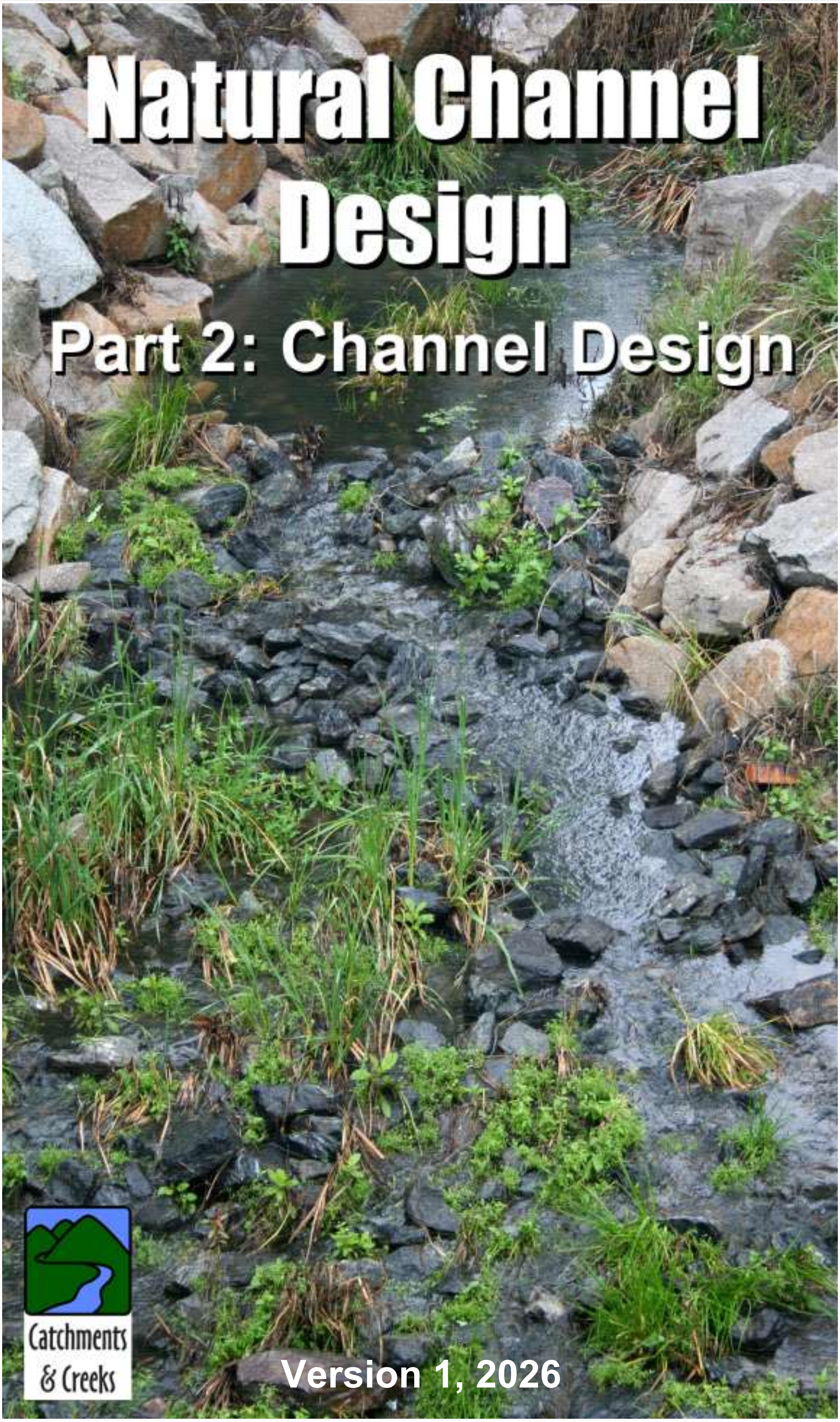
Natural Channel Design

Part 2: Channel Design



Catchments & Creeks

Version 1, 2026

Natural Channel Design

Part 2 – Channel Design

Version 1, April 2026

Prepared and illustrated by: Grant Witheridge, Catchments and Creeks

Published by: Catchments and Creeks, Bargara, Queensland

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Copies of this document may be downloaded from: www.catchmentsandcreeks.com.au

Cover image: Constructed riffle within a rehabilitated drainage channel upstream of Samford Road, Mitchelton, Brisbane, Queensland.

Principal reference documents

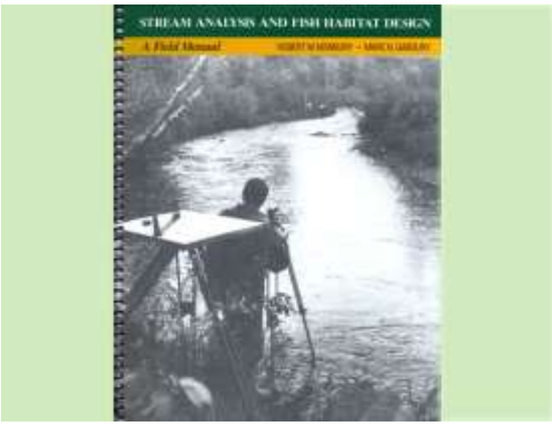
Brisbane City Council, 2000

Natural Channel Design Guidelines

Brisbane City Council, 2000, Brisbane, Queensland.

Prepared in association with Catchments and Creeks Pty. Ltd.

Out of print, but PDF is/was available from Council's website.



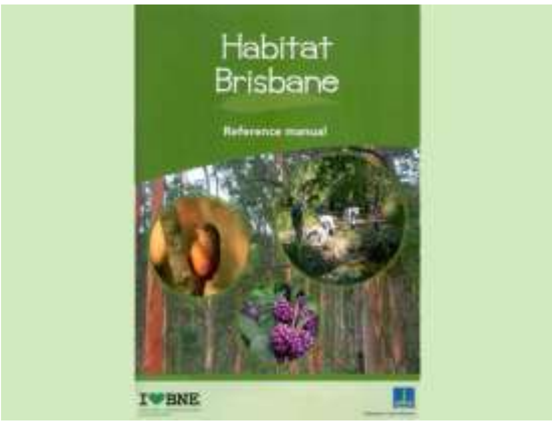
Newbury & Gaboury, 1993

Stream Analysis and Fish Habitat Design

Robert Newbury and Marc Gaboury

Published by Newbury Hydraulics Ltd. and The Manitoba Habitat Heritage Corporation, Manitoba Fisheries Branch, Gibsons, British Columbia, Canada, 1993

ISBN 0 969 6891 0 1



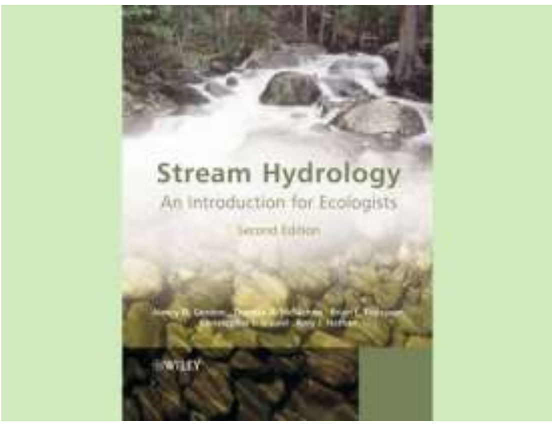
Habitat Brisbane, 2016

Habitat Brisbane – Reference manual

Brisbane City Council, 2016

CA15-454487-01-1500

A colour, hard copy document with limited release—supplied to Brisbane habitat volunteers.



Stream Hydrology

Stream Hydrology – An Introduction for Ecologists

Nabcy D. Gordon, Thomas A. McMahon and Brian L. Finlayson.

John Wiley & Sons, Chichester, UK

1st edition, 1992

2nd edition

ISBN 0-471-93084-9

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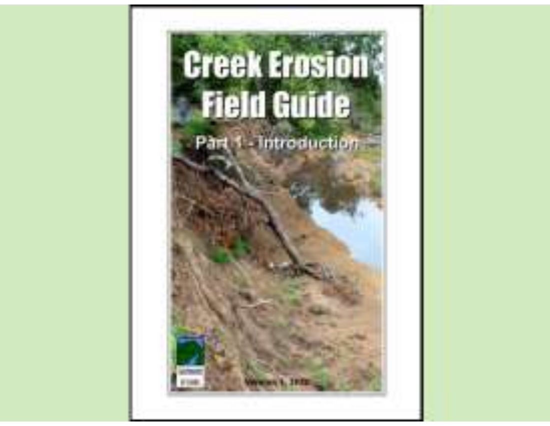


Creek Erosion Field Guide, 2021

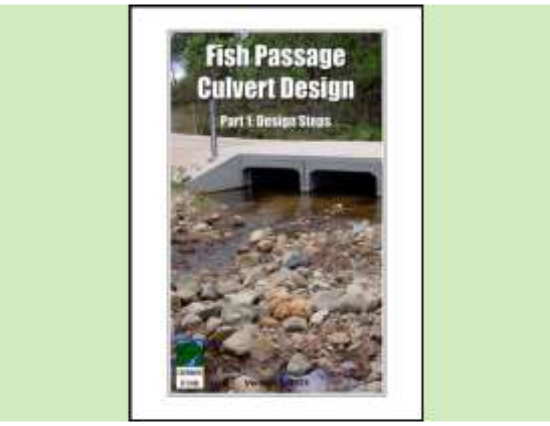
Creek Erosion Field Guide

Catchments & Creeks Pty Ltd, 2021, Bargara Queensland.

A four-part PDF document.

Version 1, April 2021

- Part 1: Introduction
- Part 2: Bed Stabilisation
- Part 3: Bank Stabilisation
- Part 4: Bank Treatment Options



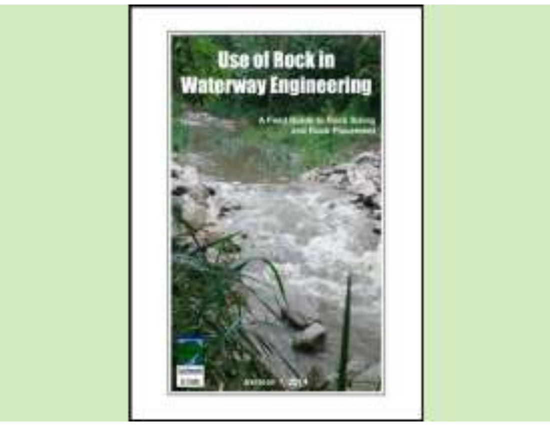
Fish Passage Culvert Design, 2026

Fish Passage Culvert Design

Catchments & Creeks, Version 2, 2026, Bargara Queensland.

A three-part PDF document.

- Part 1: Design Steps
- Part 2: Appendices A to F
- Part 3: Appendices G to M



Catchments & Creeks Pty Ltd, 2020

Use of Rock in Waterway Engineering

Catchments & Creeks Pty Ltd, 2020, Brisbane Queensland.

Version 3, 2020

A pictorial guide to the sizing and placement of rock within waterways.

ESC for Instream Works, 2020

Erosion and Sediment Control Field Guide for Instream Works

Catchments & Creeks Pty Ltd, 2020, Brisbane Queensland.

A pictorial-based guide to erosion and sediment control practices appropriate during the conduction of instream work, such as constructed drainage channels, and creek rehabilitation.

Contents

Page

Symbols (as used in parts 1, 2 & 3 of this document)

A	=	cross-sectional flow area [m^2]
A, B, C	=	equation constants
ARI	=	means ‘average recurrence interval’
b	=	bed width [m]
BLPS	=	means ‘body lengths per second’ in reference to fish swimming
D	=	water depth (also ‘y’ & ‘d’) [m]
	=	(also) channel depth from bankfull water level to channel invert [m]
D_P	=	maximum pool depth [m]
d/s	=	means ‘downstream’
d_{50}	=	nominal rock size (diameter) of which 50% of the rocks are smaller [m]
d_{90}	=	nominal rock size (diameter) of which 90% of the rocks are smaller [m]
D.V	=	depth*velocity product [m^2/s]
F	=	riffle fall measured from riffle crest to the low flow pool level within the downstream pool, or total fall of a channel reach [m]
g	=	acceleration due to gravity [m/s^2]
K	=	equation constant based on flow conditions
K_1	=	correction factor for rock shape
K_2	=	correction factor for rock grading
ha	=	means ‘hectares’
ln	=	means the natural logarithm to base-e
L_P	=	length of a pool measured during low-flow conditions [m]
L_R	=	length of a rock riffle measured from the riffle crest to the upstream end of the downstream low flow pool [m]
n	=	Manning’s roughness value
P	=	wetted perimeter [m]
Q	=	discharge [m^3/s]
Q_f	=	bankfull discharge
q	=	flow per unit width [$m^3/s/m$]
R	=	hydraulic radius = A/P [m]
S	=	channel bed slope [m/m]
s_r	=	specific gravity of rock
S_e	=	slope of energy line [m/m]
S_o	=	bed slope = $\tan(\theta)$ [m/m]
SF	=	factor of safety
T	=	total thickness of the rock layer [m]
u/s	=	means ‘upstream’
V	=	average flow velocity (also ‘$V_{average}$’) [m/s]
V_{allow}	=	allowable flow velocity [m/s]
V_c	=	the critical velocity prior to erosion, or threshold velocity [m/s]
V_{design}	=	the flow velocity used in the design of an object [m/s]
V_{d-a}	=	depth-average flow velocity [m/s]
V_{max}	=	maximum flow velocity [m/s]
V_o	=	depth-average flow velocity based on **uniform** flow down a slope, S_o [m/s]
W	=	top width of a channel measured at the elevation of the lowest bank (also ‘T’) [m]
W_P	=	width of a pool measured at low-flow conditions (also ‘W’) [m]
W_R	=	bed width of a rock riffle [m]
y	=	depth of flow at a given location (also ‘D’ & ‘d’) [m]
Y	=	depth of the face of a head-cut erosion [m]
θ	=	slope of channel bed [degrees]

Purpose of this document

This document has been prepared specifically to:

- provide guidance on the design of vegetated drainage channels
- provide general education on the topic of creek engineering
- provide this information in a manner that is both visually attractive and easy to understand.

The document does not specifically address creek rehabilitation projects; however, parts of the document are relevant to creek rehabilitation and channel modifications.

The photos presented within this document are intended to represent the current topic of discussion. These photos are presented for the purpose of depicting either a preferred or discouraged outcome (as the case may be). In many cases the photos do not represent current best practice, but are simply the best photos available to the author at the time.

The caption and/or associated discussion should **not** imply that the site shown within the photographs represents either good or bad waterway management. The circumstances, site conditions and history of each site are not known to the author, and may not be directly relevant to the current discussion. This means that the designer may have had a completely valid reason for the design presented within the photo.

About the author

Grant Witheridge is a retired civil engineer with both Bachelor and Masters degrees from the University of NSW (UNSW). He has over 45 years experience in the fields of hydraulics, creek engineering, and erosion & sediment control, during which time he worked for a variety of federal, state and local governments, as well as private organisations.

Grant commenced his career at the UNSW Water Research Laboratory (1981) constructing and operating physical flood models of river floodplains. He later worked for Brisbane City Council on creek engineering and stormwater management issues, before ended his career working through his own company Catchments & Creeks Pty Ltd.

Introduction

This is Part 2 of a four-part document which outlines a design procedure for vegetated drainage channels. Part 2 is a continuation of Part 1, meaning that it starts at Chapter 6, which focuses on the physical properties of a drainage channel. The design procedure is presented only as a guide.

The aim of the design procedure is to design a drainage channel that integrates flooding, fauna, and humans outcomes in a manner that achieves long-term sustainability with minimal ongoing maintenance. The design procedure is not appropriate for the design of creek rehabilitation, channel expansion, or channel relocation projects.

The design procedure is based on the following assumptions:

- The channel=s geometry, bed and floodplain (if any) are each influenced by different flow conditions.
- The channel width, depth, meander radius and allowable channel slope are likely to be controlled by the bankfull flow rate and the allowable bankfull flow velocity, which will likely vary as vegetation is established within the newly-formed channel.
- There is minimal drainage catchment upstream of the proposed drainage channel; therefore, the bed conditions are likely to be based on the channel slope and the low-flow conditions, but not on the migration of substrate material (i.e. it is not a waterway).
- Being a drainage channel, it is assumed that overbank flows are undesirable, and that the channel will not have an attached floodplain. However, some potential floodplain and floodway issues are addressed.
- Good aesthetics is important, especially if the drainage channel is located near residential homes, but the desire to achieve good aesthetics should not result in poor ecological outcomes (as appropriate for the channel's location).

Introduction

Design team

The aims of Natural Channel Design

- The principles of Natural Channel Design (NCD) are based on providing the required hydraulic conveyance, while maximising the channel's environmental values.
- This design approach combines the disciplines of:
  - hydraulic engineering
  - fluvial geomorphology
  - riparian biology and ecology
  - bush rehabilitation and landscape architecture.

Channel construction (USA)

NCD is not stream restoration

- Natural Channel Design is NOT a process that can be used to restore a natural waterway.
- Restoring a waterway means you are returning the waterway back to its original (natural) condition—in which case, the design is based on historical information.
- Natural Channel Design is a process used in the design of drainage channels, or in the process of enhancing the ecological values of an existing channel.

Potential non-native riverine species

Riparian biology and ecology

- Natural Channel Design should NOT be used as an excuse to introduce wildlife to a region where they do not belong.
- However, Natural Channel Design can be used to replace habitat that has been lost due to past land-use practices (always seek expert advice).
- Natural Channel Design is a team process involving water engineers, ecologists, and bush rehabilitation experts.

Waterway treated as 'water feature'

Bush rehabilitation and landscape design

- Natural Channel Design is NOT a process that should be used to convert a natural waterway into a parkland 'water feature'.
- The aim of Natural Channel Design is to make artificial drainage channels look and perform like they were natural waterways, NOT the reverse process.
- Natural Channel Design treats the riparian zone as regions of natural bushland that can contribute to the conservation of locally endemic plant species.

Like playing chess with nature


First move of Play 1


First move of Play 2


Second move of Play 1


Second move of Play 2 – Check mate!

Introduction

- As an educator, the author would to tell students that stream rehabilitation, and the management of creek erosion, is like playing chess with nature.
- A waterway is a living organism—it not only reacts to its your actions, it also reacts to external forces, such as bushfires and flood events.
- If we change the geometry or vegetation of a waterway, then we should expect the waterway to react to such changes.

Stream rehabilitation

- In stream rehabilitation projects, your task should not be limited to predicting how nature is going to respond to your first move, but also:
  - thinking about what your next move will be (based on nature's response), and
  - designing your first move so that your actions can be easily accommodate the implementation of your next move (which you have not yet confirmed because you are still waiting on nature's first move).

The management of creek erosion

- When managing creek erosion issues, the game of chess becomes slightly harder because you need to consider how nature will respond if:
  - it experiences several years without a major flood
  - it experiences a major flood before the new vegetation has matured
  - your erosion control measures begin to experience the effects of 'shading' generated by maturing plants.

The design of new drainage channels

- The focus of this document is not on stream rehabilitation, but on the design of vegetated drainage channels—channels that are often constructed in locations where a 'waterway' did not previously exist.
- Playing chess with nature becomes harder in these circumstances because, if your design is successful, then your new drainage channel will begin to look and behave like a natural waterway.

Designing to achieve a sustainable outcome

Creek engineer

Introduction

- Engineering design typically involves factors of safety that produce outcomes that are considered to be well-below the expected 'failure condition'.
- However, in creek engineering, a well-designed vegetated drainage channel will experience vegetation damage on a regular basis, followed by regrowth.
- The long-term outcomes of a vegetated drainage channel depends on the outcomes of its damage–repair cycle.

Natural sediment flow (NSW)

Sediment flow

- A waterway that is in balance with its drainage catchment, is a waterway that experiences a long-term balance between:
  - sediment inflow and outflow
  - vegetation damage and regrowth.
- This does not mean that every sector of a waterway will experience an equal amount of 'damage' and 'repair'.
- The science of River Morphology studies these issues in much greater detail.

Flood damage (Qld)

Vegetation damage

- All vegetated communities experience natural damage and repair.
- Vegetation cannot sustain endless growth.
- Similarly, riparian zones must be able to experience ongoing periods of damage in order to achieve a balanced lifecycle.
- Ideally, this balance between damage and repair is achieved through natural processes, and does not require human input (i.e. channel maintenance).

Freshwater fish (SA)

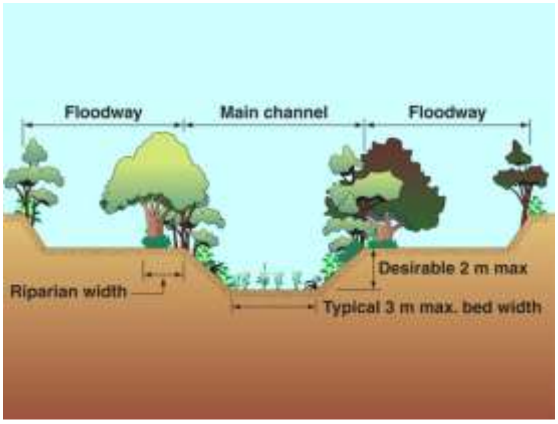
Fish passage

- It is natural for non-migrating fish to be swept downstream during flood events.
- These fish then proceed to move back upstream during normal flow conditions, and minor flood events.
- On the other hand, migrating fish have learnt to swim upstream during flood events as part of their lifecycle.
- This means that all fish habitats need to be fish friendly, even if they contain only non-migrating fish species.

Designing to minimise ongoing maintenance costs

Channel maintenance (de-silting)

Lake maintenance (dredging)



Complex channel

Maintenance access

Introduction

- As a council engineer, the author learnt that it was important to minimise maintenance costs on new council works, and assets accepted by the council as a result of new land developments.
- The author reviewed numerous development proposals that contained statements such as: *'We assume Council will be maintaining these assets'*—those 'assets' being assets that a body corporate would normally be required to own and maintain.
- Developers love to design elaborate roadside gardens, vegetated drainage channels, and lakes, that will attract home buyers to the estate, especially when they know that they (the developer) will not be required to maintain such assets.
- The author has also experienced the State Government wanting to 'gift' high-maintenance assets to a council.
- **The most important aim of any a new asset is for it to be able to perform its required tasks, and the second most important aim is for the asset to be low maintenance!**

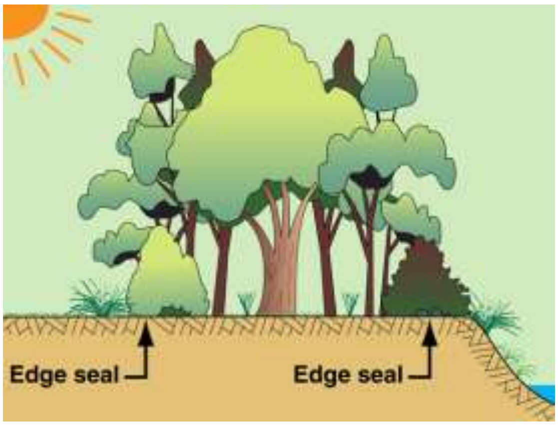
Controlling vegetation growth

- **The problem:** Vegetation does know when to stop growing!
- If the design of a drainage channel is based on the vegetation growing to a specified roughness condition, that is not its full-growth condition, then such a channel will require ongoing vegetation removal (i.e. maintenance).
- Consequently, drainage channels must be designed on the basis that plants will reach maturity (say, n = 0.15 or 0.20).

The provision of maintenance access

- Even though it is highly desirable to minimise the ongoing maintenance costs of a new asset, it is inevitable that at some stage, some degree of maintenance, or post-flood repairs, will be required.
- When maintenance teams enter an area, they should not be faced with the added cost of having to build an access track.
- Pre-formed access tracks can be used as fire breaks, fire trails, pedestrian corridors, and as grassed floodways.

Designing to minimise ongoing maintenance costs



Riparian zone planting

Meandering low-flow channel (Qld)

Newly placed and vegetated rock (Qld)

A rock mattress-lined sediment pond!

Smart landscaping

- In the author's untrained opinion, within a waterway setting, good landscaping achieves the following outcomes:
  - filtering sunlight to minimise weeds
  - providing both shallow and deep-rooted plants to help stabilise the banks
  - shading the water's edge to optimise aquatic habitat values and shelter, and
  - developing an appropriate connection between the riparian zone, the adjacent land, and the waterway.

Caution the use of pools, riffles and meandering channels

- In can be tempting for a waterway designer to incorporate pools and riffles into a channel design, but riffles traditionally exist only in sand-based, gravel-based, and rock-based waterways.
- Pools can exist is all waterways, but if the waterway does not want a pool to exist at a given location, then the waterway will quickly fill the pool, or move it.
- A channel meander is a channel feature that should be introduced with care.

Use of vegetated rock

- Traditional rock placement usually involves the rock being placed on a blanket of filter cloth with the voids left open—this meant that the texture of the exposed rocks will became a feature of the exposed surface.
- However, in a waterway environment, only the rocks placed below the water line should retain open voids (for habitat value)—all rocks placed above the water line should be integrated into the riparian vegetation (and not placed on filter cloth).

Do not build high-maintenance structures out of gabions or rock mattresses

- Urban waterways typically experience high levels of sedimentation, which can result in the need for ongoing de-silting.
- If a pond, basin, or channel is expected to be de-silted from time-to-time, then such a feature should NEVER be lined with gabions or rock mattresses.
- The wire baskets are easily damaged by most de-silting operations, other than vacuum pumping.

Drainage channels, creek engineering and river morphology

Browns Creek, Lismore, NSW in 2003

Browns Creek, Lismore, NSW in 2007

A modified rural creek (Qld)

River relocation (photo-generated image)

Introduction

- **Part 1** of this four-part document presents an overview of the different types of channel projects that can utilise the principles of Natural Channel Design.
- Typical projects include:
  - rehabilitation of degraded waterways
  - channel expansion
  - relocation of a channel
  - design of vegetated drainage channels
  - replacement of an existing concrete drain with a vegetated channel.

Drainage channels

- **Part 2** of this document presents an overview of the design of vegetated drainage channels.
- The design procedure presented here is different from that which would be used in the rehabilitation of a degraded waterway, but both tasks would share several design steps.
- Drainage channels are normally constructed to increase the flow capacity of an existing overland flow path (i.e. not an existing waterway).

Minor waterways vs major waterways

- Possibly the biggest difference between a minor waterway, such as a **creek**, and a major waterway, such as a **river**, is the influence of vegetation on the channel stability.
- If a river wants to move during a flood, then no vegetation is going to stop it from moving, but as the size of the channel reduces, the ability of the riparian vegetation to control the erosion and the lateral movement of the channel, increases.

Relocation of major waterways (rivers)

- The process of relocating a river channel is a rare event, and it is a design process that the author has never experienced.
- Major river channel works typically only occur in response to major flood damage, or where a river channel is migrating towards a public asset that cannot be moved.
- These types of channel projects rely heavily on the use of regime theory, and the input from river specialists.

6. Design of Vegetated Drainage Channels

Introduction

Vegetated drainage channel in 2001 (Qld)

The above drainage channel in 2005

Vegetated drainage channel (Qld)

Vegetated drainage channel (Qld)

Introduction

- This chapter primarily focuses on the design of new drainage channels, specifically, vegetated drainage channels.
- The design procedure is not appropriate for the rehabilitation of existing waterways; however, much of the discussion could be applied to such projects.

