually in large numbers). A process employed by animals with external fertilisation such as frogs and fish.
Specific **gauge**	A plot of the change in **stream stage** (water level) for the same **discharge** over time.
SRM	Stream Rehabilitation Manual, ie shorthand for A Rehabilitation Manual for Australian Streams, Volume 2 (ie. this manual).
Stability	Little change. The term is usually applied to a **stream** channel that does not change much over decades.
Stage	The elevation of the water surface relative to a datum.
Stakeholder	A person or group with an interest in a **stream** (the interest may or may not relate to **rehabilitation**).
Steady-state **equilibrium**	The **average condition** that a system returns to following numerous **disturbances**.
Strategy	The general approach that a manager plans to use to address a **problem**. Not a detailed plan. For example: "We will stabilise the bed" is a **strategy**; "We will stabilise the bed with a rock chute with the following design characteristics" is a detailed plan.
Stream	Drainage features from small creeks to large rivers. Generally the drainage feature occurred in some form prior to European settlement.
Stream frontage	The **riparian** zone of a **stream**, but usually defined in terms of cadastral boundaries (eg. in Victoria there is a 20 m Crown **frontage** to many **streams**).
Stream management	Managing all human interaction with a **stream** (a subset of **catchment management**).
Stream power	The proportion of a **stream**'s energy that is available to do work (ie. **erosion** and sediment transport). Roughly the product of slope and **discharge**.
Stress	**Disturbance** pressure which is placed upon a biological population, or ecological **community**, and results in a shift from an established **equilibrium**.
Subaerial **erosion**	**Erosion** of **streams** that is caused by processes unrelated to the flow of water in the **stream** (eg. **erosion** by cattle).
Sub-sampling	(**Evaluation**) Sometimes, a **sample** is made up of many sub-samples. For example, if you wanted to know the rate of **erosion** at one site, you might use several **erosion** pins. The sub-samples would be the individual pins, and the **sample** would be the **average** rate of **erosion** around all the pins at the site. This means you can estimate how much variation there is at any one site.
Substrate	In biology refers to any surface that **organisms** use. In **geomorphology** refers more specifically to the sediment on the bed of the **stream**.

Succession	The ecological process in which several communities replace one another as the physical **conditions** change.
Supercritical flow	Flow with a **Froude number** greater than 1.
Survival	In the **SRM**, refers to whether a **stream rehabilitation** action has survived for a defined period (eg. the artificial **riffles** survived the 5 year **flood** undamaged).
Suspended load	Sediment that is carried suspended in the water column.
Suspended sediment concentration	The amount of sediment carried suspended in the water column, usually measured in mg/L.
Sustainable/sustainability	Management decisions or **rehabilitation** works result in **sustainable** ecological communities if the **community** does not **degrade** and maintains its **equilibrium** without further intervention.
Target **reach**	The **reach** that you want to rehabilitate.
Target **species**	The **species** of animal or plant that you want to return to the stream.
Taxa	Plural of **Taxon**.
Taxon	A taxonomic division, such as Family or Order.
Template reach	A **reach** of **stream** that is in close to original/**natural**/pre-European **condition**. This **reach** is then used as a **template** that can be copied when rehabilitating other **reaches** of a **stream**.
Terminal un**feasibility**	A **strategy** or objective proves to be so unfeasible that it has to be abandoned or adjusted in a major way.
Terrace	A flat surface lying above the elevation of the **floodplain**. Often a former **floodplain**. **Terraces** will be seldom, if ever, flooded.
Terrestrial organisms	Animals and plants that live on the land.
Thalweg	Deepest point of a channel cross-section.
Threat	A process that through time could lead to deterioration of **condition**.
Threshold	The point at which a sudden, large change occurs, resulting from gradual changes that produced little change, eg. a gradual decline in winter flows from a dam appeared to have little impact on fish until they suddenly reached a threshold where **spawning** ceased.
Thresholds of concern	The point at which an impact (eg. pollution levels) begins to threaten the **organisms** living in a **stream**.
Total **phosphorus**	The sum of the concentrations of soluble and insoluble **phosphorus**.

Toxicants	The vast array of organic and inorganic chemicals that find their way into **streams** where they can potentially cause considerable **problems**. The Australian Water Quality Guidelines for Marine and Fresh Waters lists 18 inorganic **toxicants**, which are mainly **heavy metals**, and many more organic **toxicants**, including several pesticides, detergents, and many chemicals used in industry as solvents, chemical intermediates etc.
Trajectory	The path of **condition** that a **stream** follows after a **disturbance**. The **stream** may deteriorate or improve over time.
Trap efficiency	The proportion of sediment trapped in a particular storage zone (eg. a dam or **stream reach**).
Treatment or intervention	(**Evaluation**) This is the thing that you do to the **stream** (in this case, some **stream rehabilitation** activity).
Treatment site or reach	In **evaluation**, the **reach** or site in which the changes take place, as opposed to the **control reach** in which no change is made.
Tributary	A smaller **stream** that joins a larger one.
Tributary **streams**	**Tributary streams** are defined in the Index of Stream Condition as those **streams** which have a **catchment** area between 5,000 hectares and 30,000 hectares.
Trunk **stream**	The largest **stream** in a **catchment**.
Tubestock	Plants grown in tubes that are then individually planted as a revegetation technique.
Turbidity	The cloudiness of water caused by reduction in the transmission of light. Often caused by **suspended sediment** and other material. **Turbidity** is usually measured in Nephelometric Turbidity Units.
Uncontrolled experiment	(**Evaluation**) Does not refer to a lack of discipline, rather it refers to a project that has no control site or **reach**.
Upland **reaches**	**Stream reaches** characterised by narrow **terraces** and **floodplains**, usually occurring in the headwaters of a **catchment**.
Urban areas	**Urban areas** are shown as built up on current street directories (eg. Melways).
Value	Worth, importance. There are different types of **values** including environmental, heritage, and recreational **values**. Generally, the more **natural** the **condition** of a **stream**, the higher its environmental **value**.
Vision	The same meaning as **goal** in the **SRM**.
Watercourse	The same meaning as **stream** channel.
Waterwatch	**Community** water quality sampling program.
Weir crest	Highest point of a weir across a **stream** (ie. the lip of the weir).

Width of **stream**	The **average** distance from one **bank** of the **stream** to the other at the bankfull point (ie. the point at which the flow goes onto the **floodplain**).
Woody plants	Vegetation with a distinct trunk and branch structure, ranging from trees to small shrubs.

Bibliography

Abbe, T.B. and D.R. Montgomery, 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research and Management*, 12: 210–221.

Abbe, T.B, D.R. Montgomery and C. Petroff, 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 and F.D. Shields, Jr. (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, pp. 809–815.

Alvarado, R., 1978. *Minimum Design Standards for Log Weirs*. United States Forest Service Report, Pacific Northwest Region, Malheur National Forest.

Anderson, J., 1993. *State of the Rivers: Maroochy River and Tributary Streams*. Maroochy Shire Council and Queensland Department of Primary Industries, Maroochy, Queensland.

Andrus, C., 1991. *Improving Streams and Watersheds In Oregon: Inventory and Evaluation of Efforts to Improve the Condition of Oregon's Streams and Watersheds from 1985 to 1990*. Water Resources Department, Oregon.

Anon, 1990. *Fish Migrations in the River Murray and Fish Passage Through the Torrumbarry Fishway*. Progress Report, Jan–Oct 1990. Natural Resources Management Strategy.

ANZECC, 1992a. *Australian Water Quality Guidelines for Fresh and Marine Waters*. Australia and New Zealand Environment and Conservation Council.

ANZECC, 1992b. *Soil and Water Contamination Guidelines*. Australia and New Zealand Environment and Conservation Council.

Apmann, R.P., 1972. Flow processes in open channel bends. *Journal of Hydraulics Division, (ASCE—American Society of Civil Engineers)*, 98(5): 795–810.

AVRMA, 1994. *River Management Works—The Picture after the '93 Floods*. Association of Victorian River Management Authorities.

Barker, J., G.C. Grigg and M.J. Tyler, (1995) *A Field Guide to Australian Frogs*. Surrey Beatty and Sons Pty Ltd.

Barton, J. and F. Cron, 1979. *Restoration of Fish Habitats in Relocated Streams*. Department of Transportation Federal Highway Administration, Washington DC.

Bell, I. and T. Priestley, 1999. Management of stock access to the riparian zone. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide.* Cooperative Research Centre for Catchment Hydrology, pp. 51–56.

Benson, M.A. and D.M. Thomas, 1966. A definition of dominant discharge. *Bulletin of the International Association of Scientific Hydrology*, 11: 76–80.

Beschta, R.L., W.S. Platts and J.B. Kauffman, 1992. *Field Review of Fish Habitat Improvement Projects in the Grande Ronde and John Day River Basins of Eastern Oregon*. USDE, Benneville Power Administration, DOE/BP-2 1493-1, Portland, Oregon.

Beschta, R.L., W.S Platts, J.B. Kauffman and M.T. Hill, 1994. Artificial stream restoration—money well spent or an expensive failure? In: *Environmental Restoration, Proceedings UCOWR 1994 Annual Meeting, Big Sky Montana*. The Universities Council on Water Resources, pp. 76–102.

Bilby, R.E., 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed, *Ecology*, 62: 1234–1243.

Bilby, R.E., 1984. Removal of woody debris may affect stream channel stability. *Journal of Forestry*, 82: 609–612.

Bird, J.F., 1982. Channel incision at Eaglehawk Creek, Gippsland Victoria. *Proceedings of the Royal Society of Victoria*, 94: 11–22.