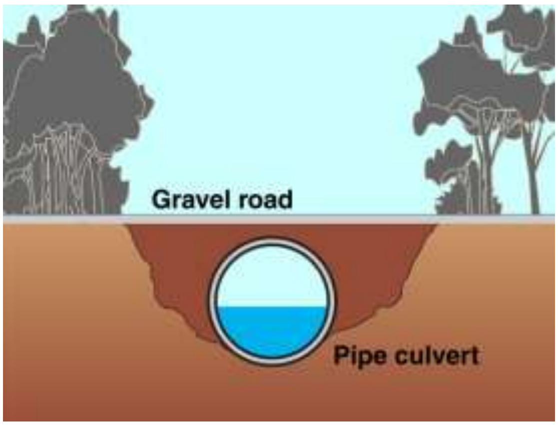
Design of vegetated drainage channels

- The design procedure is based on the following design steps:
  - Define the project's objectives.
  - Nominate the various design storms.
  - Nominate the allowable flow velocity.
  - Determine the required flow area and channel profile.
  - Select the bank gradients, surface conditions, and Manning's roughness.
  - Determine the required channel gradient.
  - Determine the channel alignment and meander conditions.
  - Design the bed conditions.
  - Design of bed stabilisation structures.
  - Design the channel's inflow conditions.
  - Design the channel's outflow conditions.
  - Design public and maintenance access.
  - Design the planting scheme.
  - Design the early phase erosion control measures.

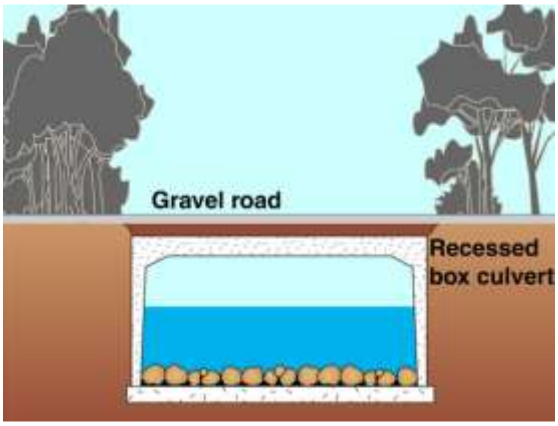
Typical legislation attached to drainage designs

- Most States and Territories have policies and/or legislation that controls activities in and around recognised waterways.
- A waterway can be recognised through the definitions attached to the legislation, or identified by a mapping system.
- Storm drains are usually not recognised as waterways, even if they are designed to mimic a natural waterway; consequently, there can be an absence of legislation applicable to such drainage channels.

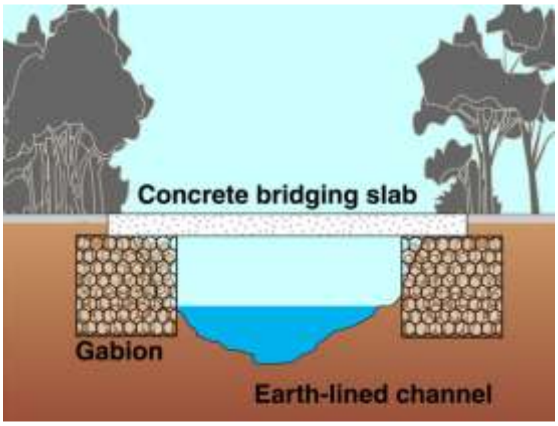
1 Define the Project’s Objectives



The culvert that the farmer wanted



What the engineer designed



What the farmer built

Introduction

- As previously discussed, the focus of this chapter is on the design of vegetated drainage channels; not on the rehabilitation or alteration of waterways.
- The fact that drainage channels are not classified as waterways does not mean that many of the ‘features’ of waterways can not be integrated into the design of these channels.

A storm drain is not a waterway

- The attributes that are likely to be associated with a vegetated drainage channel include:
  - drainage and flood control
  - habitat and movement corridor for terrestrial fauna
  - maintenance access.
- Optional attributes may include:
  - pedestrian and bikeway corridor
  - aquatic habitat, if attached to an existing aquatic habitat.

Understanding the practical reality of the construction site

- Drainage channels need to integrate well with the surrounding land use.
- The designers of vegetated drainage channels need to be aware of:
  - the capabilities of the people that will be constructing the channel (i.e. their equipment and construction skills)
  - the capabilities of the people that will be maintaining the channel (including the available equipment).

Defining the project's design objectives

Drainage designer

Introduction

- As a civil engineer, the author approach the drafting of this document from the point of view of a civil engineer, or drainage engineer (if you prefer).
- The author appreciates that it is not his job to tell YOU what YOUR design objectives should be.
- That said; the author presents below his preferred design objectives.

Government policies

1st Priority

- The first priority of a drainage designer should be to design a drainage system that meets the intent (or goals) of the government's policies and planning schemes.
- This means all policies, including:
  - public safety
  - drainage
  - flood management
  - waterway management
  - environmental and pollution control.

Maintenance costs

2nd Priority

- The second priority should be to design a drainage system that is sustainable, meaning:
  - low maintenance
  - sustainable drainage capacity (meaning ongoing vegetation growth does not cause an excessive decline in the channel's flow capacity)
  - sustainable flood damage (meaning a balance is achieved between the flood damage to vegetation, and vegetation regrowth).

Public access (Qld)

3rd Priority

- The third priority should be to find an appropriate balance between the competing uses of the drainage corridor, including:
  - human movement
  - aquatic fauna
  - terrestrial fauna
  - arboreal fauna
  - water movement
  - riparian conservation.

Controlling laws and legislation

Law courts (Qld)

Australia's High Court (ACT)

State government authority (Qld)

Local government (NSW)

Introduction

- Any physical disturbances to a waterway, including the construction of a drainage channel, could be subjected to various forms of legislation.
- Works conducted within a natural waterway can be subject to:
  - Waterway legislation (Natural Resources, or Primary Industries)
  - Fisheries legislation (Fisheries)
  - Environmental legislation (Environment Branch, including marine waters).

Common law

- Common law is a legal system that gives weight to the principle that it is unfair to treat similar facts differently on different occasions—thus judges' decisions in active cases are informed by the decisions of previously settled cases.
- The common law system (known also as 'case law') forms the basis of the Australian legal system.
- Common law is only applicable in the absence of relevant 'statute laws', including local building codes.

Instream works controlled by State legislation

- The States and Territories of Australia can formulate their own laws (Territory laws developed through the Federal Government).
- State laws apply equally to State Government works, local government works, and private works.
- **Note:** Approvals MUST be obtained from all relevant State Branches, which means Waterways, Fisheries, and Environmental.

Instream works controlled by local government planning schemes

- Local government policies and design codes are enforced through relevant State Government legislation, such as:
  - *Local Government Act* (or the like)
  - *Planning and Development Act* (or the like)
  - *Flood Control Act* (or the like).
- State legislation can empower a local government code, which can refer to an independent design guideline, such as this field guide.

Knowing what to focus on (repeated from Chapter 3 in Part 1)

In ship building, if you were commissioned to build a frigate or battleship, then you would know what you were required to build. In architecture, if you were commissioned to design a hospital or a primary school, then again you would know exactly what is required. But in creek engineering, if you were asked to rehabilitate a waterway, would you automatically know what your focus should be? Who is it in society that speaks on behalf of the waterway?

Natural Channel Design could be considered as just one of the design philosophies that could be used in the rehabilitation of a waterway. For some designers, the principles of Natural Channel Design should only be used in the design of drainage channels. So what role can it play in the rehabilitation of natural waterways? Whichever way you choose to think about these issues, the overriding question remains; *'What are you trying to achieve?'*

We can start to address this question by acknowledging that there are potentially six functions of a waterway corridor, those being:

- human movement (pedestrian and cycling)
- aquatic movement (fish passage)
- terrestrial movement
- arboreal movement
- water flow (drainage and flood control)
- riparian conservation.

A project team could then set about the task of ranking the relative importance (Essential, Important, Secondary or a Non-issue) of each of these six outcomes. Tables 6.1 to 6.6 provide examples of how the 'focus' of a creek rehabilitation project could be developed.

Table 6.1 – Human movement (author's opinion)

Requirements	Essential	Important	Secondary	Non-issue
Continuous, dual purpose pedestrian and bike pathway on at least one side of the waterway, with regular waterway crossings. Alternatively, pathways on both side of the waterway.	**Yes**			
Dual purpose, pedestrian and bike pathways located in regions where these pathways do not detract from nominated essential functions of the waterway corridor.		**Yes**		
Pedestrian and bikeway conduits incorporated into the design of new culvert crossings.	**Yes**	**Yes**		
Regular access/exit ramps to adjacent roadways, bikeways and pathways.	**Yes**	**Yes**		
Pedestrian and bike pathways located beyond the top of bank.			**Yes**	
Pedestrian crossings of the waterway to link with existing off-stream pedestrian movement corridors.	**Yes**	**Yes**	**Yes**	
Pedestrian crossings of the waterway are limited to road crossings.				**Yes**

Table 6.2 – Aquatic fauna movement (typically not a priority on drainage channels)

Requirements	Essential	Important	Secondary	Non-issue
Identify and remove (rehabilitate) all artificial fish passage barriers from the full extent of the natural fish habitat.	**Yes**	**Yes**		
Identify and remove artificial barriers to the movement of other aquatic fauna (e.g. turtles).	**Yes**	**Yes**		
Develop a program for the staged rehabilitation of all artificial fish passage barriers from the full extent of the natural fish habitat.	**Yes**	**Yes**	**Yes**	
Provide suitable riparian vegetation, and continuity of vegetation, to support fish migration during flood events.	**Yes**	**Yes**	**Desirable**	
Replace all causeway crossings, and rehabilitate existing culvert crossings.	**Yes**	**Yes**	**Desirable**	
Preference given to bridge and arch crossings of the waterway, if not mandated by State Fisheries.	**Yes**	**Yes**		
Adopt fish friendly designs for all new and replacement culverts.	**Yes**	**Yes**	**Yes**	
Introduce skylights to the nominated 'wet' cells of long culverts.	**Yes**	**Yes**	**Desirable**	
Give appropriate consideration to the rehabilitation of habitat and the movement corridors of other aquatic fauna (e.g. turtles and eels).	**Yes**	**Yes**	**Yes**	**Yes**

Examples of aquatic habitat:

Shading of the water's edge (Qld)

Open voids in rocks below water level

Table 6.3 – Terrestrial fauna movement (author's opinion)

Requirements	Essential	Important	Secondary	Non-issue
Prepare a fauna corridor master plan for the region, which links waterway corridors with major bushland corridors.	**Yes**	**Yes**		
Provide 'dry' fauna pathways under bridges, arches, and through culverts.	**Yes**	**Yes**	**Yes**	
Identify and rehabilitate discontinuities in the terrestrial movement corridors.	**Yes**			
Develop a program for the staged rehabilitation of terrestrial movement corridors.		**Yes**	**Yes**	
Shield fauna movement corridors from the effects of street lighting.	**Yes**	**Yes**		
Introduce both low level (dry pathways) and high level (lizard runs) to culverts.	**Yes**	**Yes**		
Investigate opportunities to return native fauna to waterways and vegetated drainage channels.	**Yes**	**Yes**	**Yes**	**Yes**

Table 6.4 – Arboreal fauna movement (author's opinion)

Requirements	Essential	Important	Secondary	Non-issue
Establish appropriate canopy trees adjacent to permanent water bodies to assist birds safety accessing water.	**Yes**	**Yes**	**Yes**	
Identify and rehabilitate discontinuities in arboreal movement corridors.	**Yes**	**Unlikely to be an issue.**		
Investigate the overall advantages and disadvantages of introducing nesting boxes to riparian zones.	**Yes**			
Introduce additional nesting boxes to compensate for the loss of natural nesting hollows.	**Yes**	**Yes**		

Table 6.5 – Water movement (author's opinion)

Requirements	Essential	Important	Secondary	Non-issue
Prepare a flood study of the waterway.	Yes	Yes		
Prepare a long-term program to mitigate any unacceptable flood risks.	Yes	Yes		
Prepare a master floodway corridor plan for the waterway, which identifies the preferred channel profile for each reach of the waterway.	Yes			
Integrate the floodway master plan with the open space or parkland master plan.	Yes	Yes		
Prepare guidelines on the preferred planting schemes for each reach of the waterway.	Yes	Yes	Yes	

Table 6.6 – Riparian conservation (author's opinion)

Requirements	Essential	Important	Secondary	Non-issue
Riparian zones have a minimum width of 30 metres to minimise the risk of excess weed growth in the centre of the riparian zone (i.e. controlling edge effects).	Yes			
Active weed control within riparian zone.	Yes	Yes	Yes	
Weed control within land adjacent to the riparian zones.	Yes			
Riparian zones have a minimum width of 15 metres to minimise the risk of excess weed growth in the centre of the riparian zone.		Yes		
Riparian zones have a minimum width of 5 metres to minimise the risk of excess weed growth in the centre of the riparian zone.			Yes	
Markers or edge planting is use to separate mown grassland from riparian bushland.	Yes	Yes		

Defining the project's design objectives (example)

Worst bad outcome	Least bad outcome	Least good outcome	Best good outcome
Waterway channel exists within an open grassed floodway with no shade, shelter, or riparian values. Open plan on-line urban lake with no riparian values.	Full public access exists along the waterway, with only the minimum riparian corridor. Active bikeway and pathway located adjacent the riparian zone.	Regular bikeway and pedestrian crossings of the waterway. Primary bikeway and pedestrian corridor located along the adjacent roadway system.	Continuous bikeway and/or pathway located within the floodway, and outside a health riparian zone. Fish-friendly waterway crossings.

Human movement outcomes

Worst bad outcome	Least bad outcome	Least good outcome	Best good outcome
Waterway channel exists within an open grassed floodway with no riparian values. Regular barriers to fish passage along the waterway.	Non-continuous riparian zone. Fish passage along the waterway is restricted, but possible for some species. Minimal shading of the water.	Continuous, but restricted fish passage. Continuous riparian zone along one side of the waterway. Fish-friendly waterway crossings.	Continuous, unrestricted fish passage along the waterway. Healthy riparian zone on both sides of the waterway. No downstream barriers to fish passage.

Aquatic fauna outcomes

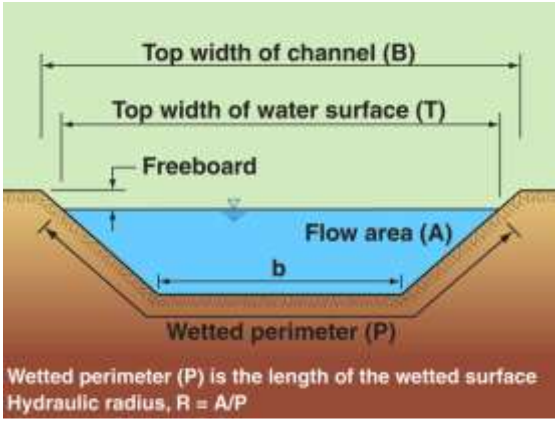
Worst bad outcome	Least bad outcome	Least good outcome	Best good outcome
The width of a near-continuous riparian zone (measured from the top of bank) is less than 3 metres.	The minimum width of a near-continuous riparian zone (each side of the water's edge) is 5 metres. Shields are placed on street lights to deflect the light away from riparian zones.	The minimum width of a continuous riparian zone (each side of the water's edge) is 15 metres for 1st order streams; 30 m for 2nd order streams; and 60 m for higher order streams.	The riparian zone is continuous along the waterway, and blends seamlessly with the adjoining bushland. A continuous corridor exists from the mountains to the sea.

Terrestrial fauna outcomes (linked to riparian width)

Worst bad outcome	Least bad outcome	Least good outcome	Best good outcome
Invasive and noxious weeds are not being controlled. Biodiversity of native plants is in decline. A single plant species is forming a mono-culture.	Aggressive weeds are replaced with non-aggressive weeds. Low-invasive grasses replace highly-invasive and noxious weeds.	Weeds are replaced with native plants. Some non-endemic native plants are being used to control high-risk erosion sites.	The risk of weed invasion is removed. Weeds are controlled on adjoining land. Riparian zones are dominated by locally endemic native plants.

Riparian values

Step 2: Nominate the various design storms



Freeboard

Introduction

- Traditionally there has only been one design storm linked with the design of drainage channels, and in most cases that is likely to continue.
- That design storm was either:
  - 1-in-50 year (2%) storm with freeboard to adjacent private land, or
  - 1-in-100 year (1%) storm with freeboard to adjacent floor levels.

Bikeway

Nomination of the 'design storm'

- In the author's opinion, the following recommendations apply:
  - adopt the 2% storm if the drainage channel is expected to be well-maintained, such as a mown grass swale
  - adopt the 1% storm if the drainage channel's vegetation includes woody species
  - adopt a minimum 1-in-2 year flood level for bikeways.

Bankfull flow (Qld)

Bankfull discharge

- The bankfull discharge is of critical importance when designing waterway rehabilitation and relocation projects, but it is usually not relevant to the design of drainage channels.
- In waterways, the bankfull discharge can influence the:
  - maximum flow velocity within the main channel
  - depth and width of the channel
  - minimum radius of channel bends.

Designing for a sustainable level of flood damage

Flood damage to riparian vegetation

Introduction

- In traditional engineering, a drainage channel would be designed for non-damaging flow conditions during the nominated design storm.
- However, in Natural Channel Design it is necessary to allow for an acceptable level of vegetation damage during major storms.
- The theory being that damaged vegetation should have sufficient time to repair itself before the next storm/flood event.

1-in-2 year flood (Qld)

Minor damage

- A minor storm may be considered to be the 2 year ARI event.
- The expected outcomes of a minor storm could be:
  - very minor in-bank damage
  - non-scouring in-bank flow velocities
- Flows usually contained within the banks of the channel during such storms, with no additional safety hazards occurring within accessible public areas.

1-in-10 year flood (Qld)

Significant damage

- A significant storm may be considered to be the 10 year ARI event.
- The expected level of damage during a minor storm could be:
  - some in-bank vegetation damage
  - minor movement of bed material
  - scour holes downstream of tree trunks with minor loss of trees within over-bank area, and some damage to shrubs.

1-in-50 year flood (NSW)

Infrequent severe damage

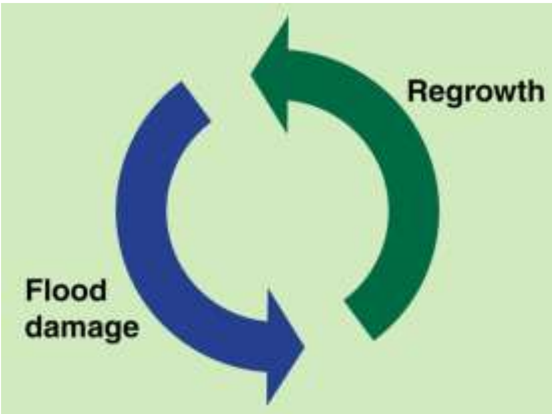
- During a 20-50 year ARI event: Significant shrub damage. Moderate tree loss. Isolated bank damage. Moderate damage to over-bank grassed areas.
- During a 100 year ARI event: Significant but repairable vegetation damage. No major water storage embankment failures. Moderate bank erosion. No significant re-alignment of watercourse. No flood damage to habitable floor levels of homes.

Step 3: Nominate the allowable flow velocity

Unknown answer

Introduction

- The design of grass or rock-lined drains is based on the allowable flow velocity for those particular materials.
- For concrete-lined drains, the critical design aim is usually to avoid the formation of supercritical flows.
- However, for vegetated drainage channels, the allowable flow velocities for various types of vegetation, and planting communities, are yet to be fully understood.



Damage–repair cycle

A sustainable level of damage

- The introduction of this document included a discussion on 'designing to achieve sustainable damage', which would at first appear to be a poor engineering outcome; however:
  - in Natural Channel Design we must learn to accept that some vegetation damage will occur during flood events
  - and, if the rate of damage equals the rate of natural regrowth, then the long-term outcomes are considered 'good'.

Flood damage to young plants

Allowable flow velocity during site revegetation

- In addition to setting limits on the allowable flow velocity during flood events, there is also a need to set limits on the maximum flow velocity during those storm events that are likely to occur during the early growth phase of the plants.
- Recently established plants can be damaged by much lower flow velocities than those that can damage mature plants.

Channel design

Frequency	EY	AEP (%)	(1 in X)	ARI	Engineering Design
Very frequent	12				Stormwater treatment
	6	99.75	1.002	0.17	
	4	98.17	1.02	0.25	
	3	95.02	1.05	0.33	
	2	86.47	1.16	0.50	
Frequent	1	63.20	1.58	1	Drainage design
	0.69	50.00	2.00		
	0.50	39.35	2.54	2	
	0.22	20.00	5.00		
	0.20	18.13	5.52	5	
Infrequent	0.11	10.00	10	10	Floodplain management
	0.05	5.00	20	20	
	0.02	2.00	50	50	
	0.01	1.00	100	100	
Rare	0.005	0.50	200	200	
	0.002	0.20	500	500	
	0.001	0.10	1000	1000	
	0.0005	0.05	2000	2000	Major infrastructure
Extremely rare	0.0002	0.02	5000	5000	
	[illegible]	[illegible]	[illegible]	[illegible]	
			[illegible]	[illegible]	
Extreme			PMP	PMF	

Design storm terminology (ARR)

Selection of the 'design storm'

- The 1-in-50 year (2%) flood event is typically chosen because it represents a major flood event during which some vegetation damage would normally be expected.
- The 1-in-100 year (1%) flood can be chosen is floor level flooding is a concern.

In the caption (left) 'ARR' means the *Australian Rainfall and Runoff* publication.

Mature riparian bushland (Qld)

Allowable flow velocity through vegetation

- Recommended permissible flow velocity for vegetated channels varies with the channel roughness.
  - For **n = 0.03**, V_{allow} < 2.0 m/s, or refer to an appropriate grass drain table
  - For **n = 0.06**, V_{allow} < 1.7 m/s
  - For **n = 0.09**, V_{allow} < 1.5 m/s
  - For **n = 0.15**, V_{allow} < 1.0 m/s.
- A Manning's roughness of n = 0.15 is considered to represent mature bushland.

Early growth phase (Qld)

Selection of the design storm for checking flow velocities during the early growth phase

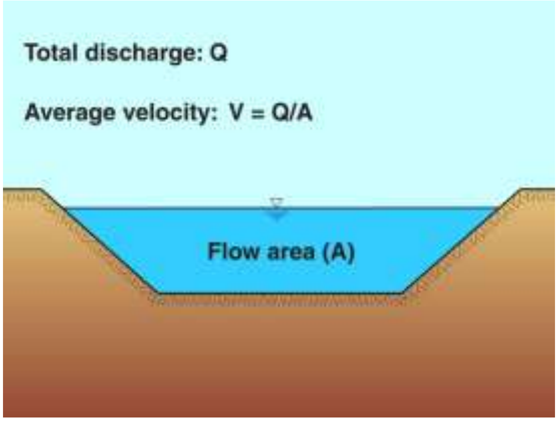
- A hydraulic analysis should be performed on a lightly vegetated channel condition to determine the flow velocity that is likely to occur during a 1-in-2 year (40%) storm event.
- A Manning's roughness of n = 0.05 to 0.06 would typically represent these lightly vegetated channel conditions.

Minor flood damage to new plants

Allowable flow velocity through newly-established vegetation

- During these early phase conditions, an allowable flow velocity could be set at 1.6 to 1.7 m/s.
  - For **n = 0.05**, V_{allow} < 1.6 m/s
  - For **n = 0.06**, V_{allow} < 1.7 m/s.

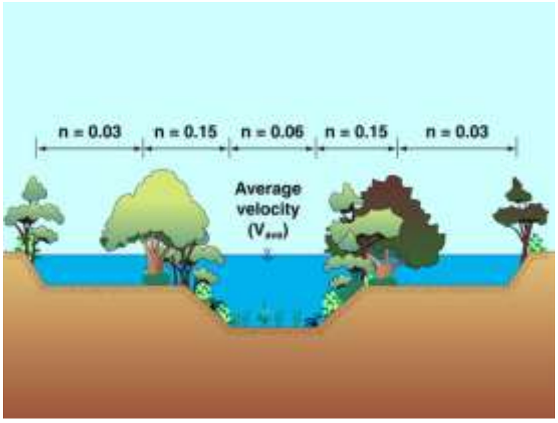
Determination of the through velocity in a complex channel



Average velocity

Introduction

- In hydraulics there are various flow velocities that can be of interest:
  - the local velocity, or spot velocity, for fish passage
  - the depth-average velocity for sizing rock and soil scour checks
  - the average flow velocity for general flow analysis, and
  - the through velocity for checking the flow velocity passing through a safety screen, or through bushland.



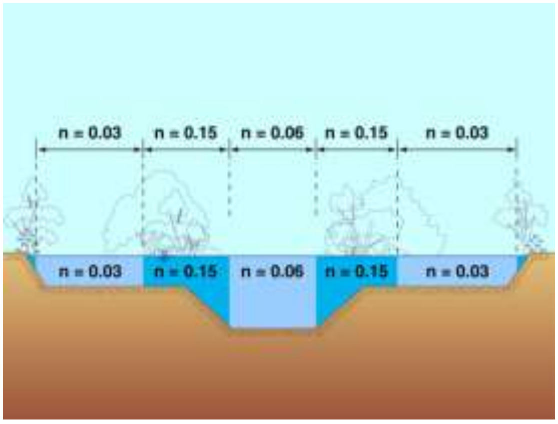
Average velocity

Average flow velocity (V)

- The average flow velocity is defined as the total discharge (Q) divided by the total flow area (A).

$$V = Q/A \quad [m/s]$$

- In complex cross-sections there may be areas of zero flow due to flow isolation; in such cases these areas are excluded from the total flow area.
- The symbol for velocity is normally a lower case ‘v’, but an upper case ‘V’ is often used, such as in this publication.



Complex channel roughness

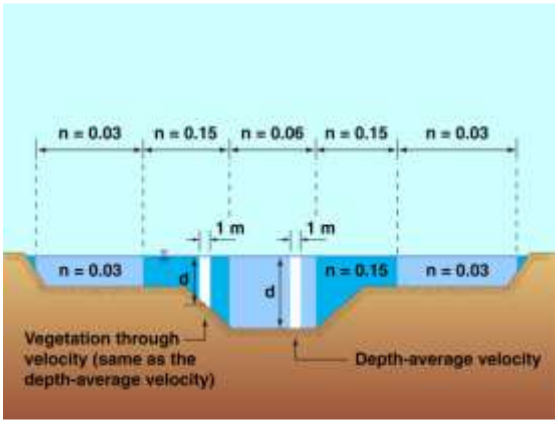
Calculation of the depth-average velocity

- For the purpose of these simple velocity checks, the velocity passing through a section of vegetation (the ‘through velocity’) may be based on the depth-average velocity for that sector.
- The channel is first analysed in the normal manner using programs such a HecRas, or a 2D hydraulic model.
- This first analysis gives us the local hydraulic gradient, **‘S’** in units of [m/m].
- The flow velocity that is expected to be passing through a section of vegetation (the ‘through velocity’) may be based on the depth-average velocity (**$V_{d\text{-}a}$**).

Units for **$V_{d\text{-}a}$** are [m/s]:

$$V_{d\text{-}a} = (1/n) \cdot D^{2/3} \cdot S^{1/2}$$

where: **n** = the Manning’s roughness for that section of vegetation; **D** = water depth at that location (sometimes presented as ‘d’ or ‘y’); and **S** = hydraulic gradient.