Bird, J.F., 1985. Review of channel changes along creeks in the northern part of the Latrobe River basin, Gippsland Victoria, Australia. *Zeitschrift für Geomorphologie*, 55: 97–111.

Bird, P.R., J.J. Lynch and J.M. Obst, 1984. Effect of shelter on plant and animal production. *Proceedings of the Australian Society of Animal Production*, 15: 270–273.

Bisson, P.A., R.E. Bilby, M.A. Bryant, A.A. Dolloff, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski and J.R. Sedell, 1987. Large woody debris in forested streams in the Pacific Northwest: past, present and future. In: E.O. Salo and T.W. Cundy (eds.), *Streamside Management: Forestry and Fishery Interactions*. College of Forest Resources, University of Washington, Institute of Forest Resources, Contribution No. 57, Seattle, Washington, pp. 143–190.

Bonham, A.J., 1980. *Bank Protection Using Emergent Plants Against Boatwash in Rivers and Canals*, Report IT206. Hydraulic Research, Wallingford.

Bonney, N., no date. *What Seed is That*? Finsbury Press Pty Ltd.

Booth, D.B., D.R. Montgomery and J.P. Bethel, 1996. Large woody debris in urban stream channels of the Pacific Northwest. In: Roesner, L.A. (ed.), *Effects of Watershed Development and Management of Aquatic Ecosystems*. Engineering Foundation Conference Proceedings, Snowbird, Utah, 4–9 August.

Bootle, K.R., 1991. *Wood in Australia: Types, Properties and Uses*. McGraw Hill, Sydney.

Borchadt, D., 1993. Effects of flow and refugia on drift loss of benthic macroinvertebrates: implications for habitat restoration in lowland streams. *Freshwater Biology*, 29: 221–227.

Boulton, A., 1999. The role of subsurface biological filters in gravel bed river rehabilitation strategies. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide.* Cooperative Research Centre for Catchment Hydrology, pp. 81–86.

Bourman, R., 1975. Environmental geomorphology: examples from the area south of Adelaide. *Proceedings of the Royal Geographical Society of Australasia (South Australian Branch)*, 76: 1–23.

Bowler, J.M., 1978. Quaternary climate and tectonics in the evolution of the Riverine Plain, southeastern Australia. In: J.L. Davies and M.A.G. Williams (eds.), *Landform Evolution in Australasia*. Australian National University Press, Canberra, pp. 70–112.

Bradbury, J., P. Cullen, G. Dixon and M. Pemberton, 1995. Monitoring and management of streambank erosion and natural revegetation on the Lower Gordon River, Tasmanian Wilderness World Heritage Area, Australia. *Environmental Management*, 19(2): 259–72.

Bradley, J.N., 1970. *Hydraulics of Bridge Waterways*. US Department of Transport, Washington, 111 pp.

Brekhovskikh, V.F., V.K. Debolsky, G.N. Vishnevskaya and N.S. Zolotareva, 1991. Erosion of cohesive bottom sediments: the influence of benthos. *Journal of Hydraulic Research*, 29(2): 149–60.

Breusers, H.N.C. and A.J. Raudkivi, 1991. *Scouring*. Balkema, Rotterdam.

Brierley, G.J., 1999. River styles: an integrative biophysical template for river management. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide*. Cooperative Research Centre for Catchment Hydrology, pp. 93–100.

Brierley, G.J. and K. Fryirs, 1997. *River Styles in Bega Catchment: Implications for Management*. Workshop and Field Days. Land and Water Resources Research and Development Corporation and Macquarie University.

Brierley, G.J., K. Fryirs and T. Cohen, 1996. *Geomorphology and River Ecology in Southeastern Australia: An Approach to catchment Characterisation: Part One: a Geomorphic Approach to Catchment Characterisation*. Working Paper, 9603. Graduate School of the Environment, Macquarie University, Sydney.

Brierley, G.J. and C.P. Mum, in press. European impacts on downstream sediment transfer and bank erosion in Cobargo Catchment. *Catena*.

Brizga, S.O., 1991. *River Channel Changes in Gippsland, Victoria*. PhD Thesis, University of Melbourne.

Brizga, S.O., M.F. Carden and N.M. Craigie, 1996a. The role of non-structural options in the management of laterally unstable streams in NE Queensland. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, pp. 289–94.

Brizga, S.O., I.D. Rutherfurd, H. Locher, C. Kenyon, I. Reinfelds, D. Fabel and B.L. Finlayson, 1996b. *Sedimentation in the Lower Yarra River*. Environmental Report Series, 10. Melbourne Parks and Waterways.

Brooks, A., 1994. *Vegetation and Channel Morphodynamics along the Lower Bega River*. Honours Thesis, Macquarie University.

Brooks, A., 1999. Lessons for river managers from the fluvial Tardis: direct insight into post-European channel changes from a near-intact alluvial river. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide.* Cooperative Research Centre for Catchment Hydrology, pp. 121–128.

Brookes, A., 1987. Restoring the sinuosity of artificially straightened stream channels. *Environmental Geology and Water Science*, 10(1): 33–41.

Brookes, A., 1989. *Channelized Rivers. Perspectives for Environmental Management*. John Wiley and Sons, Chichester, 326 pp.

Brookes, A., 1990. Restoration and enhancement of engineered river channels: some European experiences. *Regulated Rivers: Research and Management*, 5: 45–56.

Brookes, A., 1996. River restoration experience in northern Europe. In: A. Brookes and F.D. Shields, Jr. (eds.), *River Channel Restoration*. John Wiley and Sons, Chichester, pp. 233–67.

Brookes, A. and F.D. Shields, Jr., 1996. Perspectives on river channel restoration. In: A. Brookes and F.D. Shields, Jr. (eds.) *Channel Restoration. Guiding Principles for Sustainable Projects*. John Wiley and Sons, Chichester, pp. 1–19.

Brush, L.M., 1961. Drainage basins, channels and flow characteristics of selected streams in central Pennsylvania. *United States Geological Survey Professional Paper* 282F, pp. 145–181.

Bryant, M.D., 1983. The role and management of woody debris in west coast salmonid nursery streams. *North American Journal of Fisheries Management*, 3: 322–330.

Bunn, S.E., P.M. Davies and D.M. Kellaway, 1997. Contributions of sugar cane and invasive pasture grass to the aquatic food web of a tropical lowland stream. *Marine and Freshwater Resources*, 48: 173–9.

Bunn, S.E., P.M. Davies, D.M. Kellaway and I.P. Prosser, 1998. Influence of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian shading. *Freshwater Biology*, 39(1): 171–8.

Burston, J. and W. Brown, 1996. Watercourse revegetation—just a walk in the park! In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, pp. 247–51.

Caitcheon, G., 1990. Sedimentation in Lake Albert–the history of sediment sources and catchment sediment yields. *Australian Journal of Soil and Water Conservation*, 3(4): 42–6.

Chadwick, A. and J. Morfett, 1993. *Hydraulics in Civil and Environmental Engineering: Second Edition*. E & FN Spoon, London.

Chang, H.H., 1988. *Fluvial Processes in River Engineering*. John Wiley and Sons, New York.

Charbonneau, R. and V.H. Resh, 1992. Strawberry Creek on the University of California, Berkeley Campus: a case history of urban stream restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 2: 293–307.

Chessman, B.C., 1995. Rapid assessment of rivers using macroinvertebrates: a procedure based on habitat-specific sampling, family-level identification and a biotic index. *Australian Journal of Ecology*, 20(1): 122–129.

Chessman, B.C., J.E. Growns and A.R. Kotlash, 1997. Objective derivation of macroinvertebrate family sensitivity grade numbers for the SIGNAL biotic index: application to the Hunter River system, New South Wales. *Marine and Freshwater Research*, 48: 159–172.

Chong, S.E., 1970. The width, depth and velocity of the Sungei Kimla Perak. *Geographica*, 6: 72–83.

Chow, V.T., 1959. *Open Channel Hydraulics*. McGraw Hill, New York.

Clark, C., 1987. Deforestation and floods. *Environmental Conservation*, 14: 67–69.

Clay, C.H., 1995.*Design of Fishways and Other Fish Facilities.* CRC Press, Boca Raton, Florida.

Coehn, J., 1988. *Statistical Power Analysis for the Behavioural Sciences*, 2nd Edition. Lawence Erlbaum, Hillsdale, New Jersey.

Commonwealth Department of Finance, 1991. *Handbook of Cost–Benefit Analysis*. Australian Government Publishing Service, Canberra.

Conrick, D. and J. Ribi, 1996. *Urban Stream Rehabilitation: Principles and Guidelines*. Brisbane City Council, Brisbane.

Copeland, R.R., 1983. *Bank Protection Techniques Using Spur Dikes*, miscellaneous paper HL-83-1. US Army Corps of Engineers, Vicksburg, Mississippi.

Coppin, N.J. and I.G. Richards, 1990. *Use of Vegetation in Civil Engineering*. Construction Industry Research and Information Association/Butterworths, London, 292 pp.

Cowan, W.L., 1956. Estimating hydraulic roughness coefficients. *Agricultural Engineering*, 37: 473–5.

Cremer, K.W., C. Van Kraayenoord, N. Parker and S. Streatfield, 1995. Willows spreading by seed. Implications for Australian river management. *Australian Journal of Soil and Water Conservation*, 8(4): 18–27.

Cunnane, C., 1978. Unbiased plotting positions— review. *Journal of Hydrology*, 37: 205–222.