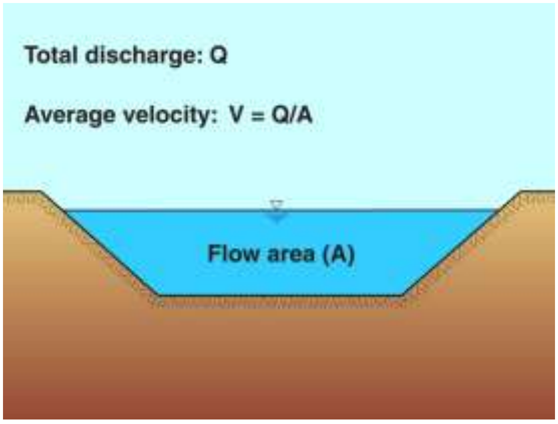


Depth–average flow velocity

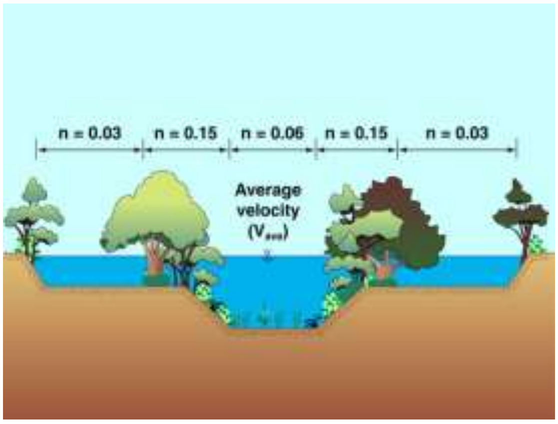
Step 4: Determine the required flow area and channel profile

Determine the Required Flow Area and Channel Profile

A very large, trapezoidal channel



Simple 'area–velocity' relationship



Complex multi-stage trapezoidal channel

Introduction

- If you design a channel based solely on achieving an allowable flow velocity, then you can, theoretically, design a very deep channel with a very small bed gradient.
- However, a 10 metre deep drainage channel is rarely seen in nature, and possibly should not be seen in urban areas.
- Ideally, as the flow area increases, the channel geometry should become more complex.

Determination of the flow area

- In its simplest form, the area–velocity relationship can be presented as:

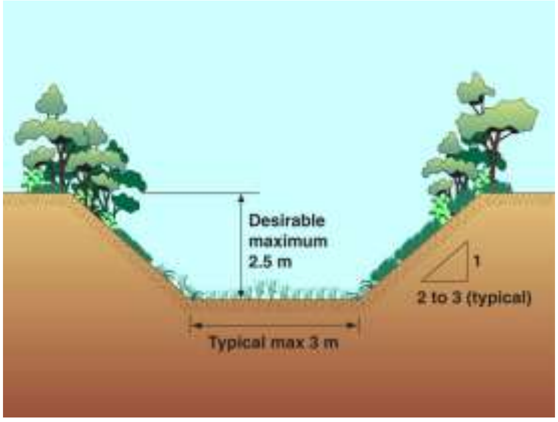
Flow area = (Discharge)/(Allowable velocity)

- However, in complex channels, the allowable velocity will not be constant for each region of vegetation.
- Instead, the allowable flow velocity will depend on the vegetation roughness at any given location within the cross-section, which can make the determination of the required flow area more complex.

Selection of the type of channel profile or cross-section

- Small channels can start out as simple, single-stage trapezoidal channels.
- However, as the flow area increases, channel depth and bed width limits can begin to apply, which forces the channel to take the form of a complex, multi-stage (benched) trapezoidal channel.
- There are a good reasons why natural channels take a similar form, and these same reasons apply to the design of vegetated drainage channels.

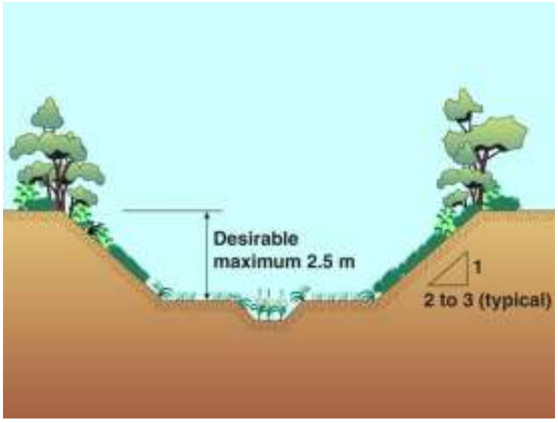
Dimensional limits for constructed drainage channels



Single-stage trapezoidal channel

Vegetated channel with no formal low-flow channel (D1 & D2)

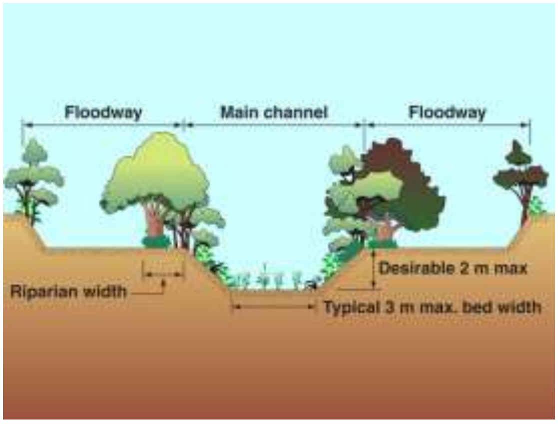
- A bed width greater than approximately **3 m** can become impractical in constructed ephemeral drainage channels.
- If a wider channel is required, then consider the inclusion of a separate low-flow channel.
- Channel vegetation should not be dominated by grasses, even though some grasses and other ground covers will usually be required for scour control.



Inclusion of a low-flow channel

Vegetated trapezoidal channel with low-flow channel (D3)

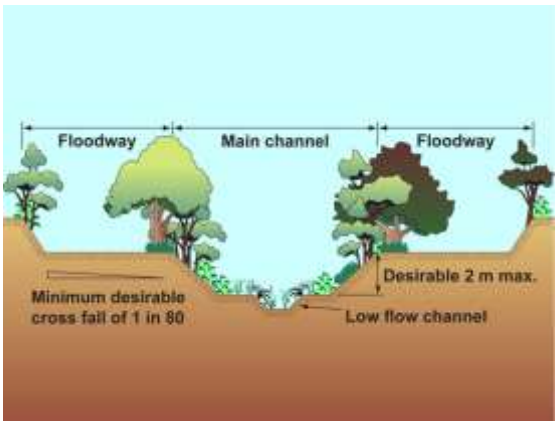
- A well-defined low-flow channel forms part of the channel bed to assist in fish passage (if required?), and the control of soil moisture levels across the channel bed.
- A desirable maximum channel depth of **2.5 m** is recommended, otherwise excessive erosion and vegetation damage may occur during high flows and/or excessive sedimentation may occur during low flows.



Single-stage channel with floodways

Two-stage vegetated channel (W1 to W4)

- Channel capacity (excluding floodway) is typically 1-in-1 year to 1-in-10 year ARI.
- A channel capacity exceeding 1-in-10 year ARI should be avoided.
- A desirable maximum main channel depth of **2 m** (relative to top of the lower bank) is recommended instead of 2.5 m (above).
- Care must be taken to ensure any meandering of the channel does not adversely affect the passage of floodwater along the floodways.



Multi-stage channel with floodways

Multi-stage vegetated channel

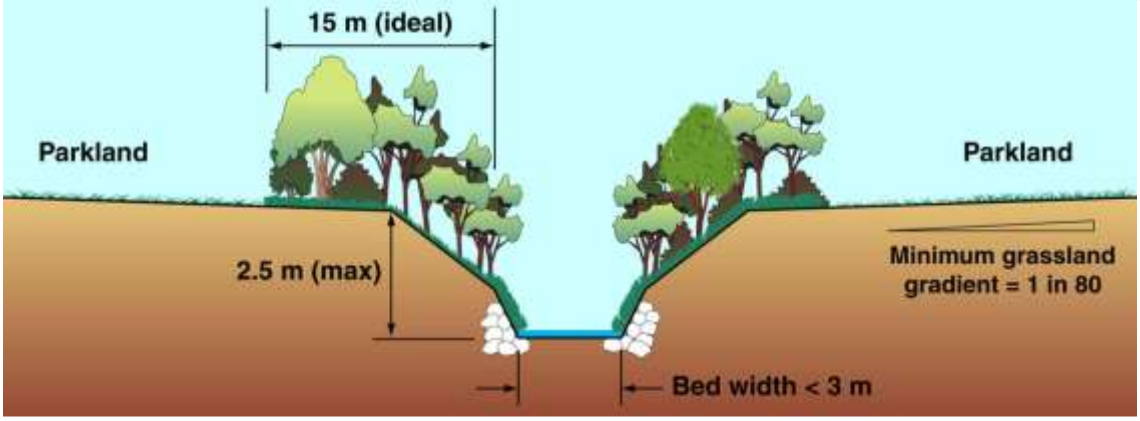
- Channel capacity (ex. floodways) typically 1-in-1 year to 1-in-10 year ARI.
- A channel capacity exceeding 1-in-10 year ARI should be avoided.
- Low-flow channel capacity is based on the actual dry weather flow rate.
- The main channel is usually designed as a low-maintenance, heavily-vegetated, closed-canopy system.

Option D1 (Drainage channel with bank height NOT exceeding 2.5 m)

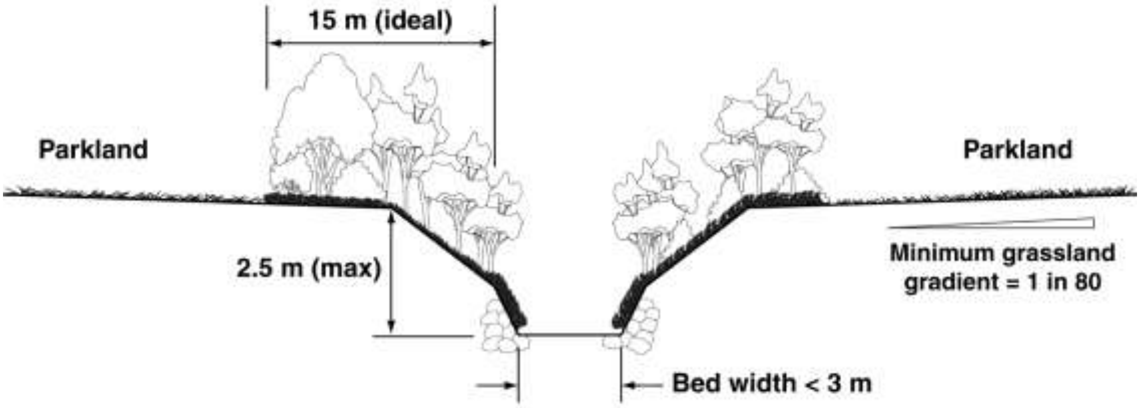
Enlarged creek channel (Qld)

Option D1

- If the available, or desirable, corridor width does not allow sufficient space for the benching of the channel banks, then it is likely that the channel banks will need to be reinforced with vegetated rock.
- Rarely will the rock need to extend to the top of the channel banks (refer to Step 5).
- Designers should avoid the use of synthetic (i.e. plastic-based products) within drainage channels and waterways.



Cross-section and riparian conditions



Cross-section and riparian conditions

The above creek after plant growth

Maximum recommended bank height

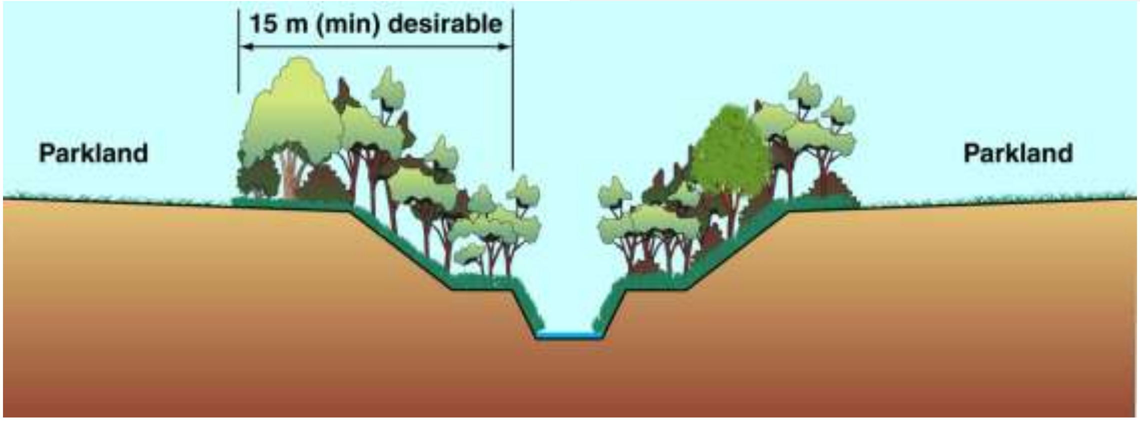
- Desirable maximum channel depth is **2.5 m**, otherwise excessive erosion and vegetation damage can occur during high flows, and/or excessive sedimentation may occur during periods of low flow.
- If the channel banks are benched, then the desirable maximum bank height reduces to **2 metres**.

Option D2 (Drainage channel with a bed width NOT exceeding 3 m)

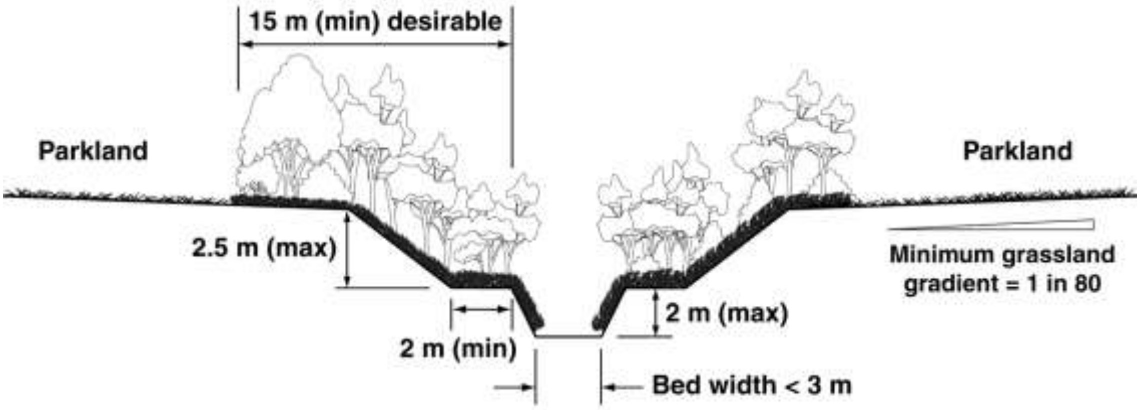
Benched storm drain (Qld)

Option D2

- If the bed width is relatively narrow, say less than 3 metres, then the main channel could possibly function without a low-flow channel.
- If a pool–riffle system is established within an alluvial waterway, then the riffles should extend across the full width of the bed, not just the low-flow channel.
- Within a pool–riffle system, it is likely that the 'pools' may need to be wider than 3 metres (refer to Chapter 10).



Vegetated drainage channel <u>without</u> a low-flow channel



Design requirements

The above storm drain after plant growth

Maximum recommended bed width

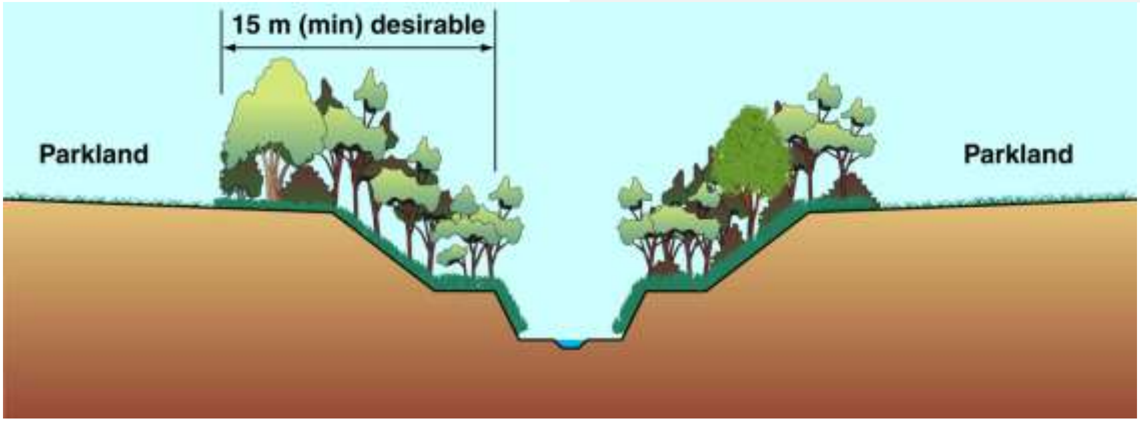
- As the bed width increases, the risk of reed invasion and sedimentation problems will also increase.
- From the author's experience, the bed width of a drainage channel rarely exceeds 1 to 2 metres, after which the use of a low-flow channel is required.
- On channel relocation projects, the bed width should be based on the existing upstream and downstream bed conditions.

Option D3 (Drainage channel with a bed width exceeding 3 m)

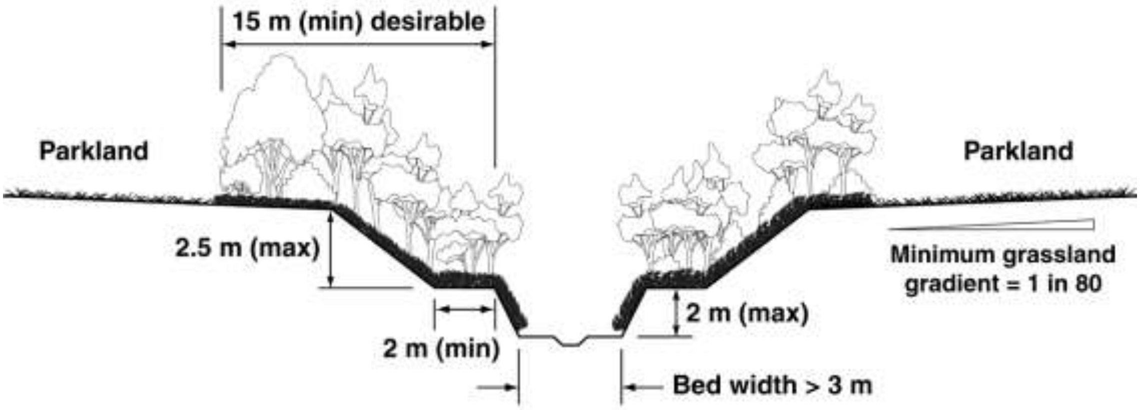
Earth-lined low-flow channel (Qld)

Option D3

- As discussed at the beginning of this design step, it is generally desirable to limit the width of the main channel to the minimum necessary in order to avoid weed and sedimentation problems.
- However, if the required channel conveyance forces the design towards a wider bed width, then consideration should be given to the formation of a low-flow channel within the bed of the channel.



Vegetated drainage channel with low-flow channel



Design requirements

Rock-lined low-flow channel (Qld)

Low-flow channels

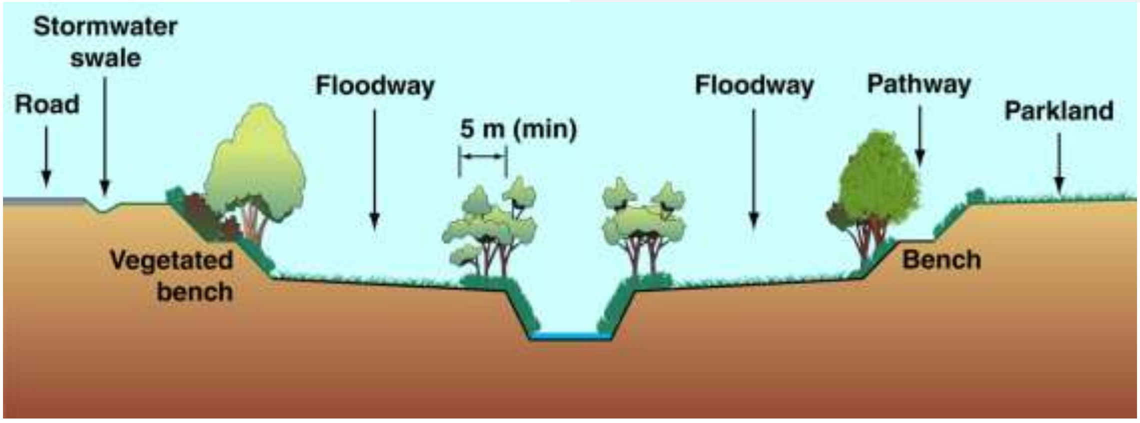
- Low-flow channels are best formed as:
  - earth-lined low-flow channels, typically stabilised with plants like *Lomandra*, or
  - rock-lined channels.
- In certain regions, it may be necessary to adopt a concrete-lined low-flow channel in order to limit mosquito breading (i.e. public health issues).
- If a concrete-lined invert is adopted, then rock must be placed each side of the concrete (as discussed in Step 8).

Option W1 (Maximising flood flow)

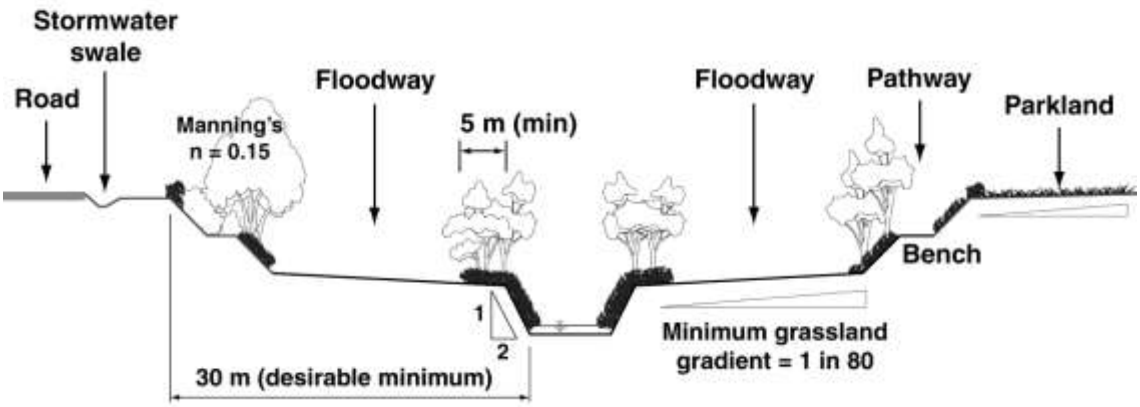
Grassed floodway (Qld)

Option W1

- The inclusion of floodways to a floodplain can provide several benefits, including:
  - improved public access
  - improved fire control
  - improved control of wildlife movement
  - improved flood control
  - the provision of public open space
  - the provision of sporting facilities
  - the separation of bikeways from pedestrian pathways.



Cross-section and riparian conditions



Design requirements

Grassed floodway (Qld)

Minimum recommended riparian width

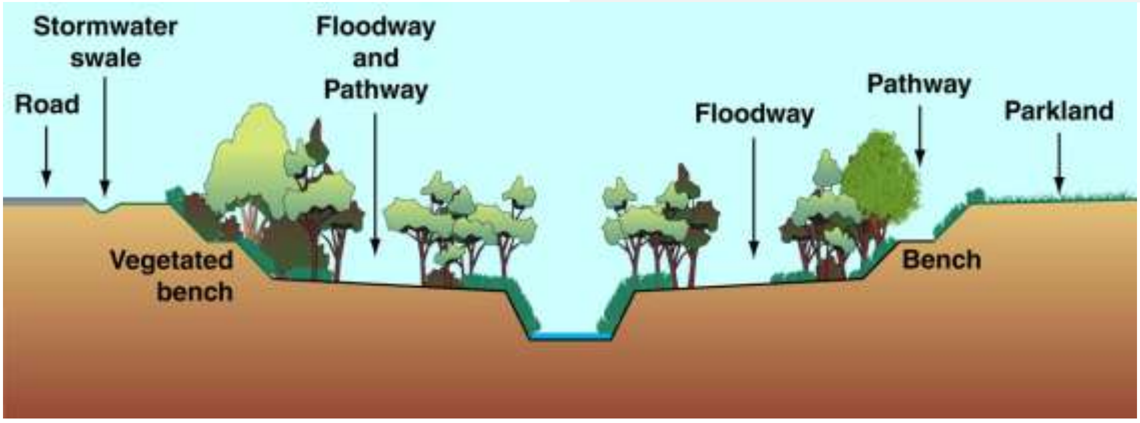
- The minimum width of the riparian zone can be based on:
  - bank stability (i.e. 3 x bank height)
  - control of edge lighting for weed control (variable, but can be as small as 5 m)
  - habitat values for terrestrial wildlife (5 m for 1st order streams, 10–15 m for 2nd order streams, 15–30 m for 3rd order streams); however, a minimum riparian width of 15 metres is considered by many to be desirable.

Option W2 (Benched high banks)

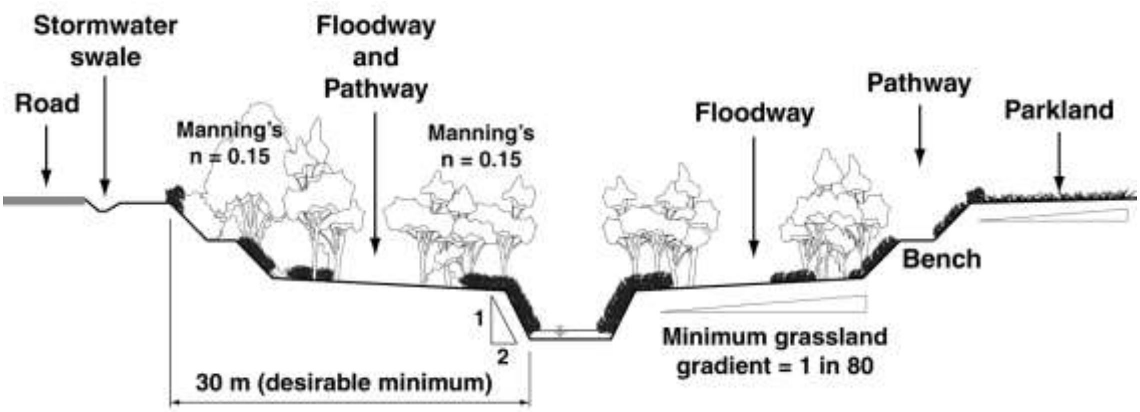
Benching (Qld)

Option W2

- Benching can be used to form:
  - floodways and floodplains adjacent to the main channel
  - tall stable channel banks.
- The horizontal (benched) surface can be:
  - left open (grassed or paved) to allow pedestrian movement, or
  - vegetated to maintain a constant cover of bushland.



Cross-section and riparian conditions



Design requirements

Pathway established on a bench (SA)

Benching of tall banks

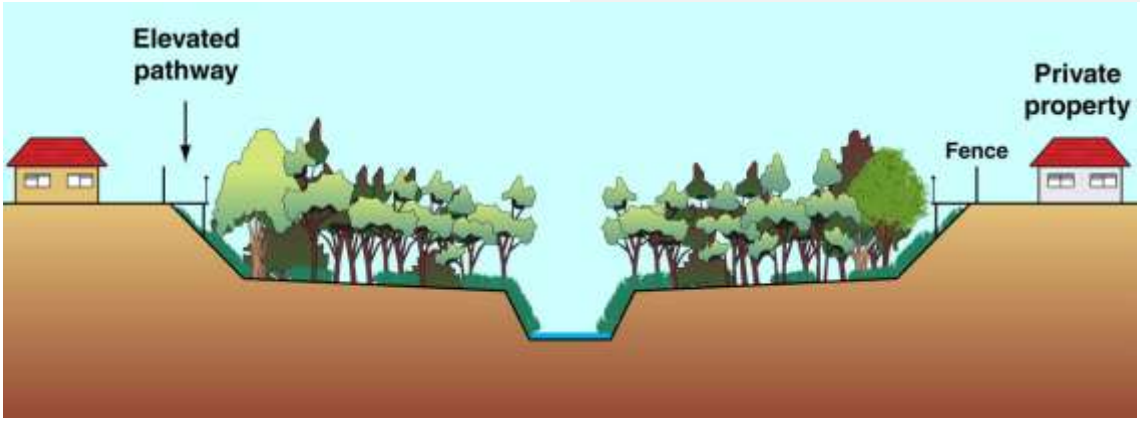
- The benching of tall banks can provide several benefits, including:
  - increased structural stability of the bank, which reduces the risk of a land slip
  - reduced risk of erosion or a land slip within the lower bank, causing similar erosion in the upper bank.

Option W3 (Residential property adjacent to the waterway)

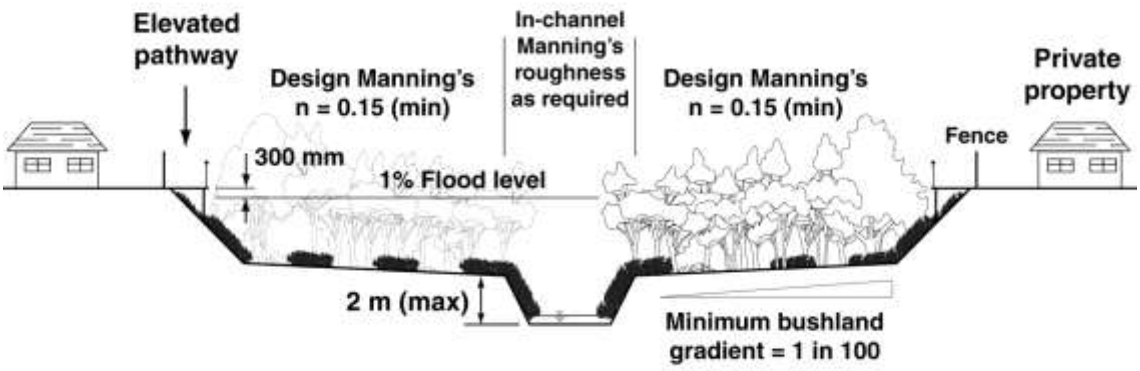
Waterway corridor (Qld)

Option W3

- Allowing urban properties to adjoin bushland not only increases the risk of garden clippings being thrown over the fence into the bushland, but it also:
  - increases the risk of wildlife, such as snakes, entering private properties, and
  - increases the fire risk.
- If parts of the waterway corridor have private property frontage, then elevated pathways can be installed adjacent to these properties in order to achieve a continuous linkage of public access.



Cross-section and riparian conditions



Design requirements

Elevated pathway (SA)

Pathways

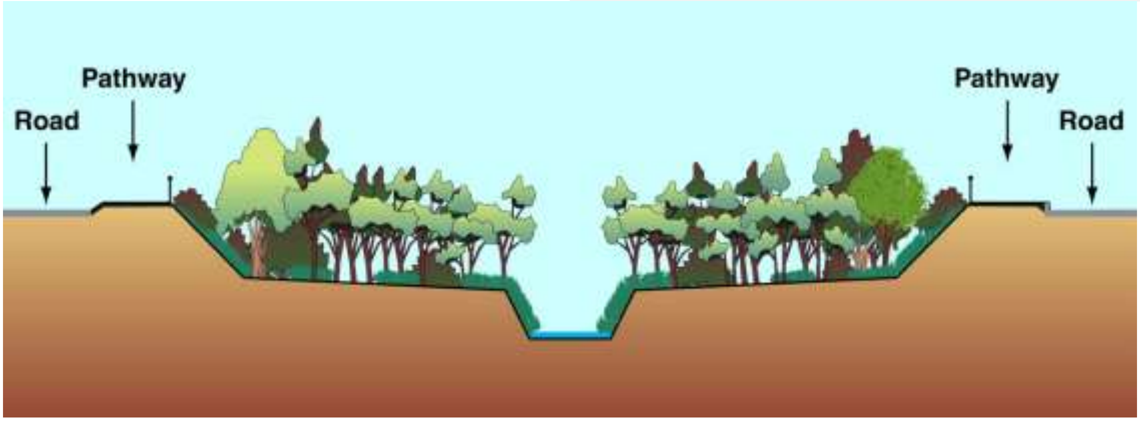
- To improve public access, an elevated pathway can be placed between residential properties and the bushland.
- These pathways can perform the task of pedestrian pathways, bikeways, and if adequately built, maintenance access and fire fighting.
- Elevated pathways are unlikely to experience the erosion problems experienced by low-level boardwalks.

Option W4 (Road and pathway at top of bank)

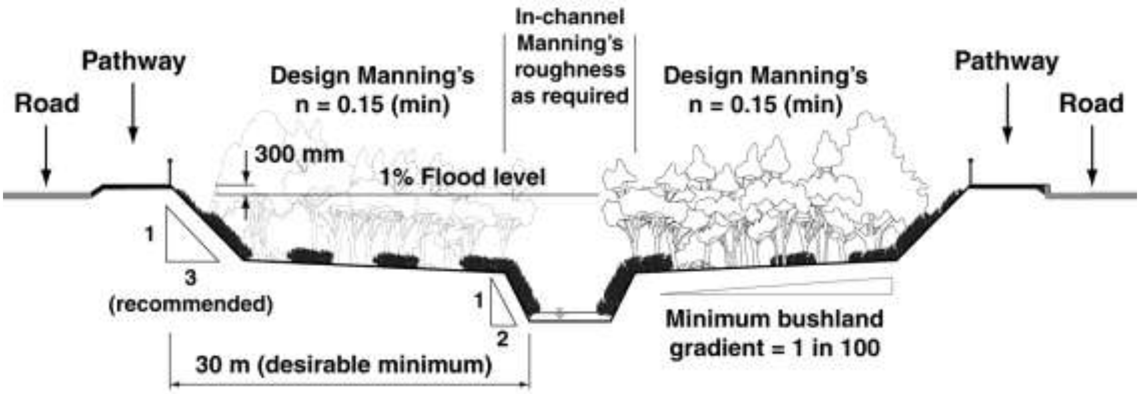
Overbank pathway (SA)

Option W4

- When there are no corridor width limitations, then the drainage corridor could be developed as self-sustaining bushland.
- Ongoing maintenance would only involve the removal of weeds, which could be performed by hand, or by a bushland community group.



Cross-section and riparian conditions



Cross-section and riparian conditions

Disposal of domestic garden waste

The benefits of placing a roadway or public pathway at the top of bank

- Past history has shown that if urban properties abut bushland reserves, then domestic garden waste, including grass clippings, can be thrown over the fence into the bushland.
- Placing roads and pathways at the top of bank allows:
  - good public access
  - good fire control
  - good maintenance access.

Table 6.7 – Typical Manning's n roughness (Chow, 1959)

Channel description	Manning's roughness	Channel description	Manning's roughness
Winding open soil drain	0.025	Winding drain, some weeds	0.032
Earth side with rubble bed	0.030	Stony banks, weedy bed	0.035
Deep channel, some weeds	0.050	Deep channel, dense weeds	0.080
Natural channel with vegetation	0.100	Natural channel with vines	0.200

Table 6.8 – Manning's roughness for various channel linings (Fifield, 2001)

Material	Flow depth less than 150-mm	Flow depth of 150 to 600-mm	Flow depth greater than 600-mm
Bare, rough-cut soil	0.023	0.020	0.020
Jute net	0.028	0.022	0.019
Wood excelsior blanket	0.066	0.035	0.028
TRM – unvegetated	0.036	0.026	0.020
TRM – grassed	0.023	0.020	0.020
Gabion/rock mattress	Manning's roughness as for loose rock assuming, d_{50}/d_{90} = 0.8		

Table 6.9 – Manning's roughness for grassed channels (50–150mm blade)

R (m)	Swale Slope (%)					
	0.1	**0.2**	**0.5**	**1.0**	**2.0**	**5.0**
0.1	Outside data range	Outside data range		0.105	0.081	0.046
0.2		0.091	0.068	0.057	0.043	0.030
0.3	0.078	0.064	0.053	0.043	0.031	0.030
0.4	0.063	0.054	0.044	0.033	0.030	0.030
0.5	0.056	0.050	0.038	0.030	0.030	0.030
0.6	0.051	0.047	0.034	0.030	0.030	0.030
0.8	0.047	0.044	0.030	0.030	0.030	0.030
1.0	0.044	0.044	0.030	0.030	0.030	0.030
>1.2	**0.030**	**0.030**	**0.030**	**0.030**	**0.030**	**0.030**

Table 6.10 – Manning's roughness of rock lined channels with shallow flow

	d_{50}/d_{90} = 0.5					d_{50}/d_{90} = 0.8				
d_{50} =	**0.1m**	**0.2m**	**0.3m**	**0.4m**	**0.5m**	**0.1m**	**0.2m**	**0.3m**	**0.4m**	**0.5m**
R	**Manning's roughness (n)**					**Manning's roughness (n)**				
0.2m	0.06	0.10	0.14	0.17	0.21	0.03	0.06	0.08	0.09	0.11
0.3m	0.05	0.08	0.11	0.14	0.16	0.03	0.05	0.06	0.08	0.09
0.4m	0.05	0.07	0.09	0.12	0.14	0.03	0.04	0.05	0.07	0.08
0.5m	0.04	0.06	0.08	0.10	0.12	0.03	0.04	0.05	0.06	0.07
0.6m	0.04	0.06	0.08	0.09	0.11	0.03	0.04	0.05	0.05	0.06
0.8m	0.04	0.05	0.07	0.08	0.09	0.03	0.04	0.04	0.05	0.06
1.0m	0.03	0.04	0.06	0.07	0.08	0.03	0.03	0.04	0.05	0.05

The roughness values presented in Table 6.10 have been developed from Equation 9.4.

Table 6.11 – Modified Cowan method for channel roughness: $n = (n_b + n_1 + n_2 + n_3 + n_4)m$

Channel condition		Values	Description
Channel material (n_b)	Earth	0.020	Clay-based channels.
	Bed rock	0.025	Channels cut into bed rock.
	Sand–fine gravel	0.024	Sandy creeks.
	Coarse gravel	0.026	Gravel-based creeks (refer to Table 6.10).
Degree of irregularity (n_1)	Smooth	0.000	Smooth channel.
	Minor	0.001–0.005	Excavated channels in good condition.
	Moderate	0.006–0.010	Channels with considerable bed roughness and some bank erosion.
	Severe	0.011–0.020	'Natural' channels: pools and riffles, exposed tree roots, boulders, and/or irregular banks.
Variation in channel cross section (n_2)	Uniform	0.000	Near-uniform channel section.
	Gradual	0.001–0.005	Large and small cross sections alternate occasionally (typically n_2 = 0.003).
	Severe	0.010–0.015	Large and small cross sections alternate frequently (significant pool-riffle system).
Effect of obstructions (n_3) excluding vegetation	Negligible	0.0–0.004	A few scattered obstructions (boulders, trees, logs) that occupy less than 5% of the channel.
	Minor	0.005–0.015	Obstructions occupy 5–15% of the channel and the obstructions are generally isolated.
	Appreciable	0.020–0.030	Obstructions occupy 15–50% of the channel.
	Severe	0.040–0.050	Obstructions occupy more than 50% of the channel (eg. severe debris collection).
Amount of vegetation (n_4) Considerat-ion should be given to the obstruction caused by vegetation relative to channel width and depth	Small	0.002–0.010	Grasses and/or weeds with the flow at least three times the height of the vegetation.
	Medium	0.010–0.025	Grass and/or weeds with the flow one to two times the height of the vegetation; or reeds or tree seedlings growing with the flow two to three time the vegetation height; or minor bed vegetation with medium bank vegetation.
	Large	0.025–0.050	Grasses and/or weeds with flow depth equal to vegetation height; or weedy beds with thick bank vegetation; or moderate shrub growth across the bed and banks.
	Very large	0.050–0.100	Grass and/or weeds more than twice the height of flow depth; or dense, strong reed growth; or significant shrub growth within the channel; or significant inflexible vegetation within channel.
Degree of channel meandering (m)	Minor	1.00	Channel sinuosity is 1.0 to 1.2
	Appreciable	1.15	Channel sinuosity is 1.2 to 1.5
	Severe	1.30	Channel sinuosity is greater than 1.5
			or; $m = 0.57 + 0.43$ (Sinuosity), but < 1.3

Table 6.12 – Suggested Manning's n for a watercourse floodplains

Minimum	Normal	Maximum	Description
A. Pasture, no brush			
0.025	0.030	0.035	Short grass – use design charts for grass
0.030	0.035	0.050	High grass – use design charts for grass
B. Cultivated areas			
0.020	0.030	0.040	No crop
0.030	0.040	0.050	Mature crop
C. Brush			
0.035	0.050	0.070	Scattered brush, heavy weeds
0.040	0.060	0.080	Light brush and trees
0.070	0.100	0.160	Medium to dense brush
D. Trees (also refer to Table 6.13)			
0.080	0.100	0.120	Heavy stand of timber, a few fallen trees, little undergrowth, tree branches above flood level.
0.100	0.120	0.160	As above, but with tree branches below flood level.
0.110	0.150	0.200	Dense tree cover


Grassed pasture (tall grass)


Cultivated land (mature crops)


Brush (easy to walk through)


Trees (difficult to walk through)

Manning's roughness (author's opinion)

Manning's n = 0.03 (short grass)

n = 0.03 (mown grass)

- Example condition: Short grass with the water depth >> grass height.

Manning's n = 0.04

n = 0.04

- Example condition: Short grass with water depth >> grass height on a slightly irregular earth surface.
- Alternatively; trees at 10 metre spacing within <u>well-maintained</u> grass.

Manning's n = 0.05

n = 0.05 (poorly-maintained grass)

- Example condition: Long grass on an irregular (bumpy) surface with few trees. Irregular ground could make grass cutting difficult.
- Alternatively, trees at 8 metre spacing on an even, <u>well-maintained</u> surface, no shrubs, no low branches.
- Alternatively; trees at 10 metre spacing within <u>poorly-maintained</u> grass, or undulating ground.

Manning's n = 0.06

n = 0.06

- Example condition: Long grass, trees at 6 metre spacing, few shrubs.
- The vegetation is not maintained, but is easy to walk across. Fallen trees and flood debris are removed after each event.

Manning's roughness (author's opinion)

Manning's n = 0.07

n = 0.07

- Example condition: Trees at 5 metre spacing, no low branches, few shrubs, walking may be difficult in some areas.

Manning's n = 0.08

n = 0.08

- Example condition: Trees at 4 metre spacing, some low branches, few shrubs, few restrictions to walking.

Manning's n = 0.09

n = 0.09

- Example condition: Trees at 3 metre spacing, weeds and long grasses may exist in some locations.
- Walking becomes difficult due to fallen branches and woody debris.

Manning's n = 0.10

n = 0.10

- Example condition: Trees at 2 metre spacing, low branches, regular shrubs, no vines.
- Canopy cover possibly shades weeds and it is difficult to walk through.

Manning's roughness (author's opinion)

Manning's n = 0.12

n = 0.12

- Example condition: Trees at 1.5 metre spacing with some low branches, a few shrubs.
- Slow to walk through.

Manning's n = 0.15

n = 0.15 (a recommended 'design' value)

- Example condition: Trees and shrubs at one (1) metre spacing, some vines, low branches, fallen trees, difficult and slow to walk through.
- Alternatively, a continuous coverage of woody weeds with sparse leaves and no vines.

Manning's n = 0.20

n = 0.20 (a recommended 'design' value)

- Example condition: Trees and shrubs at one (1) metre spacing plus thick vine cover at flood level and fallen trees.
- Very difficult to walk through.
- Alternatively, a continuous coverage of healthy shrubs and woody weeds from ground level to above flood level.

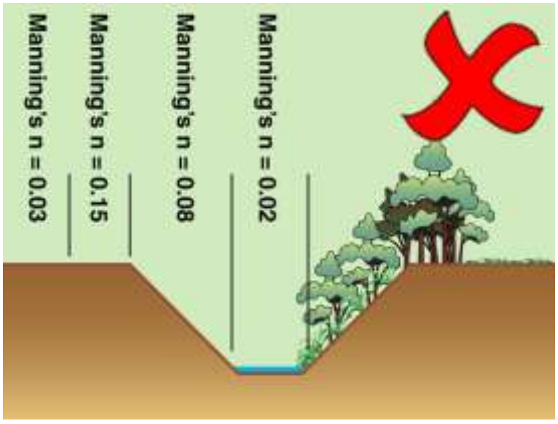
Vegetation flattened by floodwater

Variations with flow depth and flow velocity

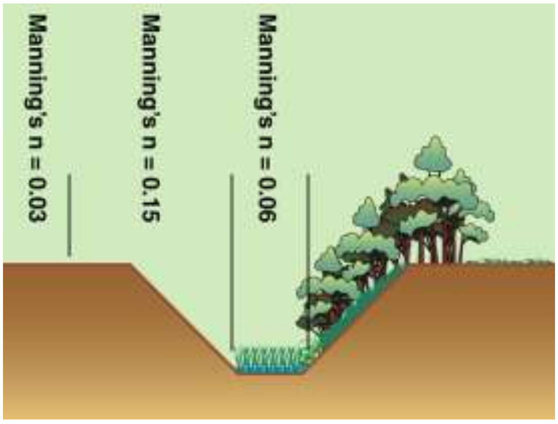
- The chosen Manning's roughness must be appropriate for the flow conditions being studied.
- Highest flood levels are usually achieved while the vegetation remains standing.
- However, the highest flow velocities, and erosion risks, can occur after much of the vegetation has been flattened by excessive shear stress generated by either flow depth or flow velocity.

Discussion

You are on notice!



Unsustainable landscape design



Likely long-term outcome of the above

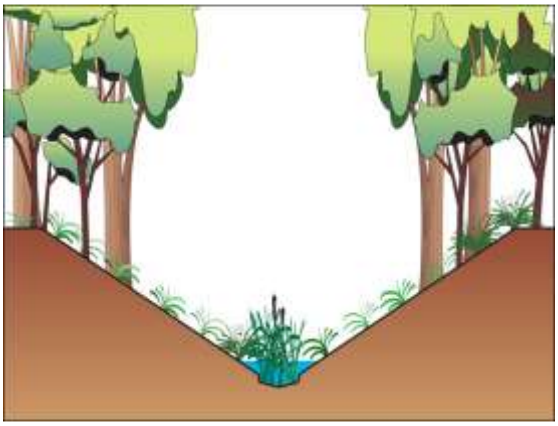
Introduction

- It is NOT the job of local governments to maintain your drainage corridors at your nominated Manning's roughness value.
- If YOU need to maintain a Manning's roughness that is less than the roughness condition of mature bushland, then what YOU need to do is:
  1. Design a drainage channel using a combination of:
     – mown grass at a Manning's roughness of, say, n = 0.03, and
     – non-maintained mature bushland at a Manning's roughness of, say, n = 0.15 or 0.20.
  2. Get the local government to agree to accept the ownership of the drainage reserves, and the ongoing mowing of any grassed floodways.
  3. Alternatively, get the estate's body corporate to agree to the ownership of the drainage reserves, and the ongoing mowing of the floodways.

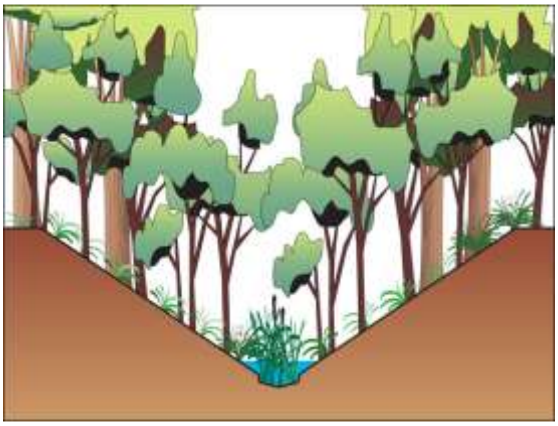
Grassed floodway beside a creek (Qld)

Vegetation roughness values used in the design of channels

Maintenance of a drainage channel



What a designer may have wished!



The likely long-term outcome of the above

Grassed floodway next to a creek (Qld)

Introduction

- As a creek engineer, and an ex-council engineer, the author believes that the most important outcome of a drainage system is to achieve drainage/flood control, and the second most important outcome is to achieve this using a low maintenance solution.
- Achieving a low maintenance outcome means a lowering of the financial burden carried by the public through their council rates.

The long-term growth of bushland

- The hydraulic roughness of vegetation is a measure of how the vegetation resists the flow of water.
- Hydraulically, this 'roughness' is modelled using a Manning's roughness value (n).
- Designers MUST resist the temptation to nominate a specific Manning's roughness that would require ongoing maintenance of the vegetation in order to maintain that roughness condition.
- This is because bushland will continue to grow until it reaches a mature condition.
- Therefore; designers MUST adopt appropriate mature bushland roughness values:
  - riparian zones without vines will eventually achieve a Manning's roughness of at least: **n = 0.15**, or
  - riparian zones with vines will likely achieve a Manning's roughness of at least: **n = 0.20**.
- A lower composite channel roughness can only be achieved by introducing a mixture of grassed floodways and bushland.

Grassed floodways

- Of course, grassed floodways require regular mowing, and therefore they can become a high-maintenance asset, but such land is considered a normal component of public open space.
- The regular mowing of grassland is generally welcomed by the local community; however, the regular thinning of riparian bushland is unlikely to be welcomed by the greater community.

Isolated trees in a field of mown grass

Well-maintained parkland (Qld)

Soil erosion at the base of a tree

Landscape option L1

- Lightly treed landscapes such as this often appear within floodplains that have been designated as public open space.
- However, landscape designers need to be honest about the likely usage of these areas as compared to open floodways.
- If flow velocities are high, then soil erosion can occur around the base of these trees.
- A better ecological outcome is achieved by grouping the trees as 'bushland' sitting beside an open grassed floodway.

Caution: Erosion at base of isolated trees in floodways

- If <u>isolated</u> trees exist within an area of high flow velocity, then:
  - these high-velocity floodwaters can generate turbulence and flow eddies around the base of the tree trunk
  - which can form an scour hole downstream of the tree (shown left)
  - which can eventually cause the tree to topple and fall into its own scour hole.

Well-maintained shaded parkland (Qld)

Isolated trees in a field of non-woody lower storey plants

Wet-soil floodplain forest (Qld)

Landscape option L2

- This landscape condition involves single trunk trees located within a field of non-woody groundcovers (e.g. grasses).
- Importantly, the lower storey plants are able to fold flat when floodwaters pass through the riparian vegetation.
- It is usually flood damage and/or fire that prevents the establishment of a permanent middle storey (i.e. shrubs).
- **Note**: In many case this could be an unstable (immature) planting scheme.

Riparian floodways

Landscaping of riparian zones that cross through floodways

- These planting schemes are ideal for riparian zones that cross a floodway (i.e. where the channel migrates from one side of the valley floor to the other).
- *Lomandra* (and the like), and native grasses (see Step 13), can be effective as the lower storey plants.
- **Caution**: While in shade, *Lomandra* can be limited to a growth of around 0.5 m, but in full sun they can grow to around 1.0 m, which can interfere with flood flows.

Vegetated floodway with medium canopy cover (foreground conditions)

Isolated trees with woody lower storey, but no middle storey plants

Bushland with lower storey plants (Qld)

Bushland with lower storey plants (NSW)

Landscape option L3

- This landscape option involves single trunk trees located within a field of woody groundcovers.
- These woody lower storey plants will not necessarily fold flat when floodwaters pass through the bushland.
- **Note**: The author is grossly unfamiliar with this planting scheme, and consequently is unwilling to provide additional information on such a landscape option—readers should seek their own expert advice.

Potentially unstable growth status

- The author suspects that it is flood damage and natural bushfires that prevents the long-term establishment of middle storey plants (i.e. shrubs); however, it can also be the soil conditions and the available seed content.
- In the author's untrained opinion, these landscapes are likely to represent an unstable growth condition (with respect to plant growth and hydraulic roughness).

Bushland with lower storey plants located within a low-velocity floodplain (Qld)

Upper storey canopy cover with middle and lower storey plants

Mature bushland (Qld)

Complex bushland (Qld)

Landscape option L4

- In the author's opinion, designers of vegetated drainage channels should assume that all bushland will eventually achieve a Manning's roughness of at least **n = 0.15**.
- Therefore, a Manning's roughness of 0.15 is the minimum value that should be adopted for any bushland.
- Of course, open grassed floodways will have a Manning's roughness of around **n = 0.03 to 0.05** depending on surface irregularities.

The effect of vines

- If the bushland is likely to contain vines, whether native, or as weeds, then the minimum recommended 'design' Manning's roughness is **n = 0.20**.

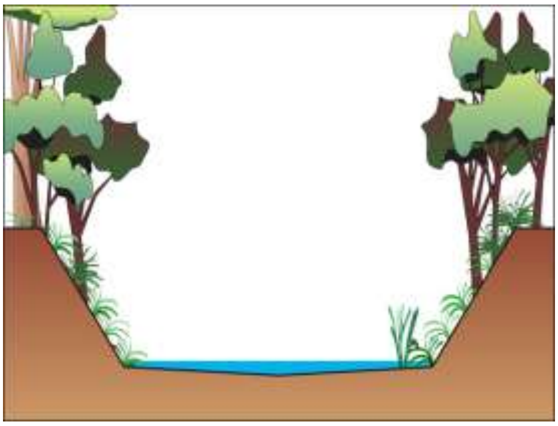
Complex riparian bushland (Qld)

Potential problems generated by excessive bed width

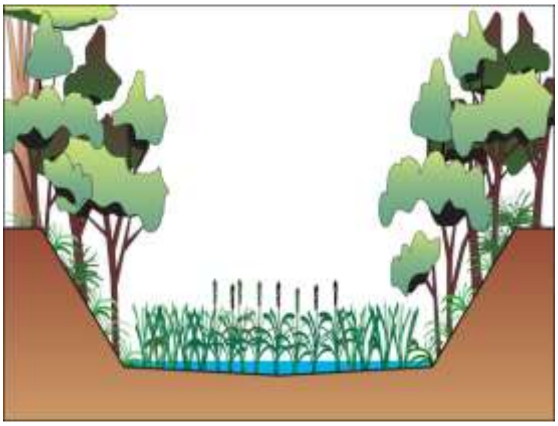
Excessive weed growth

The effects of reeds on bed roughness

- Designers of drainage channels are often tempered to nominate a wide bed width in order to accommodated the required design flow.
- However, if the bed width is wider than the waterway would naturally desire, then the bed will slowly become choked with reeds, weeds and sediment.
- A maximum bed width of 3 metres is recommended, but low-flow channels are rarely wider than 1 metre.



What the designer originally desired



What the waterway finally delivered!

Growth of weeds and reeds across the channel bed

- Ideally, designers should adopt the following design philosophy:
  - select a narrow bed width based on the catchment area, or local data (such as the upstream channel width)
  - achieve the required channel flow area by benching one, or both sides of the channel
  - select a bench height that would allow good canopy cover to be achieved over the channel; otherwise, selecting a bench height based on the desired flood immunity of the bench.
- It is very important for the banks of the channel to be 'stronger' (more resistant to erosion) than the channel bed, which usually means heavy use of plants like *Lomandra* on the lower bank areas.
- If sediment deposition is expected to become a problem, then consider placing a sediment extraction pond upstream of the channel works, or at the outlet of the upstream piped drainage network.