D'Aoust, S., 1998. Ballasting of large woody debris structures—new insights. *Streamline* (British Columbia's Watershed Restoration Technical Bulletin), 3: 17–18.

Dalton, G., 1993. *Direct Seeding of Trees and Shrubs: a Manual for Australian Conditions*. Primary Industries (South Australia), Adelaide.

Danley, H.D., M.J. Eubanks and C.L.J. Jemigan, 1995. *Twentymile Creek Habitat Restoration Project*. US Army Corps of Engineers, Mobile, Alabama.

Darby, S. and C.R. Thorne, 1996. Predicting stage–discharge curves in channels with bank vegetation. *Journal of Hydraulic Engineering*, 122(10): 583–586.

Davies-Colley, R.J., C.W. Hickey, J.M. Quinn and P.A. Ryan, 1992. Effects of clay discharges on streams. 1. Optical properties and epilithon. *Hydrobiologia*, 248: 215–234.

Davis, J. and B. Finlayson, 1999. The role of historical research in stream rehabilitation: a case study from Central Victoria. In: I. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide, South Australia*. Cooperative Research Centre for Catchment Hydrology, pp. 199–204.

DC&E, 1990. *Environmental Guidelines for River Management Works*. Office of Water Resources, Department of Conservation and Environment, Victoria, Melbourne.

De Silva, S.S., P.R. Cumaranatunga and C.D. De Silva, 1980. Food, feeding ecology, and morphological features associated with feeding of four co-occuring cyprinids (pisces: Cyprinidae). *Netherlands Journal of Zoology*, 30: 54–73.

DeBano, L.F. and B.H. Heede, 1987. Enhancement of riparian ecosystems with channel structures. *Water Resources Bulletin*, 23: 463–470.

Department of Water Resources, no date. *Manual of River Management Practices*. Department of Water Resources, Muswellbrook, NSW.

Derrick, D.D., 1997. Harland Creek Bendway Weir/Willow Post Bank Stabilisation Demonstration Project. In: S.S.Y. Wang, E.J. Langendoen and F.D. Shields, Jr. (eds.), *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. Mississippi, pp. 351–356.

Diehl, T.H., 1997. *Potential Drift Accumulation at Bridges*. Publication No. FHWA-RD-97-028, US Department of Transportation Federal Highway Administration, Research and Development, McLean, Virginia.

DNRE, 1997a. *Index of Stream Condition: A Reference Manual*. Department of Natural Resources and Environment, Victoria, 109 pp.

DNRE, 1997b. *Index of Stream Condition: User's Manual*. Department of Natural Resources and Environment, Victoria, 67 pp.

DNRE, 1997c. *Index of Stream Condition: Trial Applications*. Department of Natural Resources and Environment, Victoria, 127 pp.

DNRE, no date. *Exotic Trees Along Watercourses*. Department of Environment and Natural Resources, South Australia.

Drummond, I., J.W. Tilleard and B. Dyer, 1995. *Retards and Groynes: Design Guidelines (Update of 1991 version)*. Standing Committee on Rivers and Catchments, Victoria.

Dury, G.H., 1965. Theoretical implications of underfit streams. *United States Geological Survey Professional Paper* 452C.

DWR, 1992. *The NSW Sand and Gravel Extraction Policy for Non Tidal Rivers*. NSW Department of Water Resources.

Dyer, B.G., A.W. Western and R.B. Grayson, 1995. *Hydraulic Characteristics of Retards*. Centre for Environmental Applied Hydrology, University of Melbourne, Melbourne.

Dyson, J.R., 1966. Sand deposits in the MacDonald and Colo Rivers. *Journal of Soil Conservation Service of N.S.W.*, 22(4): 158–173.

Elser, A.A., 1968. Fish populations of a trout stream in relation to major habitat zones and channel alterations. *Transactions of the American Fisheries Society*, 97(4): 389–397.

Enger, P.F., E.T. Smerdon and F.D. Masch, 1968. Erosion of cohesive sediments. Report of the Task Committee on erosion of cohesive sediments. *Journal of the Hydraulic Division (ASCE—American Society of Civil Engineers)*, 94(HY4): 1017–1049.

Erskine, W.D., 1986. River metamorphosis and environmental change in the Macdonald valley, New South Wales, since 1949. *Australian Geographical Studies*, 24: 88–107.

Erskine, W.D., 1990. Environmental impacts of sand and gravel extraction on river systems, In: P. Davie and D. Low Choy, *The Brisbane River: A Source Book for the Future*. Australian Littoral Society and Queensland Museum, Brisbane, pp. 295–302.

Erskine, W.D., 1990. Hydrogeomorphic effects of river training works: the case of the Allyn River, N.S.W. *Australian Geographical Studies*, 28: 62–76.

Erskine, W.D., 1992a. Channel response to large-scale river training works: Hunter River, Australia. *Regulated Rivers*, 7: 261–278.

Erskine, W.D., 1992b. *An Investigation of Sediment Sources in the Genoa River Catchment*. East Gippsland River Management Board.

Erskine, W.D., 1993. Erosion and deposition produced by a catastrophic flood on the Genoa River, Victoria. *Australian Journal of Soil and Water Conservation*, 6: 35–43.

Erskine, W.D., 1994. Sand slugs generated by catastrophic floods on the Goulburn River, New South Wales. In: L.J. Olive, R.J. Loughran and J.A. Kesby (eds.), *Variability in Stream Erosion and Sediment Transport, Canberra*. International Association of Hydrological Sciences (IAHS), pp. 143–151.

Erskine, W.D., 1996. Response and recovery of a sand-bed stream to a catastrophic flood. *Zeitschrift für Geomorphologie*, 40(3): 359–383.

Erskine, W.D., I.D. Rutherfurd, T. Ladson and J.W. Tilleard, 1993. *Fluvial Geomorphology of the Goulburn River Basin*. Consultants Report, ID&A Consultants. Mid-Goulburn Catchment Coordinating Group Inc.

Erskine, W.D., I.D. Rutherfurd and J.T. Tilleard, 1990. *Fluvial Geomorphology of the Tributaries to the Gippsland Lakes*. Consultants report to the Department of Conservation and Environment, Victoria.

Erskine, W.D. and M.J. Saynor, 1995. *The Influence of Waterway Management on Water Quality with Particular Reference to Suspended Solids, Phosphorus and Nitrogen*. Broken River Management Board, Department of Conservation and Natural Resources, Victoria, 82 pp.

Erskine, W. and N. Terrazzolo, 1996. *Potential Environmental Impacts of Sand and Gravel Extraction on the Mid-Goulburn River, Victoria*. Consulting Report, Appendix A. North Central Waterways Management Board.

Erskine, W.D. and R.F. Warner, 1998. Further assessment of flood- and drought-dominated regimes in south-eastern Australia. *Australian Geographer*, 29(2): 257–261.

Erskine, W.D. and L.J. White, 1996. Historical river metamorphosis of the Cann River, East Gippsland, Victoria. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, pp. 277–282.

European Inland Fisheries Advisory Commission, 1965. Water quality for European fish: report on finely divided solids and inland fisheries. *International Journal of Air and Water Pollution*, 9: 151–168.

Eyles, R.J., 1977a. Birchams Creek: the transition from a chain of ponds to a gully. *Australian Geographic Studies*, 15: 146–157.

Eyles, R.J., 1977b. Changes in drainage networks since 1820, Southern Tablelands, N.S.W. *Australian Geographer*, 13: 377–386.

Farraday, R.V. and F.G. Charlton, 1983. *Hydraulic Factors in Bridge Design*. Hydraulics Research Station Limited, Wallingford, England.

Finlayson, B.L. and T.A. McMahon, 1988. Australia v the World: a comparative analysis of streamflow characteristics. In: R.F. Warner (ed.), *Fluvial Geomorphology of Australia*. Academic Press Australia, Sydney, pp. 17–40.

Frankcombe, M. and L. Whitfield, 1992. *Interim Report on the Role of Eductor Dredging in the Queensland Mining Industry*. Unpublished interim report. Department of Resource Industries, Queensland.

Frankenberg, J., 1995. Willows: the species, their biology and control. *In: Willows, Weeds and Fish, Proceedings of the River Basin Management Society Summer Conference, 20 November, Geelong*. River Basin management Society, Melbourne.

Frankenberg, J., W.K. Tennant and W. Tilleard, 1996. Mechanisms of streambank erosion. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, pp. 93–98.

French, R., 1986. *Open-Channel Hydraulics*. McGraw-Hill Book Co, Singapore.

Frissell, C.A., W. Liss, C.E. Warren and M.D. Hurley, 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management*, 10(2): 199–214.

Frissell, C.A. and R.K. Nawa, 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. *North American Journal of Fisheries Management*, 12: 182-197.

Galay, V.J., 1983. Causes of river bed degradation. *Water Resources Research*, 19(5): 1057–1090.

Garvin, R.J., M.R. Knight and T.J. Richmond, 1979. *Guidelines for Minimising Soil Erosion and Sedimentation from Construction Sites in Victoria*, TC-13. Land Disturbance Working Party, Soil Conservation Authority, Melbourne.

Gaydon, B.P., G.A. Murphy, L. Hinrichsen and A. Markham, 1996. Management plan for the Upper Condamine River and tributaries. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, pp. 149–155.

Gilbert, G.K., 1917. Hydraulic mining debris in the Sierra Nevada. *United States Geological Survey, Professional Paper*, 105: 1–154.

Gippel, C.J., 1985. Changes in stream channel morphology at tributary junctions, Lower Hunter Valley, New South Wales. *Australian Geographical Studies*, 23: 291–307.

Gippel, C.J., 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering*, 121: 388–395.

Gippel, C.J., B.L. Finlayson and I.C. O'Neill, 1996a. Distribution and hydraulic significance of large woody debris in a lowland Australian River. *Hydrobiologia*, 318: 179–194.

Gippel, C.J., B.L. Finlayson and I.C. O'Neill, 1998. *Managing Snags in Rivers*. Land and Water Resources Research and Development Corporation, Canberra. Online at <http://www.lwrrdc.gov.au>.

Gippel, C.J., I. O'Neill and B. Finlayson, 1992. *The Hydraulic Basis of Snag Management*. Report to the Land and Water Resources Research and Development Corporation. University of Melbourne.

Gippel, C.J., I.C. O'Neill, B.L. Finlayson and I. Schnatz, 1996b. Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research and Management*, 12: 223–236.

Gordon, N.D., 1996. *The Hydraulic Geometry of the Acheron River, Victoria, Australia*. Centre for Environmental and Applied Hydrology, Department of Civil and Environmental Engineering, University of Melbourne, Melbourne.

Gordon, N.D., T.A. McMahon and B.L. Finlayson, 1992. *Stream Hydrology, an Introduction for Ecologists*. John Wiley and Sons, Chichester.

Gore, J.A., 1985. Mechanisms of colonization and habitat enhancement for benthic macroinvertebrates in restored river channels. In: J. Gore (ed.), *The Restoration of Rivers and Streams*. Butterworth Publishers.

Gore, J.A. and F.L. Bryant, 1988. River and stream restoration. In: J.J. Cairns (ed.), *Rehabilitating Damaged Ecosystems*, I. CRC Press, Boca Raton, Florida, pp. 23–38.

Gore, J.A. and L.S. Johnson, 1980. *Establishment of Biotic and Hydrologic Stability in a Reclaimed Coal Strip-mined River Channel*. Water Resources Research Institute Report. University of Wyoming, Laramie.

Gore, J.A. and R.D.J. Judy, 1981. Predictive models of benthic macroinvertebrates density for use in in-stream flow studies and regulated flow management. *Canadian Journal of Fisheries and Aquatic Science*, 38: 1363–1370.

Gore, J.A. and F.D. Shields, Jr., 1995. Can large rivers be restored? *Bioscience*, 45(3): 142–152.

Gorman, O.T. and J.R. Karr, 1978. Habitat structure and stream fish communities. *Ecology*, 59(3): 507–515.

Grant, T., 1995. *The Platypus: a Unique Mammal*. University of New South Wales Press, Sydney.

Gray, D.H. and R.B. Sotir, 1995. *Biotechnical Stabilization of Steepened Slopes*. Transportation Research Board 74th Annual Meeting.

Gray, D.H. and R.B. Sotir, 1996. *Biotechnical and Soil Bioengineering Slope Stabilisation: a Practical Guide for Erosion Control*. Wiley, New York, 378 pp.

Grayson, R.B., B.L. Finlayson, C.J. Gippel and B.T. Hart, 1996. The potential of field turbidity measurements for the computation of total phosphorus and suspended solids loads. *Journal of Environmental Management*, 47: 257–267.

Green, R.H., 1979. *Sampling Design and Statistical Methods for Environmental Biologists*. Wiley, Chichester.

Greening Australia Ltd, 1990. *Sowing the Seed. Direct Seeding and Natural Regeneration*.

Gregory, K., A. Gurnell and C. Hill, 1985. The permanence of debris dams related to river channel processes. *Hydrological Sciences*, 30(3): 371–381.

Gregory, K.J., A.M. Gumell, C.T. Hill and S. Tooth, 1994. Stability of pool–riffle sequence in changing river channels. *Regulated Rivers: Research and Management*, 9: 35–43.

Gurnell, A.M. and K.J. Gregory, 1981. The influence of vegetation on stream channel processes. In: T.P. Burt and D.E. Walling (eds.), *Catchment Experiments in Geomorphology*. Geo Books, Norwich, pp. 515–535.

Hader, W., 1991. *Technical Exchange, Water Resources Bavaria*. New South Wales Department of Land and Water Conservation Publication, Sydney.

Hanley, N. and C.L. Spash, 1993. *Cost–Benefit Analysis and the Environment*. Edward Elgar Publishing Co.

Hansen, H.O. and B.L. Madsen (eds.), 1996. *River Restoration—Danish Experience and Examples*. National Environmental Research Institute Denmark, Silkeborg, 99 pp.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr. and K.W. Cummins, 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research*, 15: 133–302.

Harrelson, C.C., C.L. Rawlins and J.P. Potyondy, 1994. *Stream Channel Reference Sites. An Illustrated Guide to Field Technique*. General Technical Report, RM-245. Forest Service, United States Department of Agriculture, Fort Collins, Colorado, USA.

Harris, J.H., 1980. *Ecology of Selected Estuarine Organisms*. Technical Report. University of New South Wales, Sydney.

Harris, J.H., 1984. Impoundment of coastal drainages of south-eastern Australia, and a review of its relevance to fish migration. *Australian Zoologist*, 21: 235–250.

Harris, J.H. and M. Mallen-Cooper, 1994. Fish passage developments in the rehabilitation of fisheries in mainland south-eastern Australia. In: I. Cowx (ed.), *Proceedings of the International Symposium and Workshop on Rehabilitation of Inland Fisheries, Hull*. Fishing News Books, pp. 185–193.

Hart, B.T., P. Bailey, R. Edwards, K. Hortle, K. James and A. McMahon, 1990. Effects of salinity on river, stream and wetland ecosystems in Victoria, Australia. *Water Research*, 24: 1103–1107.

Hart, B.T., P. Bailey, R. Edwards, K. Hortle, K. James and A. McMahon, 1991. A review of the salt sensitivity of the Australian freshwater biota. *Hydrobiologia*, 210: 105–144.

Hart, B.T. and I.D. McKelvie, 1986. Chemical limnology in Australia. In: P. De Dekker and W.D. Williams (eds.), *Limnology in Australia*. Commonwealth Scientific and Industrial Research Organisation/Dr W Junk, Melbourne, pp. 3–32.

Hart, D.D., 1978. Diversity in stream insects: regulation by rock size and microspatial complexity. *Verh. International Verein. Limnology*, 20: 1376–1381.

Harvey, A.M., 1969. Channel capacity and the adjustment of streams to hydrologic regime. *Journal of Hydrology*, 8: 82–98.

Harvey, A.M., D.H. Hitchcock and D.J. Hughes, 1979. Event frequency and morphological adjustment of fluvial systems. In: D.D. Rhodes and G.P. Williams (eds.), *Adjustments of the Fluvial System*. Kendall Hunt, Dubuque, Iowa, pp. 139–167.

Harvey, M.D. and C.C. Watson, 1986. Fluvial processes and morphological thresholds in incised channel restoration. *Water Resources Bulletin*, 22(3): 359–368.

Hean, D.S. and G.C. Nanson, 1987. Serious problems in using equations to estimate bedload yields for coastal rivers in N.S.W. *Australian Geographer*, 18(2): 114–124.

Heede, B.H., 1972. Influences of a forest on the hydraulic geometry of two mountain streams. *Water Resources Bulletin*, 8: 523–530.

Heinemann, H.G., 1981. A new sediment trap efficiency curve for small reservoirs. *Water Resources Bulletin*, 17(5): 825–830.

Henderson, F.M., 1966. *Open Channel Flow*. Macmillan Publishing Co. Inc., New York.

Henderson, J.E. and F.D. Shields, Jr., 1984. Environmental features for streambank protection measures. *Technical Report E-84-11*, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Henry, H.M., 1977. Catastrophic channel changes in the MacDonald Valley, New South Wales 1949–1955. *Journal and Proceedings, Royal Society of New South Wales*, 110: 1–16.

Herron, N., 1993. *An Investigation of Temporal and Spatial Patterns of Gully Initiation Following European Settlement in Southeastern Australia*. Honours Thesis, Macquarie University, School of Earth Sciences.

Hey, R.D., 1988. Mathematical models of channel morphology. In: M.G. Anderson (ed.), *Modelling Geomorphological Systems*. John Wiley & Sons Ltd., pp. 99–125.

Hey, R.D., 1992. River mechanics and habitat creation. In: K.T.O. Grady, P.B. Butterworth and J.C.J. Domancewski (eds.), *Fisheries in the Year 2000*, pp. 271–285.

Hey, R.D., 1994. Environmentally sensitive river engineering. In: G.E. Petts and P. Calow (eds.), *River Restoration*. Blackwell, Oxford.

Hey, R.D. and G.L. Heritage, 1988. Dimensional and dimensionless regime equations for gravel-bed rivers. In: W.R. White (ed.), *International Conference on River Regime, Wallingford, Oxfordshire, UK*. John Wiley & Sons. Ltd., pp. 1–8.

Hey, R.D. and C.R. Thorne, 1986. Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering*, (*ASCE—American Society of Civil Engineers*), 112(8): 671–689.

Hicks, B., A. Raine, G. Crabbe and M. Elsley, 1999. The use of long-stem tubestock as an alternative to willows for controlling streambank erosion. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 331–334.

Hicks, B.J. and G.H. Reeves, 1994. Restoration of stream habitat for fish using in-stream structures. In: K. Collier (ed.), *Restoration of Aquatic Habitats—Selected Papers from the Second Day of the New Zealand Limnological Society 1993 Annual Conference*. Department of Conservation, pp. 67–91.