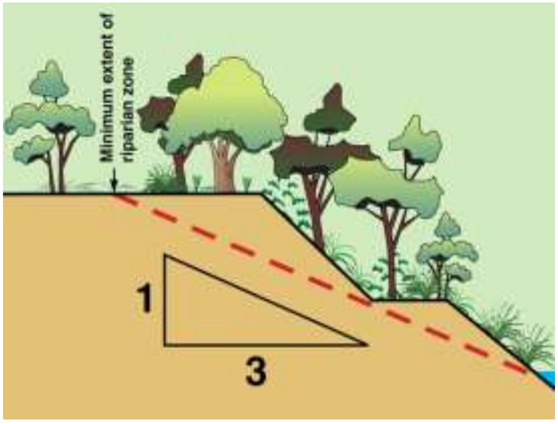
Narrow-bed drain with canopy cover

Canopy cover of the channel

- The low-flow channel may be ephemeral, or permanently wet.
- Achieving a sustainable canopy cover requires input from bushland experts with regards to plant selection.
- Achieving a sustainable canopy cover over the low-flow channel also depends on the alignment of the channel, i.e. whether the channel aligns 'north–south', or 'east–west'.

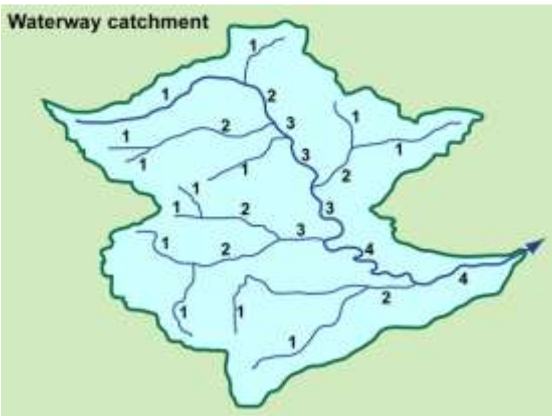
Minimum width of riparian vegetation

Riparian zone and grassed floodway (Qld)



Minimum width based on bank stability

Corridor mapping



Horton's stream order system

Minimum width of riparian zone

- The suggested minimum width is 5 m.
- However, specifying a minimum width can become problematic if it results in only this minimum width ever being provided.
- In order to filter pollutants from stormwater inflows (sheet flow runoff) the minimum width of the combined riparian zone and grassed floodway is the greater of:
  - 15 m (minimum)
  - 5 times the land slope (i.e. 25 m width for a 5% land slope).

Minimum riparian width based on bank stability

- The minimum width of the riparian zone depends on numerous local factors, including bank stability.
- It is suggested that the riparian zone should extend at least three (3) times the bank height from the toe of the bank.
- Alternatively, some guidelines recommend a minimum riparian width (*measured from the top of bank*) equal to the height of the bank.

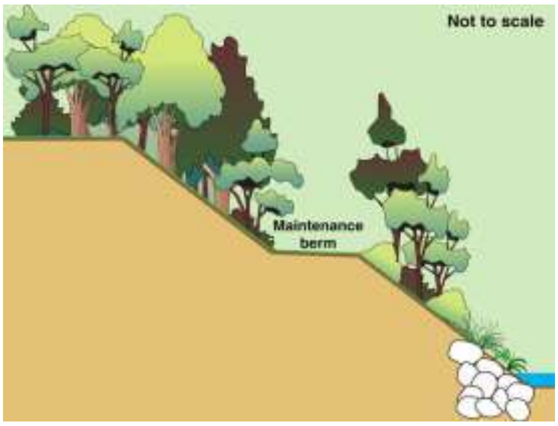
Minimum waterway corridor width

- Some authorities prepare *Waterway Corridor Maps* that identify which land must be excluded from development.
- The nominated corridor width is often measured from the centre of the creek (but may be a different distance each side of the creek)—suggested widths are:
  - 1st order streams = 15 m (each side)
  - 2nd order streams = 30 m (each side)
  - larger waterways = 60 m (thus the full width would be 2 x 60 = 120 m)

Existing corridor width recommendations

- Some guidelines nominate a minimum riparian width based on the stream order (based on 1:25,000 mapping):
  - 1st order streams = 5 m (Vic, 2008), or 10 m (NSW, 2012)
  - 2nd order streams = 10 m (Qld, 2001), or 20 m (NSW, 2012)
  - 3rd order streams = 15 m (Vic, 2008), or 30 m (NSW, 2012)
  - 4th order streams = 15 m (Vic, 2008), or 40 m (NSW, 2012).

The benefits of benching waterway banks



Permanent maintenance berm

Benefits of benching

- Benching a waterway bank can provide several benefits, including:
  - increased bank stability (especially if there is the risk of bank slumping)
  - improved access for bank maintenance and weeding operations
  - improved safety for revegetation personnel
  - permanent access for maintenance equipment.

Pedestrian pathway (Qld)

Pedestrian safety berms

- Recommended minimum width is 1.5 m.
- Pedestrian tracks that run parallel with the creek should incorporate some type of zigzag alignment that prevents floodwater from picking up excessive flow velocity along these tracks (i.e. don't let the track become a high-velocity floodway).
- These tracks should also be designed to shed stormwater runoff from the track at regular intervals in order to prevent soil scour (refer to Part 3 of this document).

Equipment access (Qld)

Construction access

- Benching can be used to allow temporary access for construction vehicles, such as when repairing major flood damage.
- If retained as a permanent feature, these benches can be revegetated to form continuous bushland, or for pedestrian access.
- The minimum width is usually based on the width of the tracked vehicle that is required to use the bench, which is likely to be around 3.0 to 3.6 metres.

Maintenance berm (Qld)

Maintenance berms

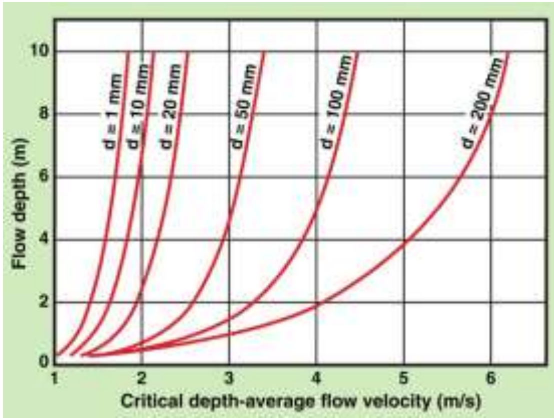
- Maintenance berms allow equipment access along the creek in situations where the top of bank:
  - contains critical riparian vegetation, such as mature habitat trees, or
  - the top of bank is privately owned land.
- Maintenance berms can also be used for pedestrian access and bikeways.
- Recommended minimum width is 4.5 m.

Problems associated with large trapezoidal channels

Large single-stage trapezoidal channel

Introduction

- The appropriate design of a drainage channel greatly depends on the site conditions and limitations.
- For the example shown here (left), the author is unaware of the site conditions and limitations, and therefore it would be 'wrong' for the author to claim that this drainage design is 'inappropriate'.
- However, there are reasons why such a channel design could, over time, prove to be problematic.



Critical flow velocity

Excess flow velocities during extreme flood events

- The deeper the channel, and therefore the larger the channel's hydraulic radius, the higher the average flow velocity, which means there is a greater risk of soil erosion during major floods.

Sedimentation deposition (Qld)

Excessive sedimentation during minor flood events

- The deeper the channel, the flatter will be the allowable channel slope in order to control flow velocities during major flows.
- This means that the average flow velocity during minor flows could be insufficient to prevent sedimentation occurring.
- Over time these channels can become blocked with sediment and weeds, which will require regular maintenance dredging.

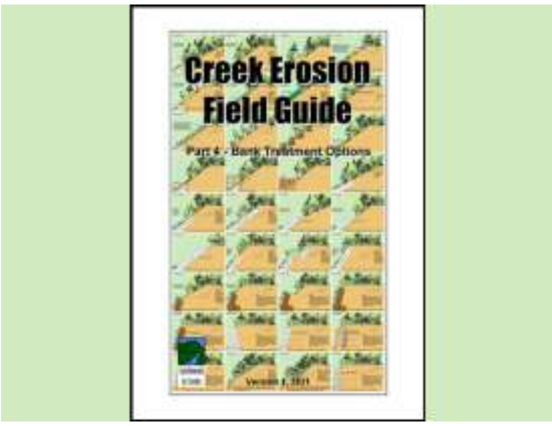
A wayward football (USA)

Poor recreational benefits

- The continuously-sloping channel bank can significantly limit the types of recreational activities that can be enjoyed within this open space.
- Ball sports can be very difficult, with the balls constantly rolling down the banks towards the low-flow channel.

Step 5: Select the bank gradients and surface conditions

Select the Bank Gradients and Surface Conditions



Creek Erosion Field Guide, Part 4

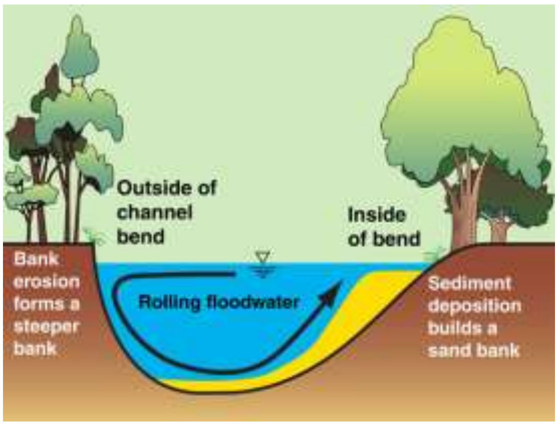
Introduction

- In the Catchments and Creeks publication *'Creek Erosion Field Guide – Part 4'*, examples are shown of possible waterway bank conditions varying from a mild slope of 1-in-6, to steep vertical banks.
- For vegetated drainage channels, the bank slope is typically between 1-in-2 and 1-in-4.
- The author had typically adopted a bank slope of 1-in-3 for his channel designs.

Revegetating a steep creek bank (Qld)

Factors affecting the bank gradient

- If the channel bank is to be grassed, and is expected to be mown, then a bank slope should be 1-in-6, or flatter.
- If the bank height exceeds 2 m, then a maximum bank slope of 1-in-3 is recommended for the safety of people working on the slope (i.e. planting, weeding, etc.).
- Of course, tall steep banks can be revegetated using hydromulching techniques which can apply a mixture of grass, shrub and tree seed.

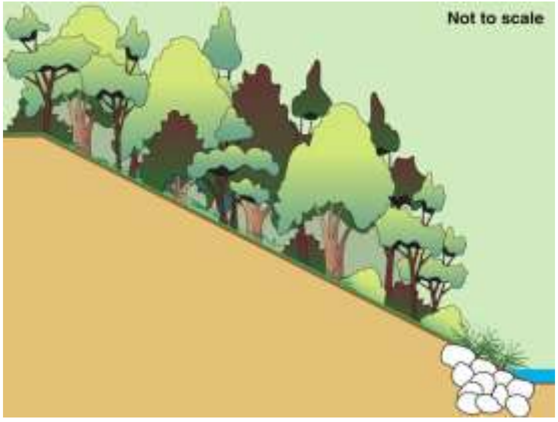


Channel profile at a channel bend

Differences between the inside and outside of a channel bend

- When working on natural creeks it is typical for the outside bank of a channel bend to have a steeper bank slope (say, 1-in-2) than the inside bank (which may be 1-in-3).
- On drainage channels, this variation in bank slope at channel bends is typically not observed, or always necessary.
- However, variable bank slopes are recommended in vegetated channels.

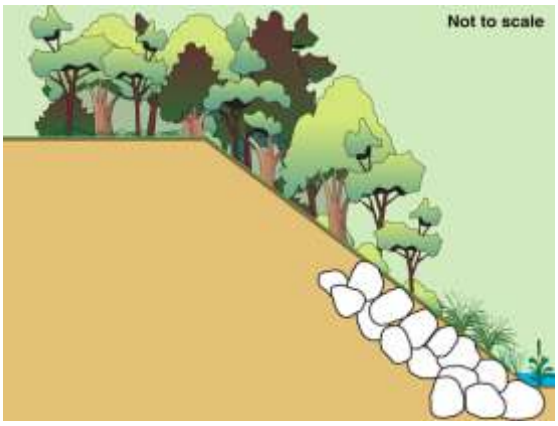
Bank gradients



Fully vegetated creek bank

Vegetated banks

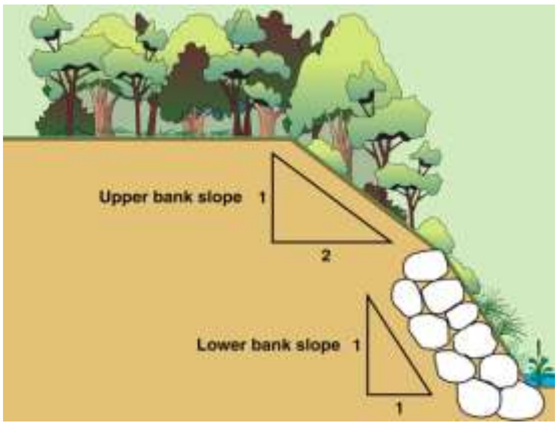
- Recommended maximum gradients:
  - 1-in-2 (V:H) on the outside of channel bends; however, such slopes can be difficult for workers to vegetate, especially on banks higher than 2 m.
  - 1-in-3 on the inside of channel bends.
- If worker safety issues are expected due to the height or steepness of the bank, then consider adding a 1.5 m wide safety berm, or 4.5 m wide maintenance berm at 3 m vertical intervals.



Dumped rock

Rock stabilisation

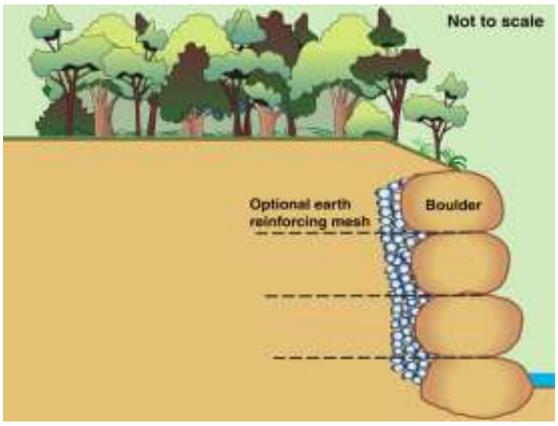
- Recommended maximum gradients:
  - 1-in-0.5 for stacked boulders
  - 1-in-1 for vegetated, individually placed rock; however, such slopes can be difficult, if not unsafe, for workers to plant
  - 1-in-2 for dumped rock on the outside of channel bends
  - 1-in-3 for dumped rock on the inside of channel bends.



Placed rock on outside of a channel bend

Placed rock

- Placed rock means individual rocks are positioned on the creek bank in a manner that ensures their stability.
- Maximum bank gradient for placed rock is:
  - 1-in-1 on the inside or outside of a channel bend.
- However, the desirable bank gradient on the inside of a channel bend is:
  - 1-in-2, but probably flatter.

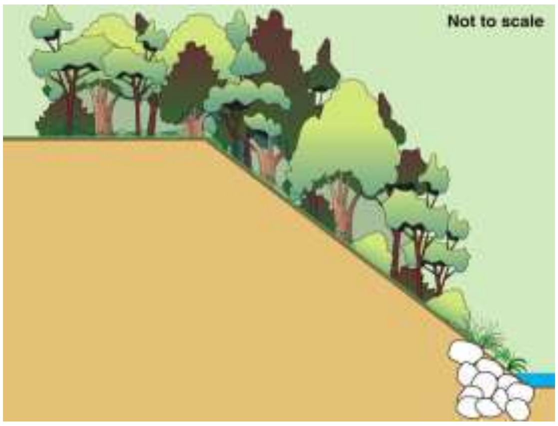


Stacked rock retaining wall

Stacked rock

- Steeper banks can be achieved with the use of stacked rocks (or boulders), but the rocks must sit on a stable bed.
- The stability of a boulder wall can be increased by integrating earth reinforcing mesh into the design (as shown left).
- **Warning:** Steep, high banks can represent a safety hazard to revegetation teams and community groups that may assist in maintaining our waterways.

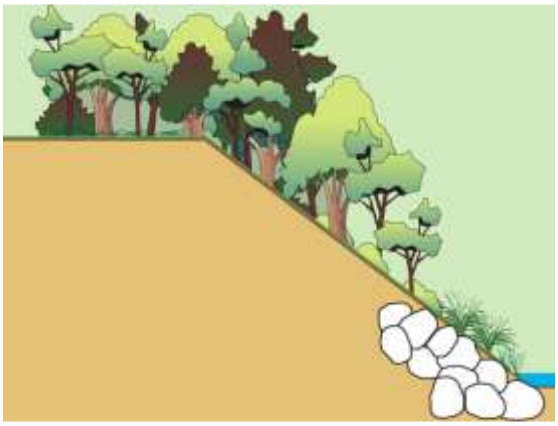
Extent of rock protection on a channel bank



Toe protection

Toe protection

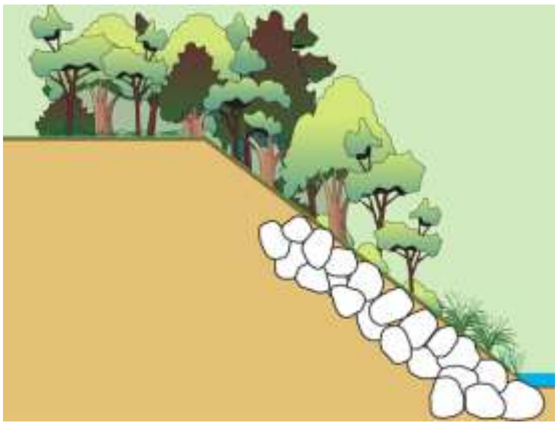
- Even if flow velocities are low enough to allow a fully vegetated bank, there may still be the need for additional stabilisation along the toe of the bank in order to protect the bank during the plant establishment phase.
- The height of the toe protection is usually 0.5 to 1.0 m above the water line.
- The rock should not sit on the bank, but should be integrated into the soil and vegetation.



One-third bank height placement

One-third bank protection

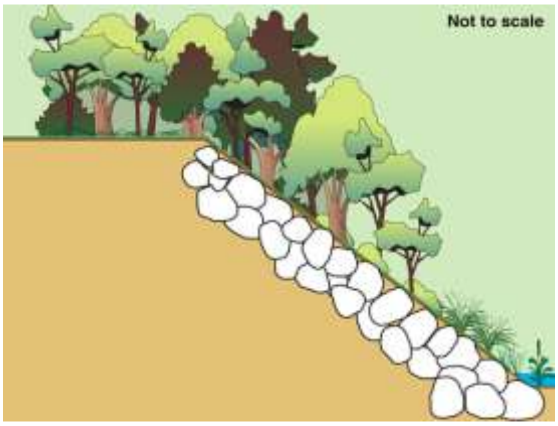
- On the inside of channel bends, the required height of the rock protection is likely to be in the range of 1 m high, to one-third of the bank height (depending on the flow velocity).
- If the average channel velocity is less than 2 m/s, then minimal rock protection is likely to be required (unless that bank is very unstable).
- If the bend represents a 'choke', then more rock is likely to be required.



Two-third bank height placement

Two-thirds bank protection

- On the outside of channel bends, the height of the rock protection is likely to be between 1/3 and 2/3 of the bank height.
- Along straight reaches, the height of rock placement is also likely to be between 1/3 and 2/3 of the bank height, with 1/3 bank height being more common.
- As the average flow velocity increases above 2 m/s, and especially above 3 m/s, the need for rock stabilisation increases.



Full bank height placement

Full-height rock placement

- Full bank height rock stabilisation is only likely to be required if:
  - the channel's average flow velocity exceeds 4 m/s
  - the bank is on the outside of a tight channel bend
  - the planned revegetation consists only of non-woody species (e.g. grasses) that will fold flat during a flood event, and therefore could encourage high flow velocities to exist close to the bank.

Establishment of vegetation over rocks

Vegetated rock stabilisation of bank (Qld)

Introduction

- The establishment of vegetation over the rocks provides many benefits including:
  - increased stabilisation of the rocks
  - improved terrestrial habitat
  - improved aquatic habitat (shelter, shading and water temperature)
  - improved fish passage conditions during periods of high flow
  - improved aesthetics.

Voids filled with soil ready for planting

Infill soil

- Experience has shown that minimal soil is lost from the voids during flood events.
- This image (left) shows a recently planted bank that experienced a bankfull flow just weeks after planting—all plants were lost, but most of the soil remained.
- **Important:** In order to allow proper plant growth, the infill soil needs to be placed progressively as the rock is placed on the bank, thus avoiding the creation of open voids deep in the rock profile.

Planting along the water's edge (Qld)

Planting along the water's edge

- Wherever practical, vegetation should extend to the water's edge to increase the value and linkage of aquatic and terrestrial habitats.
- Plants that reach over the water's edge provide essential shading of the water, which provides pockets of cool water suitable for aquatic life.
- Edge plants also assist aquatic life to shelter from terrestrial predators.

Planted rock covered with jute mesh

Use of erosion control mats

- During plant establishment it may be necessary to mulch around newly placed plants to control soil moisture loss.
- Covering such areas with a jute mesh can help to reduce the loss of mulch by wind and minor flows; however, these mats **MUST** be used with great care.
- **Note:** The complete loss of the matting during elevated stream flows can cause damage to, or the total loss of, any plants that protrude through these mats.

<u>Caution</u> the use of gabions and rock mattresses in waterways

Rock mattress lined channel (Qld)

Introduction

- Gabions and rock mattresses have been used successfully on waterways for over 100 years, but within each of these successful applications, the gabions would have integrated well with the covering vegetation.
- The key to successful long-term outcomes is the awareness that within a waterway environment, the wire baskets are only temporary structures, which ultimately must be replaced by a well-established vegetative root system.

Gabion-lined channel (NSW)

Failed basket in adjacent channel image

Vines begin to cover gabions (NSW)

Caution the use of non-vegetated gabions or rock mattresses within waterways

- Drainage channels that are lined with non-vegetated gabions or rock mattresses will likely be subjected to weed invasion.
- Worst still, examples in Queensland and NSW have shown that these structures tend to attract vines (likely originating from seeds washed from upstream residential gardens), and once these vines are established within a creek, they can damage (strangle) native vegetation.

Vines and weeds cover gabions (Qld)

Weeds and reeds cover mattresses (Qld)

Caution the use of gabions and rock mattresses in waterways

Stormwater outlet failure (Qld)

Caution the use of wire baskets in areas of high turbulence

- Traditional gabion placement, away from a waterway environment, usually involved the placement of the rocks with the voids remaining open, such that the baskets become part of the architectural feature.
- However, in a waterway environment, the wire baskets must NOT be left exposed (even if galvanised and plastic-coated).
- Sediment caught in turbulent floodwater can wear-away the protective coating and cause the baskets to fail.

Stormwater outlet failure (NSW)

Gabion drop structure failure (Qld)

Mattress-lined sediment basin (SA)

Do NOT line sediment traps and ponds with gabions or rock mattresses

- Urban waterways typically experience high levels of sedimentation, which results in the need to ongoing de-silting.
- If a pond, basin, or channel needs to be de-silted from time-to-time, then such a feature should NEVER be lined with gabions or rock mattresses.
- The wire baskets are easily damaged by most de-silting operations (other than vacuum pumping).

Mattress-lined sediment pond (Qld)

Mattress-lined in-stream pond (Qld)

Caution the use of gabions and rock mattresses in waterways

Fluting erosion in a dispersive soil (SA)

Caution the placement of gabions or rock mattresses adjacent to a dispersive soil

- If the proposed drainage channel exposes or cuts through a dispersive soil (sodic soil), then the dispersive soil must be covered with a minimum 200 mm thick layer of non-dispersive soil before placement of vegetation, rocks, gabions or rock mattresses.
- If gabions are placed directly on a dispersive soil, then tunnel erosion can occur under the gabions, which can cause failure of the structure.

Tunnel erosion under a rock mattress

Deep rilling adjacent a rock mattress

Open channel drop structure (Qld)

Caution the use of gabions and rock mattresses in the formation of open channel drop structures

- When used in the formation of open channel drop structures, the wire cages of gabions and rock mattresses can be subjected to damaged caused by sediment and debris carried by floodwater.
- Long-term success is best achieved when the structures are fully vegetated, and a layer of rockfall netting is placed over the areas of highest water turbulence.

Open channel drop structure (NSW)

Open channel drop structure (Qld)

Step 6: Determine the required channel gradient

Determine the Required Channel Gradient

Drainage channel (Qld)

Introduction

- A vegetated drainage channel is unlikely to be designed with a meander; instead, it is likely to pass in a straight line between point A and point B.
- However, over long distances, drainage channels typically follow the natural meander of the original valley.
- In it's simplest form, the channel gradient is just the channel's total fall (F) divided by the channel length (L), but not all designs are that simple.

Non-fish-friendly drop structure (Qld)

Channel gradient for 'drainage channels'

- As a first trial, a channel is usually design with a uniform gradient, but then a check is preformed on flow velocities for (i) the minor-storm light-vegetation case, and then (ii) the major-storm full-growth case.
- If the resulting flow velocities are too high, then either:
  - reduce the channel depth
  - consider the use of grade control structures, or
  - consider increasing the channel length.

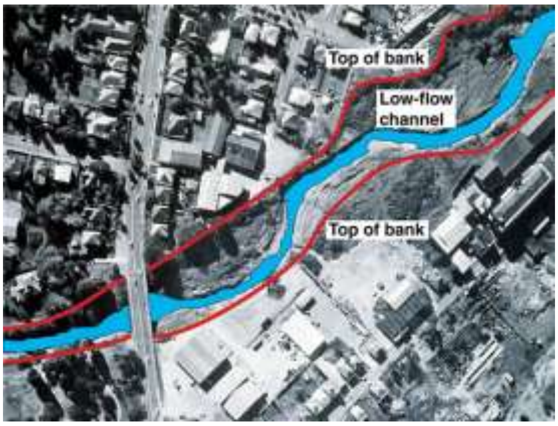
Fish-friendly rock ramp (Qld)

Channel gradient for 'creek relocation' or 'creek rehabilitation' projects

- On creek projects, fish passage is likely to be a major design consideration.
- The channel alignment should follow the natural valley slope.
- The channel gradient should be based on:
  - the natural channel gradient, or
  - an allowable velocity gradient.
- All introduced grade control structures must be fish friendly.

Step 7: Determine the channel alignment and meander conditions

Determine the Channel Alignment and Meander Conditions



Meandering low-flow channel (Qld)

Meandering river channel

Meandering low-flow channel

Introduction

- Ideally, the waterway channel should follow the natural drainage path of the valley.
- Any meander pattern should mimic the natural meander of the valley floor.
- However, meander conditions can apply to both the low-flow channel, and the main channel which carries the low-flow channel—i.e. the low-flow channel can meander across the bed of the main channel.

Typical geometry of meander patterns

- Meanders are typically not utilised within drainage channels.
- In waterways, the meander length is typically 10-14 times the channel width (W).
- Maximum bend radius (to the centreline) is typically 3W, but if measured to the outside of the channel bank, then the maximum radius is likely to be 3.5W.
- Tighter channel bends usually require significant rock stabilisation.

Benefits of a channel meander

- Meandering the channel can improve its aesthetics, increase habitat and channel diversity (through large-scale hydraulic turbulence), and can increase the effective channel length.
- Increasing the channel length is one of the most effective ways of reducing the bankfull flow velocity.
- In the author's opinion, the meandering shown in this example (left) is not sustainable (i.e. it will be altered by flows, sediment, and vegetation growth).

Example design case – Norman Creek, Brisbane

Option 1 – Slight meander

Norman Creek, Greenslopes, Brisbane

- These diagrams demonstrate the types of design options that a creek engineer may face when replacing an existing concrete drain with a vegetated drainage channel.
- Option 1 adopts a slight meander pattern that allows the continued use of the existing sports ovals.
- Option 2 adopts a more dramatic meander pattern, which could avoid the use of grade control structures.
- Option 3 is the assumed original creek alignment based on land markers.