Hilderbrand, R.H., A.D. Lemley, C.A. Dolloff and K.L. Harpster, 1998. Design considerations for large woody debris placement in stream enhancement projects. *North American Journal of Fisheries Management*, 18: 161–167.

Hodgkins, D. and G. Bennison, 1997. Can the community contribute to data collection as part of monitoring river health? *Monitoring River Health, LaTrobe University*. River Basin Management Society.

Hogan, D.L., 1986. Channel morphology of unlogged, logged and debris torrented streams in the Queen Charlotte Islands. *Land Management Report No. 49*. British Columbia Ministry for Lands.

House, R.A., 1996. An evaluation of stream restoration structures in a coastal Oregon stream, 1981–1993. *North American Journal of Fisheries Management*, 16: 272–281.

House, R.A., and P.L. Boehue, 1985. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. *North American Journal of Fisheries Management*, 5: 283–295.

House, R.A., V. Crispin and R. Monthey, 1989. Evaluation of stream rehabilitation projects—Salem district (1981–1988). *US Bureau of Land Management Technical Note TIN OR-6*.

Huang, H.Q. and G.C. Nanson, 1997. Vegetation and channel variation; a case study of four small streams in southeastern Australia. *Geomorphology*, 18: 237-249.

Hunt, R.L., 1976. A long-term evaluation of trout habitat development and its relation to improving management-related research. *Transactions of the American Fisheries Society*, 105(3): 361–364.

Hupp, C.R. and A. Simon, 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. *Geomorphology*, 4: 111–124.

Ian Drummond and Associates, 1996. *Hydraulic Geometry of Brisbane Streams: Guidelines for Natural Channel Design: Part 1—Guidelines*. Final Report. Brisbane City Council.

Ian Drummond and Associates, W.D. Erskine, J. Frankenberg, B. Sharp, Fisher Stewart and Read Sturgess and Associates, 1992. *Glenelg Catchment Waterway Management Study*. Final Report. Shire of Dundas.

Jackson, PD., 1978a. Benthic invertebrate fauna and feeding relationships of brown trout Salmo trutta Linneaus, and river blackfish *Gadopsis martoratus* Richardson, in the Aberfeldy River, Victoria. *Australian Journal of Marine and Freshwater Research*, 29: 725–742.

Jackson, P.D., 1978b. Spawning and early development of the river blackfish *Gadopsis marmoratus* (Gadopsiformes: Gadopsidae) in the McKenzie River, Victoria. *Australian Journal of Marine and Freshwater Research*, 29: 293–298.

Jenkins, G.A., N. Fernando and R.G. Black, 1997. Design of natural urban stream systems using regime equations. *27th IAHR Congress. Water for a Changing Global Community, San Francisco*. International Association of Hydrological Research (IAHR).

Johnson, A.W. and J.M. Stypula, 1993. *Guidelines for Bank Stabilisation Projects in the Riverine Environments of King County.* King County Department of Public Works, Surface Water Management Division, Seattle, Washington.

Kanaly, J., 1975. *Stream Improvement Evaluation in the Rock Creek Fishway, Carbon County (Addendum)*. Administrative report for project 5075-08-6602. Wyoming Game and Fish Department, Fish Division, Cheyenne, Wyoming.

Kapitzke, R., S. Smithers and J. Lowry, 1996. Channel change, bank stability and management for North Queensland coastal streams. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 177–182.

Kehe, S.M., 1984. *Streambank Protection by Use of Spur Dikes*. Masters of Science Thesis, Oregon State University, Corvallis, 78 pp.

Keller, E.A., 1978. Pools, riffles, and channelization. *Environmental Geology*, 2(2): 119–127.

Keller, R.J., 1995. *Meander Re-instatement Using Submerged Weirs*. Department of Civil Engineering, Monash University, Melbourne.

Kellerhals, R., 1971. Sampling procedures for coarse fluvial sediments. *Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers*, 8(August): 1165–1180.

Kilpatrick, F.A. and H.A. Barnes, 1964. Channel geometry of piedmont streams as related to frequency of floods. *United States Geological Survey Professional Paper* 422E, pp. 1–10.

Kirk, J.T.O., 1985. Effects of suspendoids (turbidity) on penetration of solar radiation in aquatic ecosystems. *Hydrobiologia*, 125: 195–208.

Kirkup, H., G. Brierley, A. Brooks and A. Pitman, 1998. Temporal variability of climate in south-eastern Australia: a reassessment of flood- and drought-dominated regimes. *Australian Geographer*, 29(2): 241–255.

Knighton, A.D., 1974. Variation in width-discharge relation and some implications for hydraulic geometry. *Bulletin of the Geological Society of America*, 85: 1059–1076.

Knighton, A.D., 1984. *Fluvial Forms and Processes*. Edward Arnold, London.

Knighton, A.D., 1987. Tin mining and sediment supply to the Ringarooma River, Tasmania, 1875–1979. *Australian Geographical Studies*, 25: 83–97.

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*, 14: 333–359.

Knighton, A.D., 1991. Channel bed adjustment along mine-affected rivers of northeast Tasmania. *Geomorphology*, 4: 205–219.

Koehn, J.D., 1986. Approaches to determining flow and habitat requirements for freshwater native fish in Victoria. In: I.C. Campbell (ed.), *Stream Protection. The Management of Rivers for Instream Uses*. Water Studies Centre, Chisolm Institute of Technology, Melbourne, pp. 95–113.

Koehn, J.D., 1987. *Artificial Habitat Increases Abundance of* Two-spined Blackfish ('Gadopsis bispinosis') *in the Ovens River, Victoria*. Technical Report Series, 56. Arthur Rylab Institute for Environmental Research, Department of Conservation and Lands, Victoria, Australia.

Koehn, J.D., T. Doeg, D. Harrington and G. Milledge, 1997a. Dartmouth Dam: effects on the downstream aquatic fauna. In: R.J. Banens and R. Lahane (eds.), *Proceedings of the 1995 Riverine Environments Research Forum of the Murray Darling Basin Commission Natural Resource Management Strategy Funded Projects*.

Koehn, J.D. and A.K. Morison, 1990. A review of the conservation status of native freshwater fish in Victoria. *The Victorian Naturalist*, 107(1): 13–25.

Koehn, J.D., S.J. Nicol and A.M. Lucas, I 997b. *River Restoration Through Integrated Management*. Draft, Project no. R7001. Murray–Darling Basin Commission, Marine and Freshwater Resources Institute, Melbourne.

Koehn, J.D. and W.G. O'Connor, 1990. *Biological Information for Management of Native Freshwater Fish in Victoria*. Victorian Department of Conservation and Environment, Melbourne, 165 pp.

Kondolf, G.M., 1994. Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning*, 28: 225–243.

Kondolf, G.M., 1995. Five elements for effective evaluation of stream restoration. *Restoration Ecology*, 3(2): 133–136.

Kondolf, G.M., 1996. Learning from stream restoration projects. In: R. Harris, R. Kattelman, H. Kerner and J. Woled (eds.), *Fifth Biennial Watershed Management Conference, University of California*. Water Resources Centre, University of California, pp. 107–110.

Kondolf, G.M. and E.R. Micheli, 1995. Evaluating stream restoration projects. *Environmental Management*, 19(1): 1–15.

Kondolf, G.M., J.C. Vick and T.M. Ramirez, 1996. Salmon spawning and habitat rehabilitation, on the Merced River, California: an evaluation of project planning and performance. *Transactions of the American Fisheries Society*, 125: 899–912.

Lane, E.W. and W.M. Borland, 1951. Estimating bedload. *American Geophysical Union Transactions*, 32: 121–123.

Langbein, W.B., 1964. Geometry of river channels. *Journal of the Hydraulics Division, American Society of Civil Engineers*, 90: 301–312.

Lee, H.Y., D.T. Fu and M.S. Song, 1993. Migration of rectangular mining pit composed of uniform sediments. *Journal of Hydraulic Engineering*, 119(1): 64–80.

Leopold, L.B. and T. Maddock, 1953. The hydraulic geometry of stream channels and some physiographic implications. *United States Geological Survey Professional Paper* 252, pp. 1–57.

Leopold, L.B., M.G. Wolman and J.P. Miller, 1964. *Fluvial Processes in Geomorphology*, W.H. Freeman, San Francisco.

Lere, M.E., 1982. *The Long Term Effectiveness of Three Types of Stream Improvement Structures Installed in Montana Streams*. Masters Thesis, Montana State University, Bozeman.

Lloyd, C.J., 1988. *Either Drought or Plenty: Water Development and Management in New South Wales*. Department of Water Resources, New South Wales, Parramatta.

Locher, H., 1996. Response of the King and Queen Rivers, Tasmania, to dramatic changes in flow and sediment load. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, pp. 271–275.

Lovejoy, S.B., 1997. Watershed management for water quality protection: are GIS and simulation models THE answer? *Journal of Soil and Water Conservation*, 52(2): 103.

LWMP Economic Committee, 1996. *Report on Workshop on Economic Methodology in Land and Water Managment Plans*. Premiers Department, NSW.

MacDonald, A., 1988. Predicting channel recovery from sand and gravel extraction in the Naugatuck River and adjacent floodplain. *National Conference on Hydraulic Engineering*, pp. 702–707.

Maiyo, S., 1996. Stream and riparian restoration: South Fork of Little Butte Creek. *Streamline. British Columbia's Stream Restoration Technical Bulletin*, 1(1): 3–5.

Mallen-Cooper, M. and J.H. Harris, 1990. Fishways in mainland south-eastern Australia. *Proceedings of the International Symposium on Fishways '90, Gifu, Japan*. Publications Committee of the International Symposium on Fishways '90, pp. 221–229.

Mallen-Cooper, M., I.T. Stuart, F. Hides-Pearson and J.H. Harris, 1995. *Fish Migration in the Murray River and Assessment of the Torrumbarry Fishway. Natural Resources Management Strategy Project N002*. Murray–Darling Basin Commission, Canberra.

Marston, R.A., 1982. The geomorphic significance of log steps in forest streams. *Annals of the Association of American Geographers*, 72: 99–108.

McCosker, R.O. and J. Duggin, 1993. *Gingham Watercourse Management Plan. Final Report*. Department of Ecosystem Management, University of New England, Armidale.

McDowall, R.M. (ed.), 1996. *Freshwater Fishes of South-Eastern Australia*, 2nd Edition. Reed, Sydney.

McGuckin, J.T., J.R. Anderson and R.J. Gasior, 1991. *Salt Affected Rivers in Victoria*. Technical Report, 118. Arthur Rylah Institute for Environmental Research.

McMahon, T. and R. Srikanthan, 1981. Log Pearson III distribution—is it applicable to flood frequency analysis of Australian streams? *Journal of Hydrology*, 52: 139–417.

MDBC, 1988. *Desnagging Hume to Yarrawonga*. Murray–Darling Basin Commission, May 1988, Working group report to the Catchment floodplain and river management committee.

Mehta, A., E.J. Hayter, W.R. Parker, R.B. Krone and A.M. Teeter, 1989a. Cohesive sediment transport. I: Process description. *Journal of Hydraulic Engineering*, 115(8).

Mehta, A., W.H.J. McNally, E.J. Hayter, A.M. Teeter, D. Schoellhamer, S.B. Heltzel and W.B. Carey, 1989b. Cohesive sediment transport. II: Application. *Journal of Hydraulic Engineering*, 115(8).

Metzeling, L., T. Doeg and W. O'Connor, 1995. The impact of salinization and sedimentation on aquatic biota. In: R.A. Bradstock, T.D. Auld, D.A. Keith, R.T. Kingsford, D. Lunney and D.P. Sivertsen (eds.), *Conserving Biodiversity: Threats and Solutions*. Beatty & Sons, Surry, pp. 126–36.

Millar, R.G., 1997. *Ballast Requirement for Lateral Log Jams*. Technical Memorandum, Ministry of Environment, Lands and Parks, Watershed Restoration Program (Canada).

Milton, L.E., 1971. *A Review of Gully Erosion and its Control*. Soil Conservation Authority of Victoria.

Mitchell, P., 1990. *The Environmental Condition of Victorian Streams*. Department of Water Resources.

Montgomery, D.R., J.M. Buffington and RD. Smith, 1995. Pool spacing in forest channels. *Water Resources Research*, 31: 1097–1105.

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

Nagel, F.L., 1995. *The Effectiveness of Bank Stabilisation Works on Baerami Creek*. Honours Thesis, Macquarie University, Sydney.

Nanson, G.C. and R.W. Young, 1981. Downstream reduction of rural channel size with contrasting urban effects in small coastal streams of Southeastern Australia. *Journal of Hydrology*, 52: 239–255.

National Research Council, 1992. *Restoration of Aquatic Ecosystems—Science, Technology and Public Policy*. National Academy Press, Washington.

Neill, C.R., 1973. *Guide to Bridge Hydraulics*. University of Toronto, Toronto.

Neilsen, M.B., 1996. Lowland stream restoration in Denmark. In: A. Brooks and F.D. Shields, Jr. (eds.), *River Channel Restoration: Guiding Principles for Sustainable Projects*. Wiley, pp. 269–290.

Nelson, R.W., G.C. Horac and J.E. Olsen, 1978. *Western Reservoir and Stream Habitat Improvements Handbook*, FWS/OBS-78/56. Western Energy and Land Use Team, Fort Collins.

Nestler, J.M., R.T. Milhous and J.B. Layzer, 1989. Instream habitat modelling techniques. In: J.A. Gore and G.E. Petts (eds.), *Alternatives in Regulated River Management*. CRC Press, Boca Raton, Florida, USA.

Newbury, R.W., 1989. *Habitats and Hydrology of Streams*. Workshop conducted by the Centre for Environmental Hydrology, University of Melbourne at Buxton, Victoria, 15–17 November, 1989.

Newbury, R.W. and M. Gaboury, 1993. *Stream Analysis and Fish Habitat Design—a Field Manual*. Newbury Hydraulics Ltd, British Columbia.

Newcombe, C.P. and D.D. MacDonald, 1991. Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management*, 11: 72–82.

NHMRC (National Health and Medical Research Council) Environmental Health Committee, 1994. *Summary—Australian Drinking Water Guidelines*.

Nicholas, S. and P. Mack, 1996. *Manage Your banks: A Practical Guide to Stream-side Management, Fencing and Water Supplies*. The Goulburn Valley Environment Group, 20 pp.

Nunally, N.R., 1967. Definition and identification of channel and overbank deposits and their respective roles in floodplain formation. *Professional Geographer*, 19: 1–4.

O'Brien, N., 1996. *Bushland Boosts Price of Farms*. The Weekend Australian.

O'Brien, T., 1996. *Design Guidelines for Fish Passage*. Paper presented to a fishways conference, Brisbane.

O'Brien, T., 1997. Rock fishways in Victoria. *Second National Fishway Workshop, Rockhampton, Queensland*.

O'Connor, N.A. and P.S. Lake, 1994. Long-term and seasonal large-scale disturbances of a small lowland stream. *Australian Journal of Marine and Freshwater Research*, 45: 243–55.

Odgaard, A.J. and C.E. Mosconi, 1987. Streambank protection by submerged vanes. *Journal of Hydraulic Engineering*, 113(4): 520–536.

Odgaard, A.J. and A. Spoljaric, 1986. Sediment control by submerged vanes. *Journal of Hydraulic Engineering*, 112(12): 1164–1181.

Odgaard, A.J. and Y. Wang, 1991a. Sediment management with submerged vanes. I: Theory. *Journal of Hydraulic Engineering*, 117(3): 267–283.

Odgaard, A.J. and Y. Wang, 1991b. Sediment management with submerged vanes. II: Applications. *Journal of Hydraulic Engineering*, 117(3): 284–302.

Office of the Commissioner for the Environment, 1988. State of the Environment Report 1988. *Victoria's Inland Waters*. Office of the Commissioner for the Environment, Melbourne.

Ontario Streams, 1998. *A Stream Rehabilitation Manual for Ontario Streams, Chapter 5, Techniques*, available online at <http://www.ontariostreams.on.ca/toc.htm>.

Outhet, D. and J. Faulks, 1994. *Tarcutta Ck and Umbango Ck: Options for Erosion and Sediment Management, Volume 1: Report*. Department of Water Resources, NSW.

Park, C.C., 1977. World wide variations in hydraulic geometry exponents of stream channels: an analysis and some observations. *Journal of Hydrology*, 33: 133–146.

Parliament of Victoria, 1994. *Eductor Dredging in Victoria*. Environment and Natural Resources Committee.

Partheniades, E., 1971. Erosion and deposition of cohesive materials. In: H.W. Shen (ed.), *River Mechanics*. River Mechanics Fort Collins, Colorado.

Pteryk, S. and G. Bosmajian, 1975. Analysis of flow through vegetation. *Journal of the Hydraulics Division, (ASCE—American Society of Civil Engineers)*, 101(7): 871–883.

Pickup, G., 1975. Downstream variations in channel characteristics, flow conditions and sediment transport in an eroding channel. *Zeitschrift für Geomorphologie*, 19: 443–59.

Pickup, G., R.J. Higgins and I. Grant, 1983. Modelling sediment transport as a moving wave—the transfer and deposition of mining waste. *Journal of Hydrology*, 60: 281–301.

Pickup, G. and R.F. Warner, 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. *Journal of Hydrology*, 29: 51–75.

Piegay, H., 1993. Nature, mass and preferential sites of coarse woody debris deposits in the lower Am Valley (Mollon Reach), France. *Regulated Rivers: Research and Management*, 8, 359–372.

Pilgrim, D.H. (ed.), 1987. *Australian Rainfall and Runoff: a Guide to Flood Estimation, I*. The Institution of Engineers, Australia.

Prosser, I.P., 1991. A comparison of past and present episodes of gully erosion at Wangrah Creek, Southern Tablelands, New South Wales. *Australian Geographical Studies*, 29: 139–54.

Prosser, I.P., J. Chappell and R. Gillespie, 1994. Holocene valley aggradation and gully erosion in headwater catchments, south-eastern highlands of Australia. *Earth Surface Processes and Landforms*, 19: 465–480.

Prosser, I.P. and C.J. Slade, 1994. Gully formation and the role of valley-floor vegetation, southeastern Australia. *Geology*, 22: 1127–1130.

Prosser, I.P. and S.J. Winchester, 1996. History and processes of gully initiation and development in eastern Australia. *Zeitschrift für Geomorphologie, Suppl. Bund*, 105: 91–109.

Przedwojski, B., 1995. Bed topography and local scour in rivers with banks protected by groynes. *Journal of Hydraulic Research*, 33(2): 257–273.

Quinn, J.M., R.J. Davies-Colley, C.W. Hickey, M.L. Vickers and PA. Ryan, 1992. Effects of clay discharges on streams. 2. Benthic invertebrates. *Hydrobiologia*, 248: 235–247.

Raine, A.W. and J.N. Gardiner, 1997. *Revegetating Streams in the Manning Catchment. A Guide to Species and Planting Methods*. New South Wales Government.