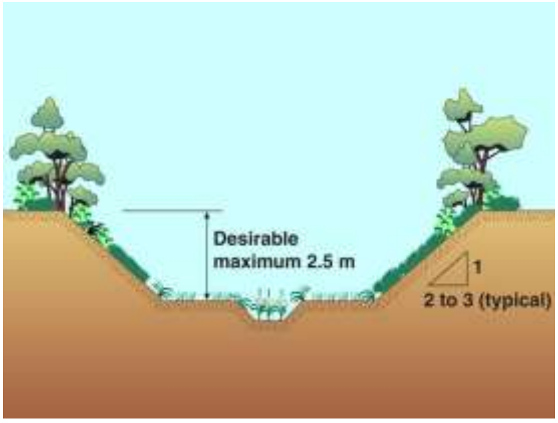
Location map of existing concrete drain

Option 2 – Large meander

Option 3 – Assumed original meander

Step 8: Design the bed conditions

8 Design the Bed Conditions



Inclusion of a low-flow channel

Rock-lined low-flow channel (Qld)

Sedimentation problems in a wide channel

Introduction

- Wherever possible, the bed conditions of a drainage channel should be determined from observations of stable bed conditions in similar local drainage channels.
- Bed conditions for creek relocation or rehabilitation projects should be based on stable conditions of similar waterways.
- A critical decision is to decide whether or not to incorporate a low-flow channel, and what type of low-flow channel should be adopted (if any).

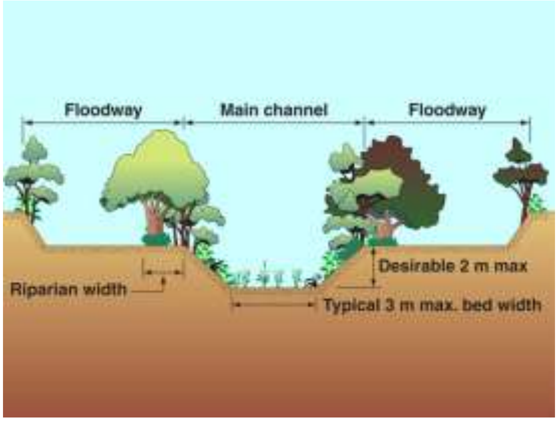
Use of low-flow channels

- Low-flow channels are usually incorporated when:
  - the channel has a persistent dry weather flow (trickle flow)
  - the channel bed width exceed 3 m.
- The width of a low-flow channel rarely exceeds 1 to 2 metres; however, always note existing conditions if available.
- Low-flow channels generally do not exist within ephemeral channels (yes, exceptions do exist).

Potential weed problems

- As the bed width of the main channel increases, the risk of reed and weed invasion increases.
- If the channel's bed width is excessive, then sedimentation problems can occur, and the channel will form it's own meandering low-flow channel.
- For creek relocation projects, the bed width should be based on an average of the existing upstream and downstream bed conditions.

Bed width



Single-stage channel with floodways

Creek channel filled with reeds

Sediment deposition in a widened creek

Benched waterway channel (Qld)

Introduction

- As previously stated, the bed width should ideally be determined from observations of similar local channels.
- If a typical two-stage trapezoidal channel is chosen (i.e. a benched channel with a main channel and attached floodways), then the width of the channel simply becomes a product of trying to fit the required flow area into the allowable corridor width, which may have been determined from the planning objectives / limitations.

Problems caused by excess reed growth

- Reeds and aquatic weed problems can occur within a channel of any width; however, the wider the channel:
  - the greater the risk of sedimentation problems, which can
  - increase the risk of weeds or reeds establishing across the bed, which can
  - force the low-flow channel to pass around the reeds, which can
  - cause erosion along the toe of the adjacent channel bank.

Problems cause by sedimentation

- In their natural conditions, waterways typically achieve a sustainable sediment flow that allows the waterway to form:
  - an ideal low-flow channel width
  - an ideal main channel width (if different)
  - an ideal channel flow area.
- If a channel is enlarged for the purpose of flood control, then it is common to find that the waterway will try to return back to its 'natural' cross-section through a process of sedimentation and weed growth.

Use of benching

- In order to achieve the flood-control benefits of a channel expansion, without experiencing the adverse effects of reed or sedimentation problems, a channel can be expanded by:
  - retaining the original bed width, and
  - retaining a narrow corridor of the original riparian vegetation, and
  - benching the channel banks to form grassed floodways, which may be bordered by additional riparian vegetation.

Understanding the role of pools, riffles and channel meanders

Pool–riffle sequence (NSW)

Introduction

- Pools can exist in isolation along any channel reach; however, riffles are almost always associated with an immediate downstream energy dissipation pool.
- A pool–riffle sequence can be used to increase the effective gradient of an alluvial waterway.

Constructed pool (Qld)

Pools

- It is common for most people to believe that aquatic life is centred around permanent pools.
- However, most people underestimate the diversity of the aquatic life that lives among the rocks that make-up a typical riffle system.

Constructed riffle (Qld)

Riffles

- The water that passes down a riffle is usually more aerated than the water passing through a pool, which is an attribute that can make riffles favourable to many of the invertebrates hiding under the rocks.
- In the pools, aquatic life needs to hunt for food.
- However, in the riffles, the food washes past the resident aquatic life (nature's 'home delivery' service).

Meandering low-flow channel (Qld)

Channel meandering

- The existence of channel meanders allows for:
  - diversity of flow conditions, which encourages the diversity of aquatic life
  - the potential for bank erosion and bank undercutting, which can provide additional shelter and habitat values
  - diversity in the substrate conditions, which can encourage an increase in the diversity of aquatic life.

Surveying local bed form conditions

Brisbane City Council, 2000

Introduction

- Designers are encouraged to seek out local waterway data, such as:
  - the expected base flow rate for different catchment areas
  - the average dimensions of in-channel pools
  - the typical gradient and length of riffles
  - the plant species locally endemic to the lower-bank, upper-bank, and over-bank areas.

Urban catchment (Qld)

Separation of urban and bushland catchments

- Local data collection can provide an indication of the minimum catchment area required to achieve a sustained base flow.
- Tables 6.13 and 6.14, below, provide examples of the type of local waterway data that can prove useful to waterway designers.
- These table were generated by Brisbane City Council for use in local Brisbane waterways.

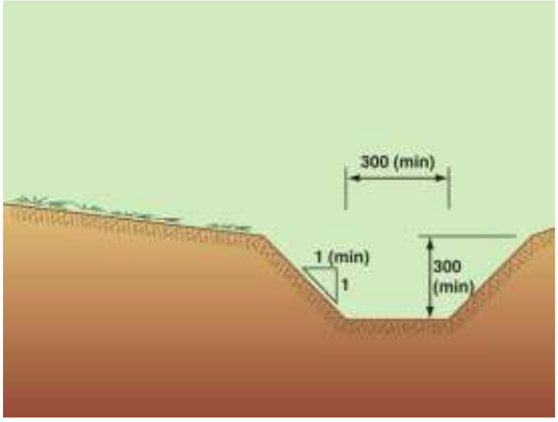
Table 6.13 – Example bed form tables based on urban creek in Brisbane, Queensland

Catchment area	Channel slope / Canopy	Bed type
Less than 30 hectares	Open canopy	Grass
	Closed canopy	Rock-lined
Greater than 30 hectares	> 1-in-20	Rock-lined
	1-in-20 to 1-in-100	30n100 ha Pool-riffle?
	1-in-20 to 1-in-100	> 100 ha Pool-riffle
	< 1-in-100	Earth
	Sandy bed	Sandy pools

Table 6.14 – Example bed form tables based on Brisbane's outer bushland creeks

Catchment area	Channel slope / Canopy	Bed type
Less than 50 hectares	Open canopy	Grass
	Closed canopy	Rock-lined or vegetated
Greater than 50 hectares	> 1-in-150	Rock-lined
	< 1-in-150	Pool-riffle system
	< 1-in-500	Earth
	Sandy bed	Sandy pools

Types of low-flow channels



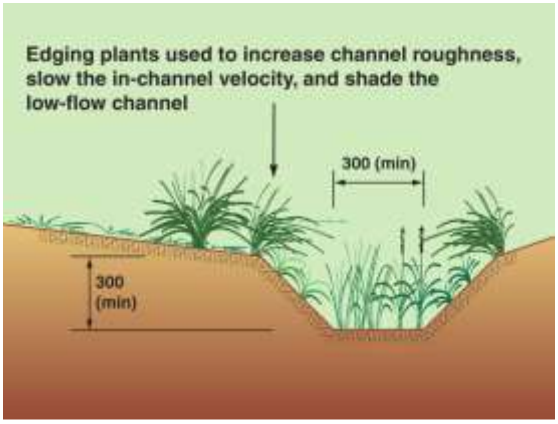
Earth-lined low-flow channel

Earth-lined low-flow channels

- Earth-lined low-flow channels are highly susceptible to erosion.
- Most earth-lined channels will eventually become vegetated, even if only with weeds.
- In many cases these channels are being maintained by annual spraying with herbicides—such practices are not considered to be ecologically sustainable.
- Generally <u>not</u> recommended unless there is a demonstrated history of successful application on other similar channels.

Earth-lined low-flow channel (Qld)

Earth-lined low-flow channel (Qld)



Vegetated low-flow channel

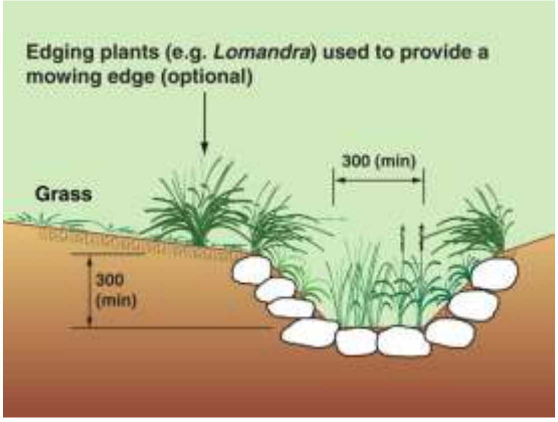
Vegetated low-flow channels

- Vegetated low-flow channels are susceptible to bank erosion if the bed becomes overgrown with reeds.
- Generally requires medium to heavy shading to control weed and reed growth.
- Allowable flow velocities are in the range of 1.4 to 2.0 m/s.
- This type of low-flow channel is generally <u>not</u> recommended unless there is a demonstrated history of successful application within existing channels.

Grassed overland flow path (Qld)

Vegetated low-flow channel (Qld)

Types of low-flow channels



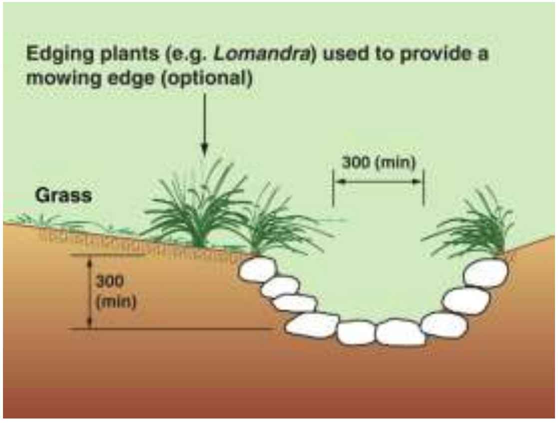
Rock-lined low-flow channel

Planted rock-lined low-flow channels

- Generally a high degree of stability.
- Very difficult to weed or de-silt without disturbing the rocks.
- Can be used in open or closed canopy environments, but best results are achieved with partial shading.
- Typical minimum rock size is 100 mm with good vegetation cover, or 200 mm for poorly vegetated channels.
- Small rocks (say < 100 mm) will generally not be stable without vegetation cover.

Rock-lined low-flow channel (Qld)

Rock-lined low-flow channel (Qld)



Rock-lined low-flow channel

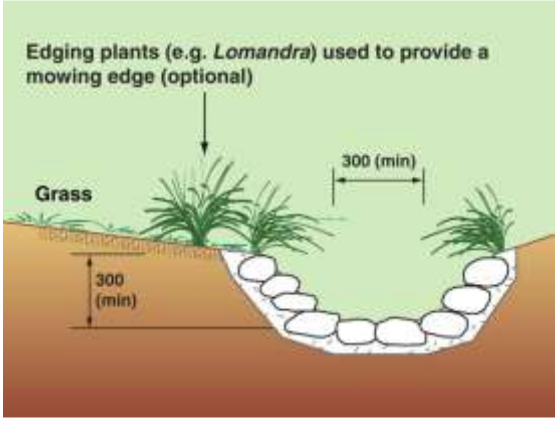
Rock-lined low-flow channel without plants

- Medium to high degree of stability.
- Channels are prone to weed and/or reed infestation, unless heavily shaded by riparian vegetation.
- Very difficult to weed or de-silt without disturbing the rocks.
- Nominal rock size [in mm] is typically based on $d_{50} = 40V^2$, with the minimum rock size being 200 mm.

Rock-lined low-flow channel (Qld)

Natural low-flow channel (NSW)

Types of low-flow channels



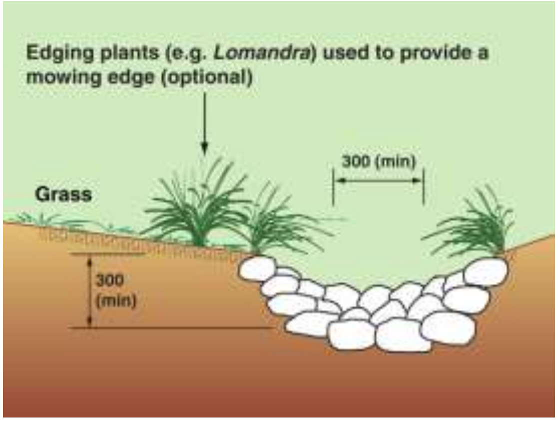
Grouted rock low-flow channel

Grouted rock low-flow channels

- High degree of stability.
- High-velocity jet-flushing (hosing) can be used to control sedimentation.
- Prone to high water temperatures unless shaded.
- Minimal ecological benefit.
- Used in constructed channels where ecological considerations are low.
- Failures (e.g. tunnel erosion) are common when placed over a dispersive soil.

Rocks grouted to concrete floor of drain

Grouted rock low-flow (Qld)



Pool–riffle system

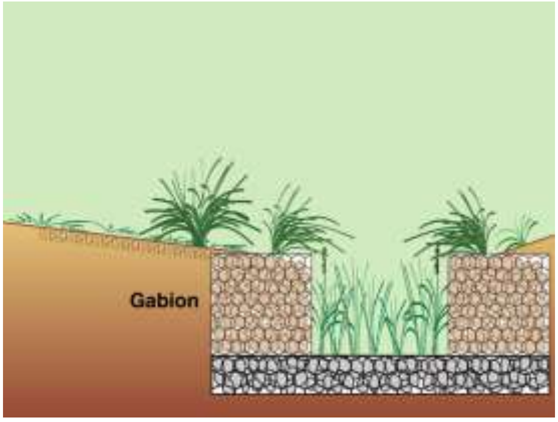
Pool–riffle systems

- Medium to high water quality benefits.
- Medium to high ecological benefits.
- May require a catchment area of at least 30 ha (urban), or 50 ha of bushland to obtain sufficient dry-weather flows to maintain water quality within the pools.
- Highly susceptible to weed and/or reed invasion, especially if located downstream of wetlands.
- Ideally, should only be used within gravel-based waterways.

Pool–riffle system (Qld)

Pool–riffle system (Qld)

Types of low-flow channels



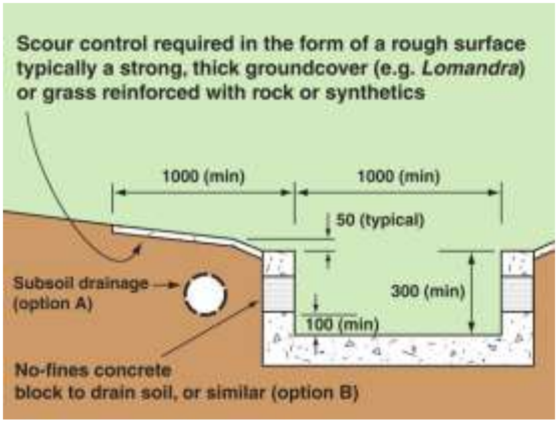
Gabion-lined channel (not recommended)

Gabion-lined channels

- In aquatic environments, the wire baskets can have a short to medium design life (even if zinc and plastic coated) unless successfully covered with vegetation.
- Very difficult to weed or de-silt.
- Weed or vine invasion is common.
- Used in open canopy channels where sufficient light exists to establish good vegetative cover over the wire mesh.
- Generally **not recommended** due to high construction and maintenance costs.

Gabion-lined low-flow channel (Qld)

Gabion-lined low-flow channel (NSW)



Concrete low-flow channel

Concrete low-flow channels

- Relatively easy to maintain and de-silt.
- Very poor water quality attributes including high water temperatures.
- Very poor ecological attributes.
- Erosion problems typically occur immediately adjacent the smooth concrete surface unless protected by rock, reinforced grass or similar (refer to the discussion on the following page).

Concrete low-flow channel (Qld)

Concrete low-flow channel (Qld)

Scour problems associated with concrete-lined low-flow channels


Concrete-lined low-flow channel (NSW)

Introduction

- In drainage channels, a low-flow channel may be incorporated into the bed of the channel in order to prevent long-term soil saturation across the bed of the channel.
- In constructed waterways, a low-flow channel may be incorporated to carry permanent, or near-permanent trickle flows, or to provide fish habitat.
- Low-flow channel should be at least 300 mm deep, but exception do occur.


Post storm low-flow condition (NSW)

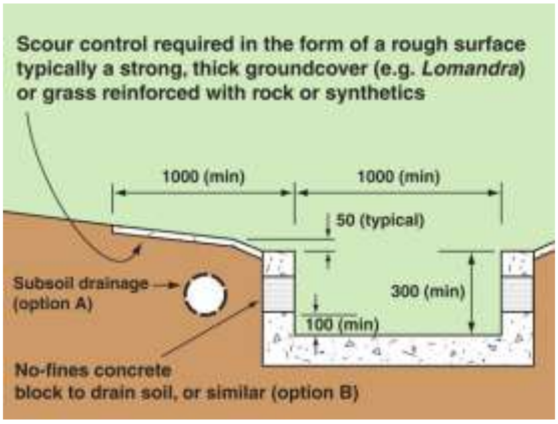
Common scour problem

- A ‘smooth’ concrete invert can induce:
  - high flow velocities, and
  - a thin boundary layer.
- These flow conditions can cause soil scour along the edges of the concrete channel.


Post storm scour problem (NSW)

The hydraulics of ‘induced flow’

- Whenever there is junction between two surface that have very different roughness conditions, a flow pattern can be established where:
  - high flow velocities generated by the smooth surface can induce similar high velocities over the adjacent rough surface, and
  - low flow velocities generated by the rough surface can slow the flow velocities passing over the adjacent low-roughness surface.



Scour protection adjacent the channel

Common solutions to this scour problem

- To reduce the risk of soil scour, a strip of erosion-resistant material should be placed over the soil.
- Solutions include:
  - stiff grasses, such as *Lomandra*
  - vegetated rock (200 mm rock)
  - vegetated rock mattress
  - porous pavers that can be integrated with vegetation (e.g. grass–blocks, as used in porous pavements).

Step 9: Design of bed stabilisation structures

9 Design of Bed Stabilisation Structures

Baffled fishway

Rock ramp fishway (Qld)

Concrete weirs (UK)

Introduction

- Bed stabilisation structures can be used to perform three different, but related, tasks:
  - control the downstream migration of loose bed material
  - stabilise steep sections of the channel (e.g. drop structures) because a stable channel gradient cannot generate the necessary total fall of the constructed channel
  - act as recessed check dams to control long-term bed erosion.

Fish-friendly structures

- Bed stabilisation structures can be designed to accommodate fish passage.
- Fish-friendly structures aim to allow the passage for all fish species during both low flows and flood flows.
- Some structures allow only limited fish passage, usually the larger species that have a greater endurance—such structures would not be considered absolutely fish friendly.
- Refer to Chapter 10 for design details.

Non-fish-friendly structures

- It is likely that a constructed drainage channel will not constitute a recognised fish habitat, which means fish passage shouldn't be a design consideration.
- Typical structures include open channel drop structures, rock chutes, and weirs.
- Design information can be found in the *Catchments and Creeks* field guides:
  - *Gully Erosion* – Part 2
  - *Creek Erosion* – Part 2.

Fish-friendly grade control structures

Natural riffle (NSW)

Terminology

- Riffles typically have a fall of around 300 to 500 mm.
- Rock chutes typically have a fall greater than 500 mm; however, these structures can be made fish friendly through the incorporation of appropriate rest areas, which may recessed into the banks.
- Design information can be found in Chapter 10, also refer to *Catchments and Creeks* field guide:
  - *Creek Erosion* – Part 3.

Constructed riffle (Qld)

Constructed riffle (Qld)

Constructed rock chute (NSW)

Constructed rock chute (Qld)

Ridge rock ramp (Qld)

Precast concrete fishway (Qld)

<u>NON</u>-fish-friendly grade control structures

Steep rock chute (Qld)

Non-fish-friendly grade control structures

- Non-fish-friendly grade control structures should not be used on parts of a drainage channel or waterway that is either:
  - currently a fish habitat
  - has the potential to becomes a fish habitat.
- Potential safety risks must also be considered.
- A maximum fall of 1 m is generally recommended (for reasons of safety), but is not essential.

Inclined drop structure (USA)

Baffled drop structures (Qld)

Stepped drop structure (ACT)

Weir (Qld)

Vertical drop structure (Qld)

Vertical drop structure (SA)

Recessed bed stabilisation structures

Recessed rock check dams (SA)

Introduction

- Recessed bed stabilisation structures may be incorporated into a drainage channel design for one or more of the following reasons:
  - prevent the ongoing migration of existing, or future, head-cut erosion
  - prevent the formation of an incised channel
  - prevent an incised low-flow channel
  - stabilise the outlet conditions of a new channel (refer to Step 11).

Recessed rock check dams (NT)

Design of recessed

- In 'ideal' conditions, the base of a recessed rock check dam should be level with crest of the immediate downstream check dam.
- In steep drainage channels, such a design condition may be impractical, in which case, consider inserting 'checks' at every 1 m fall in the bed elevation.
- A typical recessed check dam has a 1 m x 1 m trench filled with 300–400 mm rock, with all voids filled with soil.

Natural rock outcrop (Qld)

Stabilisation of the low-flow channel

- In many ways, the task of a recessed rock check dams is similar to the function of a natural rock outcrop on a creek bed.

Note: The term 'check' refers to the 'stopping' or 'arresting' of an action, which is indirectly related to the expression of 'checking' a person's hat and coat into a cloakroom.

Constructed rock riffle (Qld)

The actual constructed width of rock riffles

- If a rock riffle is constructed on the bed of a waterway or drainage channel, then the rock should:
  - extend across the full width of the channel bed, and
  - ideally extend at least 1 metre into the channel banks.
- Even though the riffle will only be exposed within the low-flow channel, this low-flow channel will likely migrate across the bed from time-to-time.

Step 10: Design the channel’s inflow conditions

Design the Channel’s Inflow Conditions

Stormwater inflow (Qld)

Introduction

- All drainage systems require the stable entry and exit of flow, including any lateral inflows.
- The flow entry into a drainage channel may consist of:
  - overland flow path, or a
  - piped drainage system.
- A series of bed stabilisation structures (Step 9) may be used to stabilise the inlet.

Bank erosion caused by a lateral inflow

Controlling head-cut and lateral bank erosion

- Consideration needs to be given to all locations where inflows occur.
- Batter chutes can be used to carry lateral inflows down channel banks.
- If uncontrolled sheet flows are allowed to pass through riparian vegetation, then such flow conditions can initiate lateral bank erosion, which can undermine the riparian vegetation (as shown left).

Exposure of a dispersive subsoil (Qld)

Stabilising a dispersive soil

- The existence of a dispersive subsoil layer can make every aspect of drainage design much more difficult.
- Dispersive soils can be held in a stable condition if the soil remains buried under a layer (say 300 mm) of non-dispersive soil.
- The recommended depth of a layer of non-dispersive soil placed over a dispersive soil depends on the likelihood of disturbances (erosion) to that upper layer of soil.

Potential erosion at the primary inlet

Scour along an overland flow path (Qld)

Introduction

- Gully erosion often starts with a minor disturbance to the soil surface, often referred to as a 'nick point'.
- Nick points can be created by a variety of actions, including:
  - a fallen tree (exposing the rootball)
  - cattle pads
  - excavation of a drainage swale
  - formation of a scour hole
  - failure of a dam by-wash (spillway)
  - initiation of lateral bank erosion.

Formation of a scour hole (Qld)

Erosion on the edge of an lake (NSW)

Scour along an overland flow path (Qld)

Erosion downstream of a farm dam (Qld)

Scour along an overland flow path (Qld)

Scour along an overland flow path (Qld)

Potential erosion at lateral inflows

Lateral bank erosion (SA)

Lateral bank erosion

- Lateral bank erosion is the erosion caused by local stormwater runoff spilling down an unstable creek or gully bank.
- These lateral inflows may initially travel towards the bank as ‘sheet flow’, but the flow usually becomes concentrated as it spills down the channel bank.
- Over time, lateral bank erosion can expand to form a separate arm of the gully or drainage channel.

Lateral bank erosion (Qld)

Lateral bank erosion (Qld)

Lateral bank erosion (NSW)

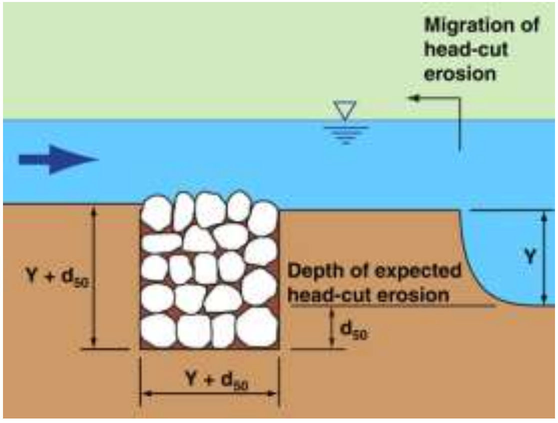
Lateral bank erosion (SA)

Erosion of a dispersive soil (NSW)

Erosion of a dispersive soil (NSW)

Step 11: Design the channel's outflow conditions

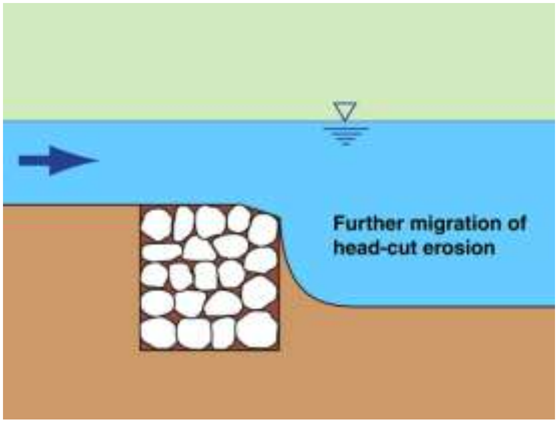
Design the Channel's Outflow Conditions



Recessed rock check dam (as built)

Introduction

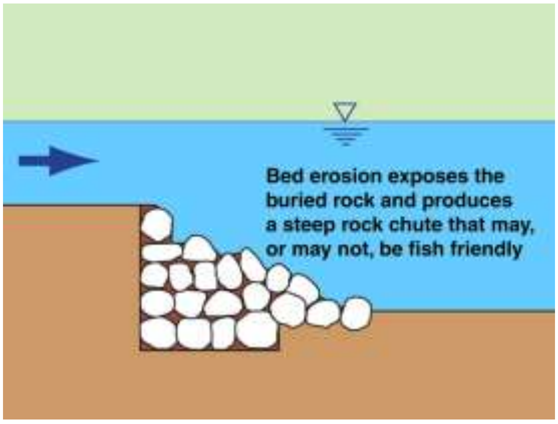
- The tailwater condition of a waterway is usually defined as the water level at the outlet of the waterway; however, this term can also apply to the downstream conditions of any reach of a waterway, such as the downstream limit of a creek rehabilitation project.
- These tailwater conditions, including the bed conditions, must be stable in order to maintain the stability of the channel.



Bed erosion approaches the check dam

Stabilise the channel bed

- Waterway designers need to investigate the long-term stability of the tailwater conditions.
- If bed erosion is possible in the near future, such as the effects of migrating head-cut erosion, then a bed stabilisation structure may be required at the downstream end of the channel.
- Such structures may consist of a recessed rock check dam (also refer to Step 9).

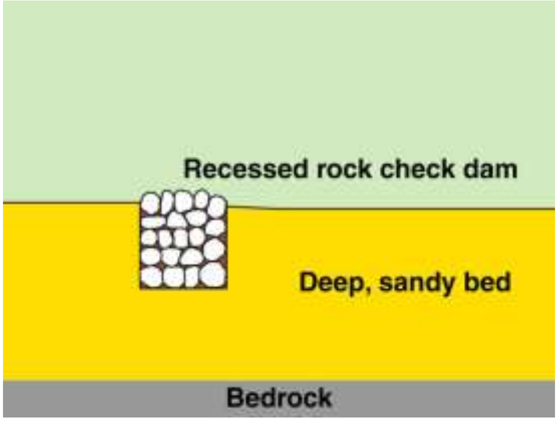


Ideal final stabilised bed condition

Flow expansion and blending bank slopes

- New channel works must blend smoothly with the existing downstream channel.
- A sudden expansion in the channel cross-section can result in the formation of large-scale eddies, which can be very damaging to a waterway and fish passage.
- A sudden contraction in the channel cross-section can be less damaging, but as a minimum, can look unnatural and unattractive.

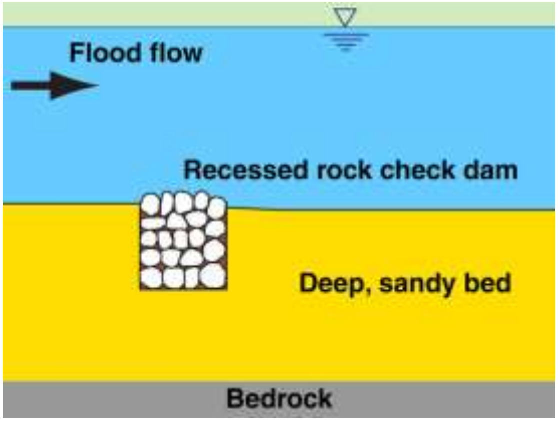
Caution the placement of rocks on a deep sandy bed



Recessed check dam in a sandy bed

Introduction

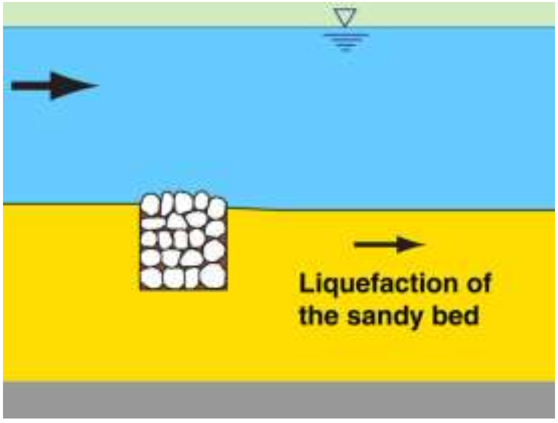
- The diagrams presented on this page highlight the potential problem that can occur if rocks are placed on a deep, sandy bed.



Flood event

Major flood event

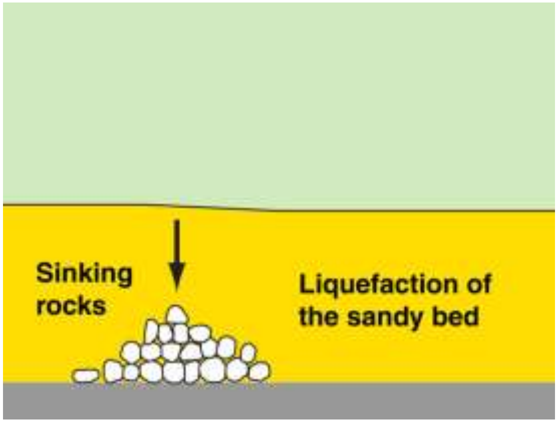
- During most floods, the sandy bed will begin to migrate down the channel, which can cause disturbance to the rocks.



Liquefaction of the sandy bed

Liquefaction of the sandy bed

- During a major flood, the sandy bed can liquefy, which can turn the sandy bed into a form of 'quicksand'.



Rock sink into the sandy bed

Sinking rocks!

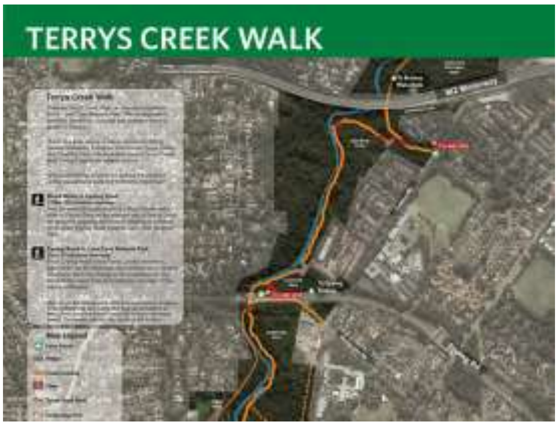
- Heavy rocks can simply sink into the sand, and consequently, they will stop providing any useful service to the waterway.

Step 12: Design public and maintenance access

Design Public and Maintenance Access

Terrys Creek walking trail (NSW)

Terrys Creek waterfall (NSW)



Terrys Creek Walk (NSW)

A note from the author

- The first twenty years of my life were spent in the suburb of Eastwood, Sydney.
- I grew-up spending a great deal of my youth playing in and around my local creek—Terrys Creek.
- I loved the idea that I could travel from suburb to suburb simply by following the walking trails that ran beside the creek.
- But as an adult I now realised how much damage I did to my beloved creek; such capturing and removing wildlife.

Finding the balance

- As a 67 year old creek engineer, I would love to have humans (except Rangers) excluded from our urban creeks.
- Us humans have enough space in the suburbs to live and play—the creeks are the last remaining place for urban wildlife.
- However, I would not want to stop a future creek engineers from exploring creeks.
- So, society needs to find a balance between public access, and the protection of our fauna habitats.

Master park and waterway planning

- State and local governments have an important role in:
  - protection waterway fauna
  - providing appropriate public access.
- My wish is that:
  - sealed walking tracks are located outside the riparian zone, and
  - bikeways are located with floodways, or along the upper bank, well-away from riparian zones.

Walking pathways

Walking track (Qld)

Walking pathways (also see Part 3)

- The key to managing walking tracks is to be aware that:
  - over time, unsealed tracks erode into shallow drains that collect and carry stormwater runoff
  - the surface of the track must rise and fall at regular intervals to force stormwater to leave the track
  - plants can be used to remove the temptation for people to take short-cuts that could eventually cause the formation of an unwanted track.

Walking track (Qld)

Walking track (Qld)

Walking track (SA)

Walking track (SA)

Walking track (Qld)

Walking track (SA)

Waterway crossings – stepping stones

Stepping stones (Qld)

Stepping stones

- The first priority of a stepping stone design should be safety.
- The key to safety is the stability of the stepping stone, and the coefficient of friction of its treading surface.
- The stability of a stepping stone depends on its foundations, which depends on the type of waterway bed (clay, sand, or gravel).
- Do NOT design a stepping stone crossing without investigating the stability of the channel bed.

Stepping stones (SA)

Stepping stones (Qld)

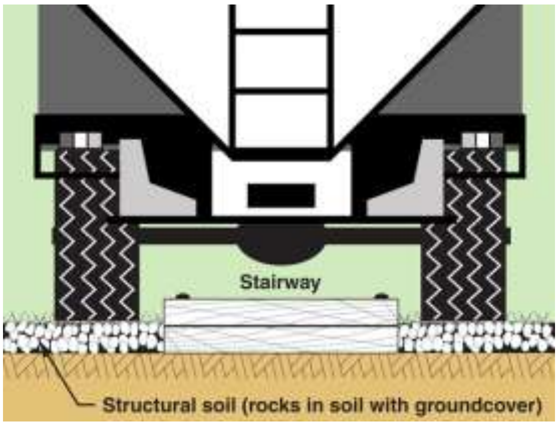
Stepping stones (Qld)

Stepping stones (SA)

Stepping stones (ACT)

Stepping stones (ACT)

Maintenance and public access



Combined vehicular and walking track

Maintenance and public access

- Most state and local governments have design guidelines for stairways.
- The National Parks Service provides good information on the management of walking tracks.
- To combine a staircase with 4WD vehicular access (i.e. fire trucks) within a <u>narrow</u> corridor, a staircase can be formed between two wheel tracks (shown left).
- If the stairs lead to a bikeway, then ensure the stairs are bike friendly.

Stairs (NSW)

Stairs (SA)

Maintenance access (Qld)

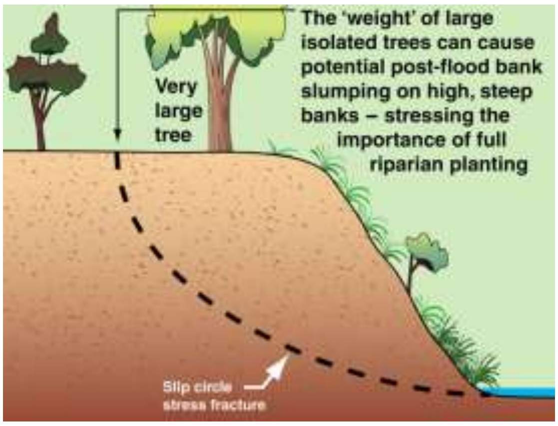
Maintenance access (Qld)

Maintenance berm (Qld)

Access ramp (Qld)

Tree planting (Qld)

Lomandra **planting on outside of a bend**



Slip circle bank failure

Planting density

- An appropriate balance between ground cover, mid-storey and canopy plants is:
  - 50% lower storey (ground covers)
  - 30% middle storey species
  - 20% upper storey (canopy) species.
- The spacing of plants in non-flood control areas could be:
  - 0.5 to 1 m for lower storey
  - 2 to 4 m for middle storey
  - 4 to 5 m for upper storey.

Planting on the outside of channel bends

- Flow velocities and erosion forces are normally greatest on the outside of channel bends.
- Banks are usually steeper on the outside of a bend in comparison to the inside bank of the same bend.
- Plants that typically work best on the outside of bends are:
  - stiff grasses (e.g. *Lomandra*)
  - shrubs with flexible branches (e.g. *Callistemons*).

Tree planting on steep, high banks

- Large trees can add significant weight to a creek bank.
- Even though the tree's root system can provide significant anchorage, if the tree is isolated from other trees, then in the days following a flood, the weight of a large tree on a wet bank can trigger a bank slump.

Note: The risk of such bank slumping is low, and should not dominate the design of riparian zones; instead, this is just one of many issues that needs to be given appropriate consideration.

How plants control soil erosion

Exposed tree roots (Qld)

A common myth

- It has been written many times that *'tree roots bind the soil together preventing it from being washed away'*, but this is only a half-truth.
- Yes; tree roots are an anchoring system, which helps in the control of slumping.
- However, tree roots do not provide much benefit to the control of soil scour, which is an important component of the two most common forms of bank erosion (bank scour and bank undercutting).

Native groundcover (Qld)

Plants that control raindrop impact erosion

- Raindrop impact erosion is important because it can wash clay into waterways, and turn floodwater 'brown'.
- Raindrop impact can be controlled by both living and non-living groundcovers, including grasses, leaf litter, organic mulches, and rock mulches.
- Tree foliage can intercept raindrops and reduce their impact energy, but water drops falling from tall trees can still cause significant soil erosion.

Dense upper storey tree cover (NSW)

Plants that control bank slumping

- Deep-rooted plants, such as trees and shrubs, are the best plants for the control of the various forms of mass movement erosion, such as bank slumping.
- The steeper the bank slope, or the higher the creek bank, the greater the need for a continuous, interlocking root system.
- On steep creek banks, middle storey plants can help to cross-link the root systems of the more spatial positioned upper storey plants.

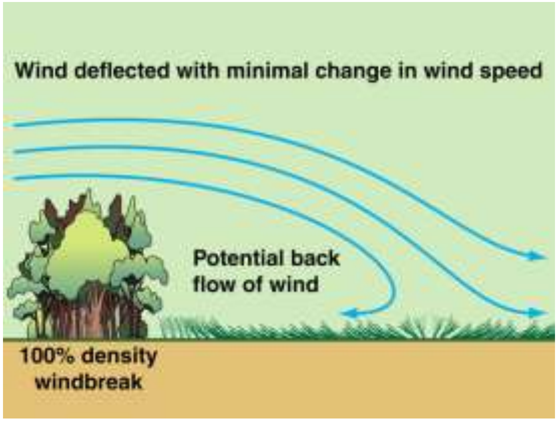
Lomandra in high-velocity flow (Qld)

Plants that control bed and bank scour

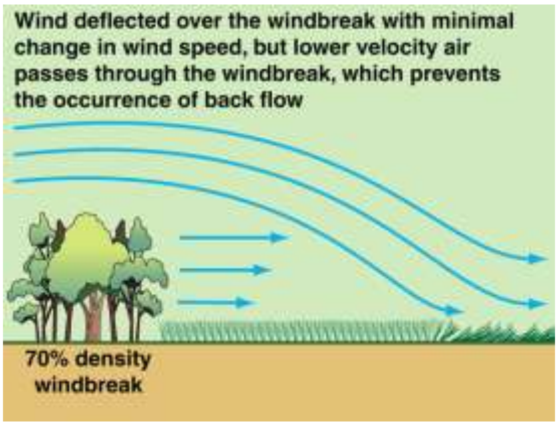
- Soil scour is the type of erosion caused by the direct contact between high-velocity flows and soil surfaces.
- It is the leafy matter of grasses that helps to build a hydraulic boundary layer, which in-turn protects the underlying soil.
- The plants with the greatest ability to control soil scour are flexible, leafy groundcovers, such as most grasses.
- In deep water, certain woody plants can help to slow flow velocities, and thus help to control soil scour.

Understanding how leafy plants can reduce local flow velocities

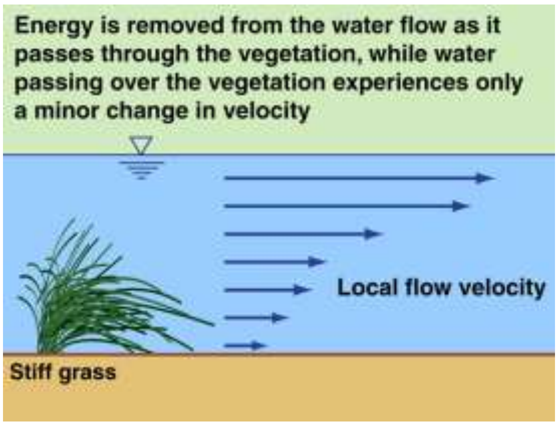
The hydraulic effects of *Lomandra*



Air flow for a 100% windbreak



Air flow for a 70% windbreak



Reduction in velocity around stiff grasses

Introduction

- All plants can help to reduce flow velocities, but different plants achieve this outcome in different ways.
- Woody plants, such as shrubs and trees, provide a resistance to the movement of floodwater, which slows the stream velocity upstream of the plants.
- However, leafy plants, such as stiff grasses, extract energy from the water, which slows the flow velocity at the plant, and immediately downstream of the plant.

Using the mechanics of air flow to better understanding water flow

- One way to understand the impact that plants have on water flow is to study how plants interact with air flow (which also moves as a 'fluid').
- If you were to build a windbreak with densely-packed vegetation, then the wind would not pass through the windbreak, but instead would only pass over it.
- In this case, there will be no real reduction in wind speed, just the 'shadow' effects.

Understanding the effects of a porous windbreak

- If the windbreak is slightly porous, then some air flow will pass through the trees.
- Only when air passes through the trees can energy be extracted from the air flow, which results in a reduction in air speed.
- The air that passes through the windbreak fills the air space immediately downwind of the trees, and this air flow helps to prevent the back flow of the high-velocity air that passed over the windbreak.

Understanding how stiff grasses can extract energy from flowing water

- In water flow, shrubs have a tendency to act like impervious windbreaks, and as a result they tend to deflect water flow around the individual shrub, which can cause significant turbulence.
- In deep water, stiff grasses act like porous windbreaks, which means they can extract energy from the water, and thereby reduce local flow velocities.
- However, in shallow water, stiff grasses may simply deflect the passing water flow.

Different plants play different roles in helping to control erosion

Lomandra plant with fibrous root system

Introduction

- Plants help to control creek erosion in two ways:
  - their root system can help to anchor the soil, which is important during floods, and in the days following a flood (thus controlling bank slumping), and
  - the leafy and woody matter above the ground can help to slow flow velocities, which reduces the erosion potential along the waterway (thus controlling soil scour).

Groundcover plants (NSW)

Groundcovers (lower storey plants)

- Groundcovers can consist of living plants and discarded leaf litter.
- It is the groundcovers, such as the various native grasses and vines, that slow flow velocities close to the ground, which helps to prevent soil scour during floods.
- What primarily stops soil scour is <u>not</u> the root system, but the leafy matter that stands above the soil.
- This leafy matter also helps to build a hydraulic boundary layer over the ground.

Riparian shrubs (Qld)

Shrubs (middle storey plants)

- Shrubs and other middle storey plants are the undervalued plants of our waterways.
- Shrubs can contribute significant hydraulic roughness to a creek (which can increase flood levels), but this roughness can also be used to push stream flows away from unstable creek banks.
- The species that are best suited to riparian areas are those that have the ability to bend with the flows, and then quickly recover or regenerate after a flood.

Trees without mid-storey plants (SA)

Trees (upper storey or canopy storey)

- Trees are often credited for doing a lot of the erosion control work that is actually performed by shrubs and groundcovers.
- Trees are the main soil anchors, they are the plants that allow our waterways to have steep and high banks.
- The right trees, planted in the right place, at the right density, can be a very powerful force in creek engineering.
- Another important attribute of trees is their shading ability, which benefits weed control and water temperatures.

Different plants play different roles in helping to control erosion

Trees with low branches (SA)

Trees with low branches

- The low branches on trees can behave like shrubs.
- They can benefit erosion control measures by slowing the overall channel velocity **upstream** of the tree.
- The trees that are best suited to riparian areas are those that have lower branches that can bend with the flow (i.e. flexible timber).

Trees with high branches (Qld)

Trees with only high branches

- The following table appears to suggest that trees with high branches do not contribute much to erosion control, BUT this table refers only to the relative importance of the tree's branches.
- All trees can contribute to the control of creek erosion as a result of:
  - their root system
  - the hydraulic roughness generated by their truck (and any low branches).

Erosion type	Ground covers		Shrubs	Trees		
	Mat forming	Stiff grasses		Tree roots	Low branches	High branches
Bank scour	Yes	In deep water	Possible	Rare	Possible	Can help slow overall flow velocities
Outside of bends	Can cause problems	In deep water	Preferred	Rare	Possible	No
Bank slumping	No	No	Assists	Yes	No	No
Bank undercutting	Lower bank	Lower bank	Assists	Some species	Possible	No
Soil dispersion	No	No	No	No	No	No
Fretting (wave action)	Yes	Yes	Some species	Some species	No	No
Bed scour	Aquatic plants	Aquatic plants	No	No	No	No
Lateral bank erosion	Possible	Can cause problems	No	Rare	No	No

Table 6.15 – The relative importance of different types of plants

The 'right' plant in the 'right' location

Site revegetation (Qld)

Site revegetation (Qld)

Introduction

- Creek rehabilitation is not a case of simply delivering a truck-load of native plants to a site, and then planting them randomly over the disturbed ground.
- Plants play an important role in the stability and everyday functioning of our creeks.
- In order to perform these tasks, the right plant needs to be planted in the right location, which means following a plan, or ensuring that the revegetation is supervised by suitably trained people.

Planting density (general guide)

- An appropriate balance between ground cover, mid-storey and canopy plants is:
  - 50% lower storey species
  - 30% middle storey species
  - 20% upper storey species.
- Plant spacing in non-flood control areas could be:
  - 0.5 to 1 m for lower storey plants
  - 2 to 4 m for middle storey plants
  - 4 to 5 m for upper storey plants.

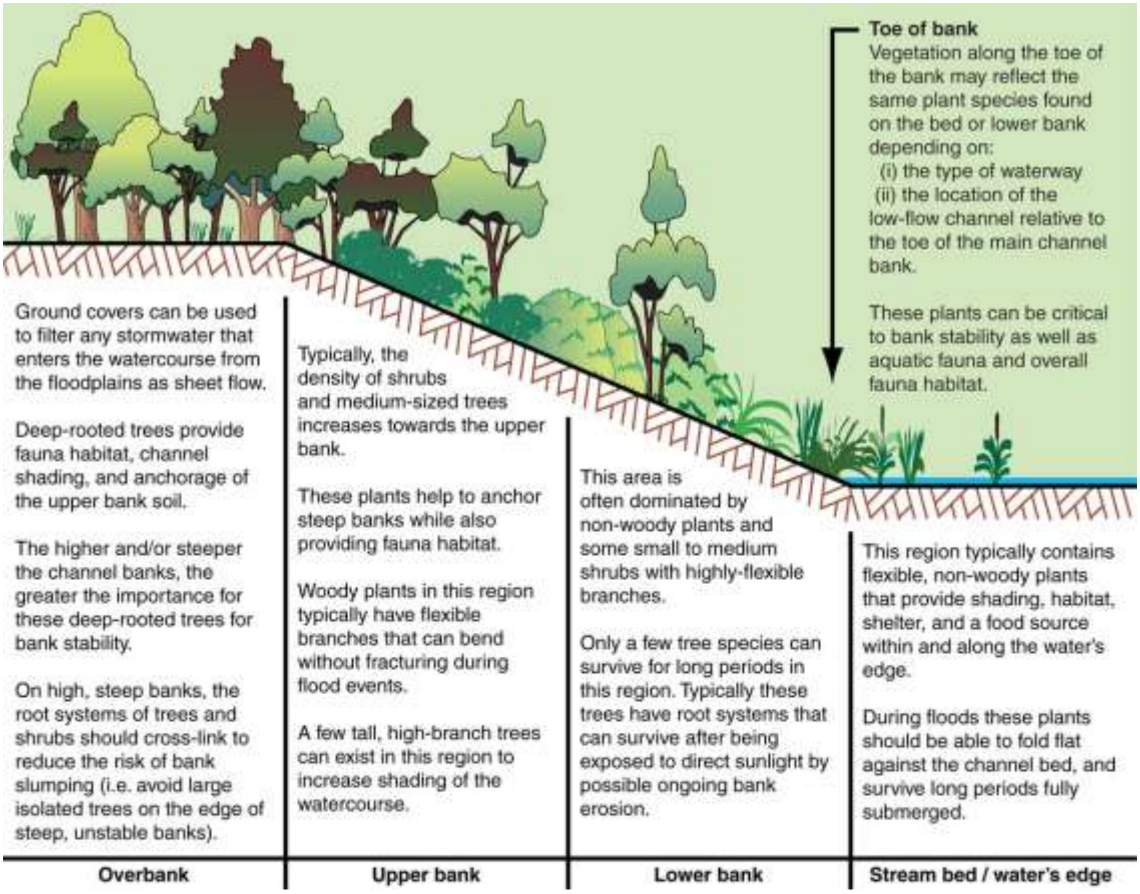


Table 6.16 – Desirable characteristics of riparian vegetation

The 'right' plant in the 'right' location

Water's edge (Qld)

***Lomandra* experiencing a minor flood**

Planting along the water's edge

- The shading of the water's edge provides the following benefits:
  - control of water temperature (especially in tropical regions)
  - sheltering aquatic life from predators
  - controlling the boundary layer and local stream velocity adjacent the bank
  - providing a food source for aquatic fauna
  - providing favourable fish passage conditions during flood events.

***Lomandra* (mat rush)**

- *Lomandra* is possibly the most important erosion control plant in Eastern Australia, but many would suggest it is also one of the most over-used plants.
- *Lomandra* is most effective when flood waters are able to overtop the plant (i.e. when located within the lower bank region)—they are <u>not</u> suited to high-velocity, shallow water conditions, such as on dam spillways.

Erosion type	Ground covers		Shrubs	Trees		
	Mat forming	Stiff grasses		Grouped or Multi-trunk	Trees with low branches	Trees with only high branches
Water's edge	Possible	Yes	Yes	Rare	Rare	Rare
Lower bank	Yes	Yes	Yes	Rare	Rare	Rare
Upper bank	Yes	Yes	Yes	Possible	Possible	Possible
Overbank (riparian)	Yes	Yes	Yes	Yes	Yes	Yes
Outside of bends	Can cause problems	Yes	Preferred	Possible	Possible	Can cause problems
Inside of bends	Yes	Yes	Yes	Yes	Yes	Yes
Flood control areas	Yes	Yes	No	No	Rare	Yes
Floodways (high velocity floodplains)	Yes	No	No	No	No	Rare

Table 6.17 – The relative importance of plant <u>location</u>

The 'right' plant in the 'right' location

Upper bank region (Qld)

Flood-damaged shrubs (Qld)

The difference between upper bank and lower bank plants

- Any plant can seed and germinate at any location, but it is the long-term survival of plants that determines their suitability.
- The fact that some species are listed for use in the lower bank region does not necessarily mean that such plants should never appear in upper bank or overbank regions.
- Planting zones are just an indication of where certain plants will dominate.

Flexible timbers

- For species located within the lower bank areas, you should be able to bend their branches without the branches breaking (within reason).
- A 'simple' rule is:
  – *If the branches point to the sky, then put them up high, if the branches point to the water, then put them near the water.*
- A better rule is to simply follow the advice of creek rehabilitation experts!

Overbank	Upper bank	Lower bank	Stream bed
Upper canopy Flooded Gum *Eucalyptus salignus* Large-leaved Grey Gum *Eucalyptus major* Hoop Pine *Araucaria cunninghamii* Pepperberry *Cryptocarya obovatus* Blackbutt *Eucalyptus pilularis* Brisbane Blue Gum *Eucalyptus tereticornis* Three Veined Laurel *Cryptocarya triplinervis*	Spotted Gum *Corymbia citriodora* Tallowwood *Eucalyptus microcorys* Swamp Box *Lophostomen suaveolens* Blue Quandong *Elaeocarpis grandis* Smell-of-the-bush *Mallotus claoxyloides*	Waterhousea *Syzygium floribundum* Black Bean *Castanospermun australe* Cheese tree *Glochidion ferdinandi* River She Oak *casuarina cunninghamiana*	
Middle storey *Alectryon tomentosus* *Drypetes deplanchei* White Bottlebrush *Callistemon salignus* Hairy Lollybush Native Quince *Guioa semiglauca* Soap Tree *Alphitonia exelsa* Red Kamala *Mallotus philippens* Native Olive *Notelaea longifolia* White Tamarind *Elattostachys xylocarpa* Flint Wood *Scolopia braunii*		Creek Bottlebrush *Callistemon viminalis* Chewing-gum Bush *Backhousia myrtifolia* Brown Myrtle *Choricarpia leptopetala* Native Guava *Rhodomyrtus psidioides* Ferns & brackens	
	Sedges and groundcovers	Bolwarra *Eupomatia laurina* Creek Matrush *Lomandra hystrix*	*Carex* *Juncus* *Ghania spp.* *Crinum pedunculatum* *Cyperus exaltatus* *Persicaria spp.*

Table 6.18 – Example of riparian species for the Brisbane region (sourced: SOWN)

Native grasses

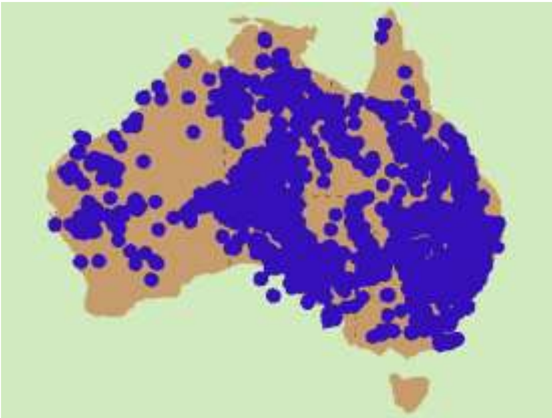
Barbed Wire grass (Lemon-scented grass)

Location maps for native grasses

- The following maps show the approximate location of recorded sightings of native grasses.
- The maps are not accurate, and were developed from a variety of sources.
- Designers should always seek local advice and locally-prepared location maps.