Raine, A.W. and J.N. Gardiner, 1995. *Rivercare: Guidelines for Ecologically Sustainable Management of Rivers and Riparian Vegetation*. Occasional Paper, 03/95. Land and Water Resources Research and Development Corporation, Canberra.

Raine, A.W., T. Hudson and J.N. Gardiner, 1997. *Revegetating Streams in the Nambucca Catchment. A Guide to Species and Planting Methods*. New South Wales Government.

Rauhala, MA., 1997. *Frog Fauna of the Australian Capital Territory: A Review*. Technical Report No. 14. Australian Capital Territory, Department of Urban Services, ACT Parks and Conservation Service.

Read Sturgess and Associates, 1992. Rapid appraisal of the economic benefits of river management. *Water Resources Management Series, No. 79*. Department of Water Resources, Victoria.

Reid, P. and P.R. Bird, 1990. Shade and shelter. In: K.W. Crerner (ed.), *Trees for Rural Australia*. Inkata, Melbourne.

Reinfelds, I., I.D. Rutherfurd and P. Bishop, 1995. History and effects of channelisation on the Latrobe River, Victoria. *Australian Geographical Studies*, 33(1): 60–76.

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

Richardson, E.V. and J.R. Richardson, 1993. Scour analysis at highway structures. In: H.W. Shen, ST. Su and F. Wen (eds.), *Hydraulic Engineering '93, San Francisco, California*. American Society of Civil Engineers, New York, pp. 400–405.

Richmond, A.D., and K.D. Fausch, 1995. Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences*, 52: 1789–1802.

Riley, S.J., 1972. A comparison of morphometric measures of bankfull. *Journal of Hydrology*, 17: 23–31.

Rosgen, D.L., 1996. *Applied River Morphology*. Wildland Hydrology, Pagosa Springs, Colorado.

Rowntree, K.M. and R.A. Wadeson, 1996. Translating channel morphology into hydraulic habitat: application of the hydraulic biotope concept to assessment of discharge related habitat changes. In: M. Leclerc, H. Capra, S. Valentin, A. Boudreault and Y. Cote (eds.), *2nd International Symposium on Habitat Hydraulics, Quebec*, pp. A282–A92.

Rush, V., 1997. *An Economic Evaluation of Controlling Gully Erosion*. Minor thesis, Department of Agriculture, La Trobe University, Bundoora, Melbourne.

Russell, D.J., 1991. Fish movements through a fishway on a tidal barrage in sub-tropical Queensland. *Proceedings of the Royal Society of Queensland*, 101(1): 109–118.

Rutherford, K., T. Cox and N. Broekhuizen, 1999. Restoring pasture streams in New Zealand: can computer models help? In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 523–526.

Rutherfurd, I.D., 1996. Sand slugs in SE Australian streams: origins, distribution and management. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 29–34.

Rutherfurd, I.D. and M. Budahazy, 1996. *A Sand Management Strategy for the Glenelg River, Western Victoria*. Report to Southern Rural Water and the Department of Natural Resources and Environment, Victoria, 9/96. Cooperative Research Centre for Catchment Hydrology, Melbourne.

Rutherfurd, I.D., I. Prosser and J. Davis, 1997. Simple approaches to predicting rates and extent of gully development. In: S. Wang, E. Langendoen and F.D. Shields, Jr. (eds.), *Management of Landscapes Disturbed by Channel Incision, Oxford, Mississippi*. United States Department of Agriculture, pp. 1125–1130.

Rutherfurd, I.D., in press. Some human impacts on Australian stream channel morphology. In: S.O. Brizga and B. Finlayson (eds.), *River Management. The Australasian Experience*. Wiley.

Sainty, G.R. and S.W.L. Jacobs, 1994. *Waterplants in Australia* (3rd Edition). Sainty and Associates, Sydney, 327 pp.

Sands, R., 1981. Salt resistance in *Eucalyptus camaldulensis* Dehn from three different seed sources. *Australian Forest Research*, 11: 93–100.

Schumm, S.A., 1969. River metamorphosis. *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*, 95(HYI): 255–273.

Sear, D.A., 1996. The sediment system and channel stability. In: A. Brookes and F.D. Shields, Jr (eds.), *River Channel Restoration: Guiding Principles for Sustainable Projects*. John Wiley & Sons, Chichester, pp. 149–177.

Seehorn, M.E., 1982. Trout stream improvements commonly used on southeastern National Forests. In: R. Wiley (ed.), *Proceedings of Rocky Mountain Stream Habitats Management Workshop, Jackson*. Wyoming Game and Fish Department, Wyoming.

Shankman, D. and T.B. Pugh, 1992. Discharge response to channelization of a coastal plain stream. *Wetlands*, 12(3): 157–162.

Sharpley, A., S.J. Smith, J.A. Zollweg and G.A. Coleman, 1996. Gully treatment and water quality in the Southern Plains. *Journal of Soil and Water Conservation*, 51(6): 498–503.

Shields, F.D. Jr., 1984. Design of habitat structures for open channels. *Journal of Water Resources Planning and Management*, 109(4): 331–344.

Shields, F.D. Jr., 1991. Woody vegetation and riprap stability along the Sacremento River mile 84.5–119. *Water Resources Bulletin*, 27(3): 527–536.

Shields, F.D. Jr., 1996. Hydraulic and hydrologic stability. In: A. Brookes and F.D. Shields, Jr. (eds.), *River Channel Restoration: Guiding Principles for Sustainable Projects*. John Wiley & Sons, pp. 433.

Shields, F.D. Jr., A.J. Bowie and C.M. Cooper, 1995a. Control of streambank erosion due to bed degradation with vegetation and structure. *Water Resources Bulletin*, 31(3): 475–489.

Shields, F.D. Jr., C.M. Cooper and S.S. Knight, 1995b. Experiment in stream restoration. *Journal of Hydraulic Engineering*, 121(6): 494–502.

Shields, F.D. Jr. and C.J. Gippel, 1995. Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering*, 121(4): 341–354.

Shields, F.D. Jr., S.S. Knight and C.M. Cooper, 1995c. Incised stream physical habitat restoration with stone weirs. *Regulated Rivers: Research and Management*, 10: 181–198.

Shields, F.D. Jr., S.S. Knight and C.M. Cooper, 1998. Addition of spurs to stone toe protection for warmwater fish habitat rehabilitation. *Journal of the American Water Resources Association*, 34(6): 1427–1436.

Shields, F.D. Jr. and N.R. Nunnally, 1984. Environmental aspects of clearing and snagging. *Journal of Environmental Engineering*, 110: 152–165.

Simon, A. and C.R. Hupp, 1987. *Geomorphic and Vegetative Recovery Processes Along Modified Tennessee Streams: An Interdisciplinary Approach to Disturbed Fluvial Systems*. Publication 167, International Association of Hydrological Sciences, pp. 251–262.

Simons, D.B. and M.L. Albertson, 1963. Uniform water conveyance channels in alluvial material. *Transactions of the American Society of Civil Engineers*, 128: 65.

Sinclair Knight Merz, 1997. *Wannon River Assessment Project for Glenelg Regional Catchment and Land Protection Board*. Final report.

Skaugset, A., B. Bilby and J. Seddell, 1994a. Influence of woody debris piece size and orientation on function in small streams. *Coastal Oregon Productivity Enhancement/Adaptive COPE Current Projects/Riparian Siviculture (original source is 1994 Adaptive COPE Annual Report)*. Oregon State University Corvallis Campus and Hatfield Marine Science Centre, Newport. Online at <http://www.cope.hmsc.orst.edu/projects/lwd.htm>.

Skaugset, A., M. Newton and L. Kellogg, 1994b. Active riparian-area management: effects on multiple forest resources. *Coastal Oregon Productivity Enhancement/Adaptive COPE Current Projects/Riparian Siviculture (original source is 1994 Adaptive COPE Annual Report)*. Oregon State University Corvallis Campus and Hatfield Marine Science Center, Newport. Online at <http://www.cope.hmsc.orst.edu/projects/aram.htm>.

Skull, S.D., A.S. Kutt and P.D. Clayton, 1996. *Review of Methods of Environmental Assessment for River Bank Stabilisation*, 95/15. Australian Centre for Tropical Freshwater Research.

Slaney, P.A., R.J. Finnigan and R.G. Millar, 1997. Accelerating the recovery of log-jam habitats: Large woody debris–boulder complexes. In: P.A. Slaney and D. Zaldokas (eds.), *Fish Habitat Rehabilitation Procedures, Watershed Restoration Technical Circular No. 9*. Ministry of Environment, Lands and Parks, and Ministry of Forests, pp. 9–1 to 9–24.

Slanina, K., 1962. Beitrag zur wiking mineralischer suspensionen auf fische. *Wasser und Abwasser*, 7.

Soil Conservation Service of NSW, 1989. *Land Degradation Survey of NSW 1987–88*. Soil Conservation Service of NSW, Sydney.

Sonneman, J. and P. Breen, 1997. The use of benthic algae and aquatic macrophytes for river health monitoring. *Monitoring River Health, Latrobe University*. River Basin Management Society.

Starnes, L.B. and W.C. Starnes, 1981. Biology of the Blackside Dace *Phoxinus cumberlandensis. American Midland Naturalist*, 106: 360–371.

Starr, B., 1999. The use of historical data in community river management planning. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide, South Australia*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 589–594.

Starr, B.J., 1995. *Numeralla—River of Change*. Report to the Numeralla and District Landcare Group, by the Department of Water Resources, NSW, Bredbo.

State of Victoria, 1995. *Nutrient Management Strategy for Victorian Inland Waters*. Planning and Policy Strategy, State of Victoria.

Stephenson, D., P. Kolovopoulos and A. Holden, 1991. Momentum transfer in compound channels. In: B.C. Yen (ed.), Channel Flow Resistance: *Centennial of Manning's Formula*, USA. Water Resources Publications.

Stewardson, M.J., I.D. Rutherfurd and W. Tennant, 1999. Physical evaluation of rehabilitation works in Broken River and Ryans Creek, NE Victoria. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide, South Australia*. Cooperative Research Centre for Catchrnent Hydrology, Melbourne, pp. 595–600.

Stewardson, M.J., L.J. White, C.J. Gippel, B.L. Finlayson and J.W. Tilliard, 1997. *A Review of Concepts for Habitat Enhancement and Rehabilitation of Historic Bed-Forms in The Lower Snowy River Above Orbost*. Centre for Applied Environmental Hydrology, Melbourne.

Stock, E. and R.J. Neller, 1990. Geomorphic transitions and the Brisbane River. In: P. Davie, E.D. Stock and Low Choy (eds.), *The Brisbane River: A Source Book for the Future*. Australian Littoral Society and Queensland Museum, Brisbane, pp. 43–54.

Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: V.T. Chow (ed.), *Handbook of Applied Hydrology*, pp. 4.39–4.76.

Sturrock, J.W., 1981. Shelter boost crop yield by 35%, also prevents lodging. *New Zealand Journal of Agriculture*, 143(3): 18–19.

Suzuki, K., 1987. Local bed form around a series of spur dikes in alluvial channels. XXII IAHR *Conference, Lausanne*. International Association of Hydrological Research (IAHR).

Swales, S., 1989. The use of instream habitat improvement methodology in mitigating the adverse effects of river regulation on fisheries. In: J.A. Gore and I. Petts (eds.), *Alternatives in Regulated River Management*. CRC Press Inc., pp. 185–208.

Swales, S. and K. O'Hara, 1980. Instream habitat improvement devices and their use in freshwater fisheries management. *Journal of Environmental Management*, 10: 167–179.

Swanson, F.J., M.D. Bryant, G.W. Lienkaemper and J.R. Sedell, 1984. Organic debris in small streams, Prince of Wales Island, Southeast Alaska. *USDA Forest Service General Technical Report PNW-166*. Pacific Northwest Forest and Range Experiment Station, United States Department of Agriculture, Forest Service, Portland, Oregon, 12 p.

Sydney Water and CSIRO, no date. *The Streamwatch Water Bug Detective Guide*. Sydney Water and the Commonwealth Scientific and Industrial Research Organisation (Double Helix).

Thorncraft, G.A. and C.S. Wardle, 1991. *Assessment of Rock-ramp Fishways*. NSW Environment Protection Authority and NSW Fisheries, Sydney.

Thorne, C.R., 1982. Processes and mechanisms of river bank erosion. In: R.D. Hey, J.C. Bathurst and C.R. Thorne (eds.), *Gravel Bed Rivers*. Wiley, Chichester, pp. 227–271.

Thorne, C.R., 1992. Bend scour and bank erosion on the Meandering Red River, Louisiana. In: P.A. Carling and G. Petts (eds.), *Lowland Floodplain Rivers: Geomorphological Perspectives*. Wiley and Sons Ltd, Chichester, pp. 95–115.

Thorne, S.D. and D.J. Furbish, 1995. Influences of coarse bank roughness on flow within a sharply curved river bend. *Geomorphology*, 12: 241–257.

Tiller, D. and L. Metzeling, 1998. *Rapid Bioassessment of Victorian Streams. The Approach and Methods of the Environmental Protection Agency*. Victorian Environmental Protection Authority, Melbourne.

Tiller, D. and P. Newall, 1995. *Preliminary Nutrient Guidelines for Victorian Inland Streams*, Publication 478. Victorian Environmental Protection Authority, Melbourne.

Trimble, S.W., 1982. Soil conservation in the Coon Creek Basin, Wisconsin. *Journal of Soil and Water Conservation*, Nov–Dec: 355–356.

Tungkillo and Harrogate Landcare Groups, no date. *Electric Fencing for Sheep and Cattle in the Hills*. Tungkillo and Harrogate Landcare Groups.

Tyler, M.J., 1994 *Australian Frogs: A Natural History*. Cornell University Press, New York, USA.

Underwood, A.J., 1996. Spatial and temporal problems with monitoring. In: G. Petts and P. Calow (eds.), *River Restoration. Selected Extracts from the Rivers Handbook*. Blackwell Science, Oxford, pp. 182–204.

US EPA, 1971. *Water Quality Criteria Data Book, Volume 3. Effects of Chemicals on Aquatic Life*. United States Government Printing Office, Washington, DC.

V.A. Poulin and Associates Ltd, 1991. Stream rehabilitation using LOD placements and off-channel pool development, *Land Management Report Number 61*, BC Ministry of Forests, Victoria, British Columbia.

Venning, J.,1988. *Growing Trees for Farms, Parks and Roadsides: a Revegetation Manual*. Lothian, Melbourne.

Victorian Department of Conservation and Environment, 1990. *Environmental Guidelines for River Management Works*. Victorian Department of Conservation and Environment.

Wager, R. and P. Jackson, 1993. *The Action Plan for Australian Freshwater Fishes*. Australian Nature Conservation Agency, Canberra.

Waldron, L.J., 1977. Shear resistance of root-permeated homogeneous and stratified soil. *Soil Science Society of America Journal*, 41: 843–849.

Wallbrink, P.J., J.M. Olley, A.S. Murray and L.J. Olive, 1996. The contribution of channel banks and gully walls to total phosphorous loads in the Murrumbidgee. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 1–6.

Warner, R.F., 1992. Floodplain evolution in a New South Wales coastal valley, Australia: spatial process variations. *Geomorphology*, 4: 447–458.

Watson, G.F., M.J. Littlejohn, J.M. Hero and P. Robertson, 1991. *Conservation Status Ecology and Management of the Spotted Tree Frog* (Litoria spenceri). Report to the Wildlife Branch, Flora and Fauna Division, Department of Conservation and Environment.

Wesche, T.A., 1985. Steam channel modifications and reclamation structures to enhance fish habitat. In: J.A. Gore (ed.), *The Restoration of Rivers and Streams: Theories and Experience*. Butterworth Publishers, Boston, 103–163.

West, S. (ed.), 1988. *The Streamwatch Manual. The Complete Streamwatch Guide to Water Quality Monitoring*. Sydney Water Corporation, Sydney.

Western, A.W., B.L. Finlayson, T.A. McMahon and I.C. O'Neill, 1997. A method for characterising longitudinal irregularity in river channels. *Geomorphology*, 21(1): 39-51.

Wharton, G., 1992. Flood estimation from channel size: guidelines for using the channel geometry method. *Applied Geography*, 12: 339–359.

White, L.J., I.D. Rutherfurd and R.E. Hardie, 1999. On the costs of stream management and rehabilitation in Australia. In: I.D. Rutherfurd and R. Bartley (eds.), *Second Australian Stream Management Conference, Adelaide, South Australia*. Cooperative Research Centre for Catchment Hydrology, Melbourne, pp. 697–703.

White, R.J. and O.M. Byrnildson, 1967. *Guidelines for Management of Trout Stream Habitat in Wisconsin*. Technical Bulletin, 31. Wisconsin Department of Natural resources, Division of Conservation, Madison, Wisconsin.

Wiederholm, T., 1984. Responses of aquatic insects to environmental pollution. In: V.H. Resh and D.M. Rosenberg (eds.), *The Ecology of Aquatic Insects*. Praeger, New York.

Williams, W.D., 1980. *Australian Freshwater Life: The Invertebrates of Australian Inland Waters*, 2nd edition. Macmillan, Melbourne.

Wolman, M.G. and L.B. Leopold, 1957. River flood plains: some observations on their formation. *United States Geological Survey Professional Paper* 282C, pp. 145–181.

Wong, W.T., 1994. Practical methods and improved techniques for fluvial sediment sampling. In: *Hydraulic Working With the Environment, International Conference on Hydraulics in Civil Engineering*. University of Queensland, pp. 73–79.

Woodfull, J., I.D. Rutherfurd and P. Bishop, 1996. Downstream decreasing channel dimensions in SE Australian rivers. In: I.D. Rutherfurd and M.R. Walker (eds.), *First National Conference on Stream Management in Australia, Merrijig*. Cooperative Research Centre for Catchment Hydrology.

Woodyer, K.D., 1968. Bankfull frequency in rivers. *Journal of Hydrology*, 6: 114–142.

Working Group on Waterway Management, 1991. *Guidelines for Stabilising Waterways*. Standing Committee on Rivers and Catchments, Victoria, Melbourne.

Yasi, M., 1997. *Flow and Bed Geometry Behind a Groyne*. PhD Thesis, Monash University, Melbourne, 342 pp.

Young, W.J., 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. *Regulated Rivers: Research and Management*, 6: 203–211.

Zapzalka, T., 1997. Restoring large woody debris to streams. *Restoration and Reclamation Review*, 2. An electronic student journal online at <http://www.hort.agri.umn.edu/h5015/rrr.htm>. Paper online at <http://www.soils.urnn.edu: 8003/hSO 1 5/97papers/zapzalka.html>.

Zipparro, V.J. and H. Hasen, 1993. *Davis' Handbook of Applied Hydraulics* (Fourth Edition). McGraw-Hill.