Black Spear (*Heteropogon contortus*)

Chloris grass



Cotton Panic grass (*Digitaria brownii*)

Curly Windmill grass

Kangaroo grass (*Themeda australis*)

Mitchell grass (*Astrebla spp.*)

Native grasses

Native Wheat grass (*Elymus scaber*)

Queensland Blue grass

Redgrass (*Bothriochloa macra*)

Spear grass (*Austrostipa species*)

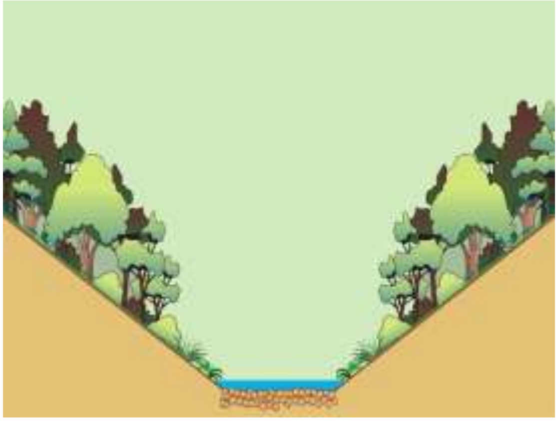
Tussock grass (*Poa labillardieri*)

Wallaby grass (*Austrodanthonia spp.*)

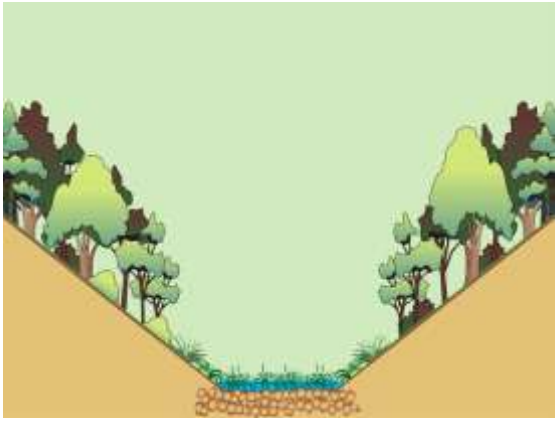
Weeping grass (Meadow rice grass)

Windmill grass (caution use of this map)

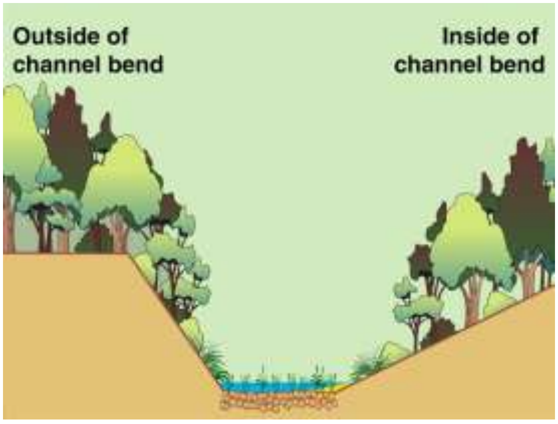
Vegetation strength



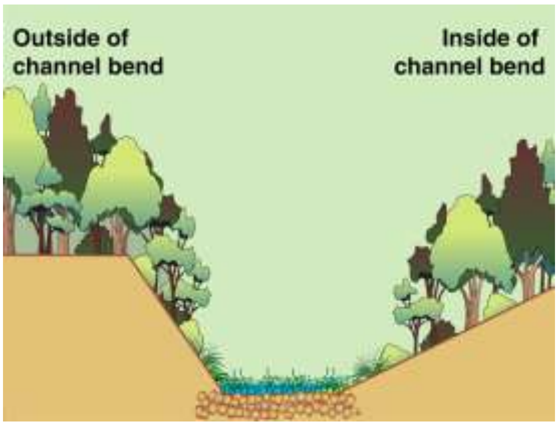
Straight channel with mild bed slope



Straight channel with steep bed slope



Channel bend with mild bed slope



Channel bend with steep bed slope

Straight channel with mild bed slope

- In the control of creek erosion, the soil, rock and vegetation that make up the bed and banks, all work together to control the erosive effects of the flowing water.
- As a general guide, along a low gradient, straight channel reach, it is preferable that the overall scour resistance of the banks is greater than the scour resistance of the bed.
- If strong, tough reeds begin to invade the creek bed, then this can initiate bank erosion.

Straight channel with steep bed slope

- If, however, the creek is steep, then there is the need for increased shear strength along the bed of the creek.
- Often this increased shear strength is provided by exposed bedrock.
- If significant bedrock is not present, then increasing the vegetation density on the banks (and thus the scour resistance of these banks) can increase the risk of bed erosion—which is a problem!

Channel bend with mild bed slope

- On channel bends, it is usual for the outside bank to be steeper than the inside bank.
- In some cases, the increased gradient of the outside bank can cause a reduction in vegetation density, which could result in a reduction in its scour resistance.
- In general, the overall scour resistance of the outside bank should be greater than the inside bank, which usually means trying to maintain a higher vegetation density on the outside bank.

Channel bend with steep bed slope

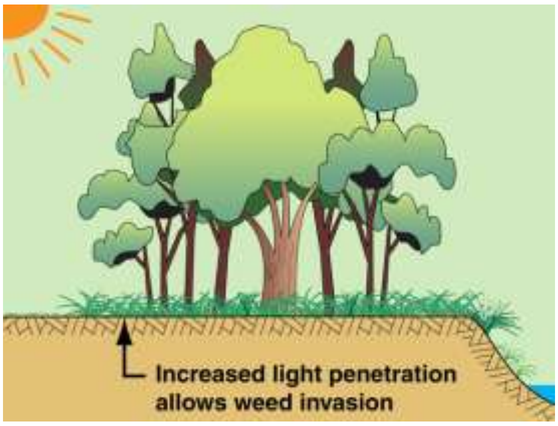
- Once again, if the channel is steep, then there is the need to maintain good shear strength along the bed of the creek.
- If significant bedrock is not present, then:
  - the overall scour resistance of the bed should be greater than the banks, and
  - the outside bank should be stronger than the inside bank.
- Always consider the potential effect a bank rehabilitation program may have on the bed of the creek.

Planting to control edge effects

Intrusion of light into a riparian area

Introduction

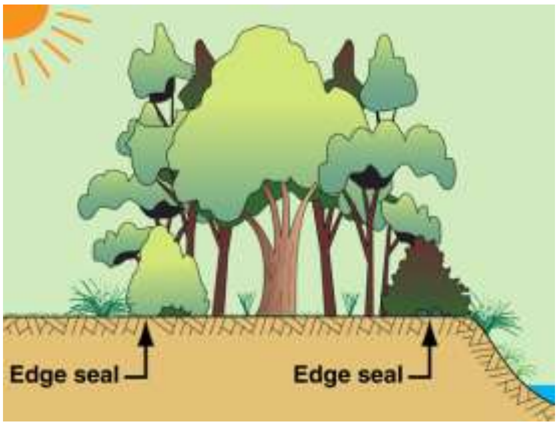
- In both rural and urban areas, riparian zones may consist of just a narrow strip of vegetation each side of the waterway.
- Many of the functions performed by riparian vegetation will be affected by the width of the riparian zone.
- The width of the riparian zone also affects the degree of light that enters the riparian zone as a result of 'edge effects'.



Weed intrusion into the riparian zone

The impact of edge effects on weed invasion

- If the edge effects are not adequately controlled, then the increase in diffuse light will bring with it an increased risk of weed invasion.



Controlling the edge effects

Controlling edge effects with appropriate planting

- Middle storey plants and robust ground covers (e.g. stiff grasses) can be used to reduce the degree of diffuse light penetrating into riparian zones.
- Appropriate edge planting can also improve the aesthetics of parks by providing a visual barrier between the highly-maintained open parkland (adjacent the waterway), and the low-maintenance riparian zone.

Forming a 'mowing edge' (Qld)

Using plants to clearly define the edge of riparian areas in order to control mowing activities

- There are over 50 species of *Lomandra* (mat rush), but only two are commonly found near creeks.
- Given the potential overuse of these two species in and around many urban creeks, consideration should be given to the other varieties of *Lomandra*, and the many other varieties of stiff grasses that could be used as edge plants.

Step 14: Early phase erosion control measures

Early Phase Erosion Control Measures

ESC for Instream Work Activities

Reference document:

'Erosion and Sediment Control Field Guide for Instream Works'

Catchments & Creeks Pty Ltd, 2020, Bargara Queensland.

Version 2, December 2020

A pictorial-based guide to erosion and sediment control practices appropriate during the conduction of instream work, such as constructed drainage channels, and creek rehabilitation.

Rock toe protection (Qld)

Use of rock

- Rock can provide permanent toe protection within clay-based creeks.
- However, rock may not be suitable for sand-based creeks because the rocks may 'sink' into the sand during a flood.
- The rock size [mm] is based on:

$$d_{50} = 40\ V^2 \qquad (14.1)$$

- If rock is also being placed above the toe, then use the same rock as determined for the rest of the bank.

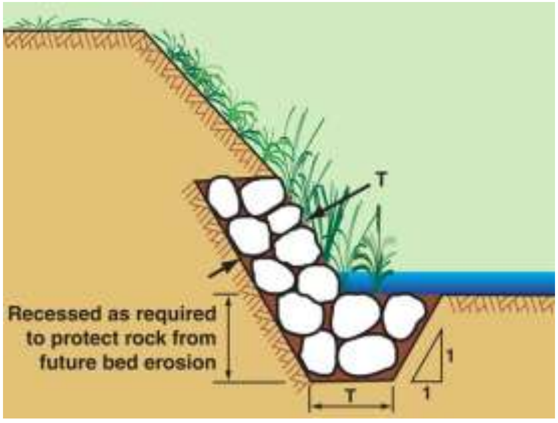
Geo log toe protection (Qld)

Alternative toe stabilisation measures

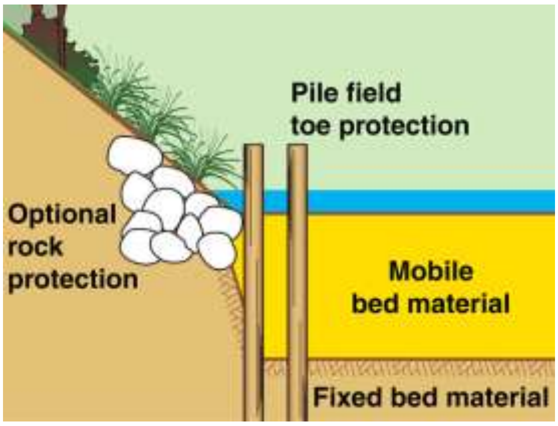
- Geo logs can be used as an alternative to rock stabilisation of the toe.
- Geo logs typically provide only temporary protection (less than 2-years) for the toe.
- These temporary protection measures are only successful if suitable vegetation is incorporated into, or around, the logs.
- It is important to ensure that bank erosion does not occur behind the logs during overtopping stream flows.

Toe stabilisation – estimating the required depth of toe protection

Undermining of toe rock



Depth of protection in a clay-based creek



Pile field installation in a sandy creek

Scour around a bridge pier (Qld)

Introduction

- If the toe protection is expected to provide long-term benefits, then it must be able to withstand the erosive effects of floods.
- Floods can disturb the toe protection in three ways:
  - direct scour
  - undermining of the toe protection, or the mass movement of the bed material
  - liquefaction of a sandy bed causing the rocks to sink into the sand.

Clay-based creeks

- In clay-based creeks, there should not be a significant amount of bed sediment, and the bed should not be mobile during a flood event.
- This means that the 'depth' of the toe protection is usually not critical (exceptions do exist).
- However, if the creek bed is slowly lowering, then the toe protection should extend below the predicted long-term bed level.

Sand and gravel-based creeks

- In sand-based creeks, rock protection can sink into the bed sand during floods, making it ineffective.
- If toe rock is to be used, then ideally, the rock should extend below the depth of the bed sand.
- In gravel-based creeks, the whole bed could move (migrate) during a major flood, which can dislodge any toe rock.
- The depth of the toe protection should not be an issue in cobble and boulder creeks.

Local bed scour issues

- If the toe protection is located downstream of a bridge or culvert, then an estimate will need to be made of the depth and shape of any associated scour holes.
- The scour depth may be estimated using appropriate design guides, such as:
  - *Supplement to Austroads Guide to Bridge Technology, Part 8, Chapter 5: Bridge Scour (2018)* The State of Queensland (Department of Transport and Main Roads), January 2019.

The use of mulch in riparian areas

Loose mulch applied to a creek bank

A potential source of pollution

- Mulch can provide many benefits to creek rehabilitation; however, it can also be considered a form of pollution within urban waterways.
- Many urban streams experience 'eutrophication' (the enrichment of the waters by nutrients) which can lead to excessive algal growth.
- If the mulch is not adequately anchored, then it can contribute to these water quality problems.

Geo logs used on a steep creek bank

Retaining loose mulch on steep banks

- The value of mulch during plant establishment increases in importance as the bank slope increases; however, the difficulties of holding the mulch in place also increases.
- Meshes, logs and geo logs can be used to help retain mulch on steep slopes.

Straw mulch (Qld)

Straw and cane mulch

- Straw and cane mulch should be used with caution adjacent to waterways, unless such mulch can be adequately anchored to prevent it from simply being blown or washed away.

Bush mulch (NSW)

Bush mulch

- Bush mulch has the potential to be more stable than straw mulch, but appropriate care must still be taken to prevent the mulch from being washed into the waterway.
- Alternatives include:
  - compost blankets
  - rock mulching
  - erosion control blankets (jute meshes).

The use of erosion control blankets in riparian areas

Jute mesh (Qld)

Terminology

- The term 'blanket' is typically used to describe rolled erosion control products that have a low shear strength.
- The term 'mat' is typically used to describe rolled erosion control products that have a high shear strength—making them suitable for placement in drainage channels.
- A 'mesh' is a blanket that has an open weave, usually made from jute or coir.

Jute erosion control blanket (SA)

Bio-degradable products

- Bio-degradable erosion control blankets are typically manufactured from:
  - jute (made from specific Asian plants), which have a useable life of a few months, or
  - coir (made from coconut fibre), which is more durable, making it more suitable for use within waterways.
- Meshes are the type of 'blankets' that are best suited for use on waterway banks.

Hydraulically-applied blanket (Qld)

Hydraulically-applied blankets

- Hydraulically-applied blankets include:
  - hydroseeding
  - hydromulching
  - compost blankets
- Hydraulically-applied blankets:
  - contain a mix of mulch, site-specific seed, and fertiliser
  - can be applied to creek banks that already contain some vegetation
  - can be applied to very steep banks.

Plastic-reinforced erosion control mat

Problems associated with plastic-reinforced mats

- Some erosion control mats contain a synthetic (plastic) reinforcing mesh that may, or may not, break down under direct sunlight.
- These synthetic reinforced mats should **not** be used in bushland and waterway environments because ground dwelling animals, such as lizards, snakes, and seed-eating birds, can become entangled in the mesh.

7. Repairing Flood Damaged Waterways

Planting in response to bank scour

Bank scour (Qld)

Introduction

- Bank scour results from high velocity flows damaging bank vegetation and subsequently exposing the underlying soil to erosion.
- This type of erosion commonly occurs:
  - in the lower levels of creek banks
  - on the outside of channel bends.

Vegetated rock stabilisation (Qld)

Vegetated rock

- The most common treatment of bank scour is the placement of rock along the lower bank.
- If this rock is left without appropriate vegetation cover, then the high velocity flows will once again be attracted to the creek bank, which can result in further bank scour immediately downstream of the rock.
- Wherever possible, rock-lined surfaces should be fully vegetated at the time of rock placement.

Shrubby creek bank (Qld)

Bank scour on the outside of channel bends

- Rock placement is common on the outside of channel bends, but if flow velocities are not excessive, then a fully vegetated treatment can be applied.
- Two types of vegetated solutions exist:
  - planting with flexible-timber shrubs (which aims to push high-velocity floodwater away from the bank)
  - planting a near-monoculture of stiff grasses (e.g. *Lomandra*) along the lower bank.

Monoculture of *Lomandra* (Qld)

Dense planting of stiff grasses

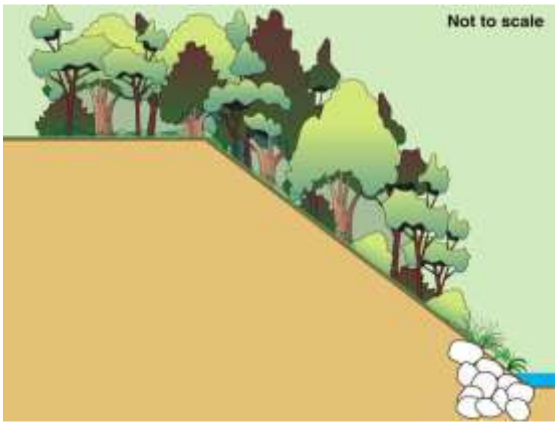
- Normal mat-forming grasses can perform well in high-velocity stormwater channels, but such planting schemes generate very shallow boundary layer conditions, which harms fish passage, and can cause erosion at the base of trees and shrubs.
- Stiff grasses, like *Lomandra*, can be very effective as a monoculture in high-velocity channels.
- Tall grasses, such as *Vetiver* grass, must be used with <u>extreme</u> caution in creeks as these plants can redirect flows.

Planting in response to bank slumping

Bank slump (Qld)

Introduction

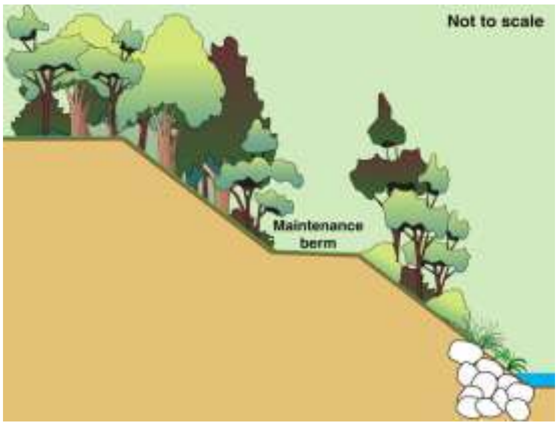
- Bank slumping is a form of 'mass movement', where the creek bank either:
  - slides as a shallow layer of soil, possibly 1 to 2 m deep, down the bank, usually with vegetation still attached, or
  - rotates as a deep 'slip-circle' type bank failure.
- Bank slumping is most common during the final stages of a flood, and during the days that follow a flood, while the banks are heavy with saturated groundwater.



Bank revegetation

Bank reshaping and revegetation

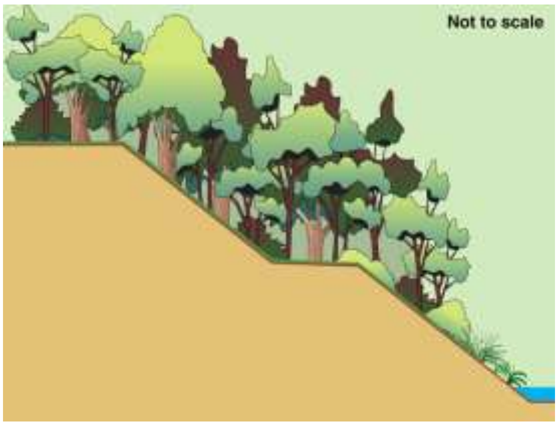
- Bank slumping often occurs when the creek banks are cleared of deep-rooted plants, and covered only in grasses.
- Treatment of a bank slump usually involves reshaping the slumped bank to form a new bank slope, then applying appropriate vegetation.
- It is typical for plants in the lower bank region to be different from the species that dominate the upper bank area.



Benching a creek bank

Benching and revegetation

- The bank treatment can involve the reshaping of the bank to form a bench, then applying appropriate vegetation.
- Benching the bank:
  - increases the bank stability
  - reduces the risk of a major bank slump if bank undercutting continues to occur.
- The bench can be used for:
  - pedestrian access
  - maintenance access.



Fully-vegetated, benched creek bank

Fully planting the bench

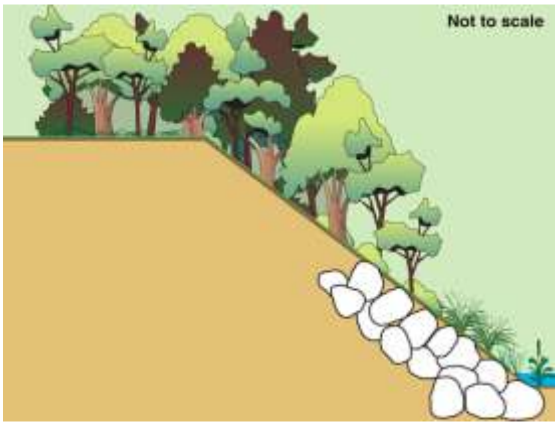
- If the risk of bank slumping remains high, then the bench can be fully planted.
- Planting the bench:
  - increases the bank stability
  - increases the interlocking of tree roots
  - reduces lateral intrusion of sunlight into the riparian zone, which reduces the risk of weed invasion.

Planting in response to bank undercutting

Bank undercutting (Qld)

Introduction

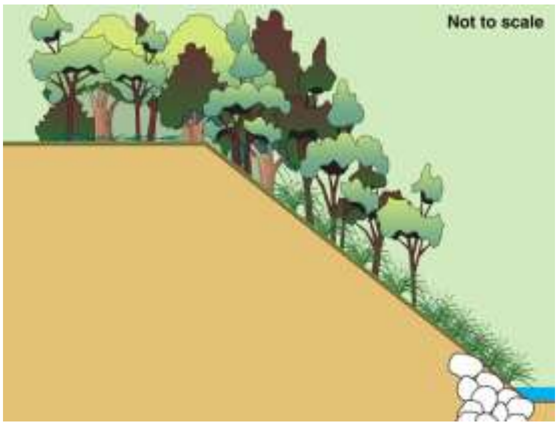
- Bank undercutting is the result of bank scour that has concentrated its effects on the lower bank region.
- Initially the upper bank cantilevers over the lower bank, but eventually the unstable upper bank collapses (slumps), and the fully-exposed bank takes on the appearance of a bank slump.
- Tree roots are often exposed by this bank erosion.



Vegetated rock stabilisation

Vegetated rock

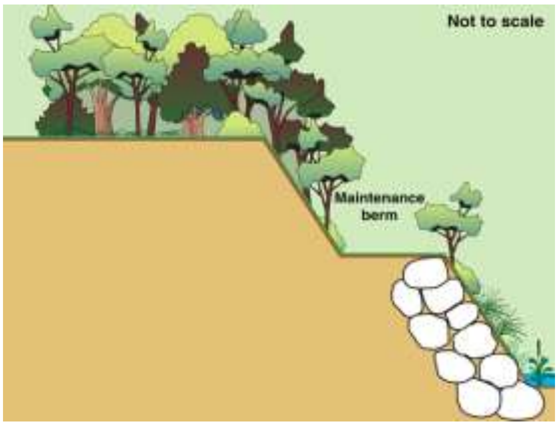
- The most common treatment of bank undercutting is the placement of rock on the affected lower bank region.
- The upper bank is battered back at an appropriate gradient depending on whether the bank is on the inside or outside of a channel bend.



Monoculture lower bank planting

Variations in upper and lower bank species

- The upper bank area should be planted with deep-rooted species.
- Trees planted near the lower bank should have root systems that can withstand partial exposure of their root system.
- All plants placed near the lower bank region should have flexible branches.
- Stiff grasses, such as *Lomandra*, work well in the lower bank area.



Benching of a creek bank

Benefits of benching in the control of bank undercutting

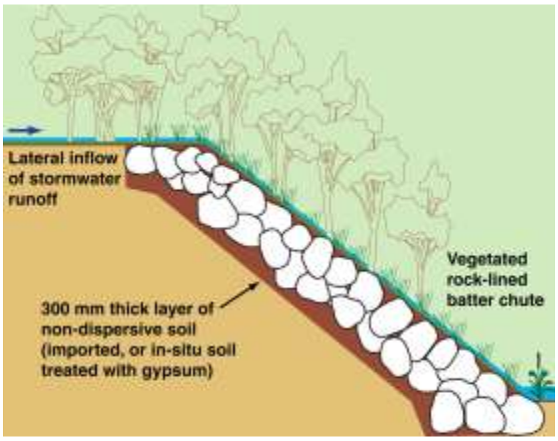
- If ongoing toe erosion and/or undercutting is expected, then benching the bank can provide the following benefits:
  - increased bank stability
  - reduced risk of a major bank slump
  - delayed disturbance and/or erosion of the upper bank area, which allows a longer establishment period for new vegetation.

Planting in response to lateral bank erosion

Lateral bank erosion (SA)

Partially-vegetated batter chute (Qld)

Stream flows deflected <u>around</u> a *Lomandra*



Batter chute built with non-dispersive soil

Lateral bank erosion

- Lateral bank erosion is a form of bank erosion that usually results from the unnatural concentration of stormwater runoff, and the effects of this runoff spilling down unstable banks.
- Even though it is classified as a form of <u>bank</u> erosion, it demonstrates many of the features of <u>bed</u> erosion.
- The treatment of lateral bank erosion is closely linked to the treatment of gully erosion and dispersive soils.

Vegetated batter chutes

- The most common treatment of lateral bank erosion is the construction of a ‘batter chute’, which is a drainage chute, usually formed from rock.
- If these rock chutes are initially formed in a non-vegetated state, then weed invasion will likely follow.
- Ideally, rock chutes should be pocket planted at the time of construction, but stiff or tall grasses should only be placed along the edges of the chute.

Problems associated with the use of stiff grasses in the treatment of lateral bank erosion

- Stiff grasses, such as *Lomandra*, work best when they are operating in deep water.
- In shallow water conditions, such as those found on a batter chute, stiff grasses begin to act as individual plants causing them to deflect passing flows rather than slow the water flow, which means stormwater runoff may be forced out of the batter chute.

Management of dispersive and slaking soils

- Lateral bank erosion commonly occurs in locations where the subsoils are dispersive.
- If the lateral bank erosion has exposed some dispersive subsoils, then the overall treatment of the erosion remains largely the same; however, the exposed surface of the dispersive soil <u>must</u> be covered with a suitable layer of non-dispersive soil prior to the formation of the batter chute.

Planting in an area of active bank erosion

Creek bank stabilisation (Qld)

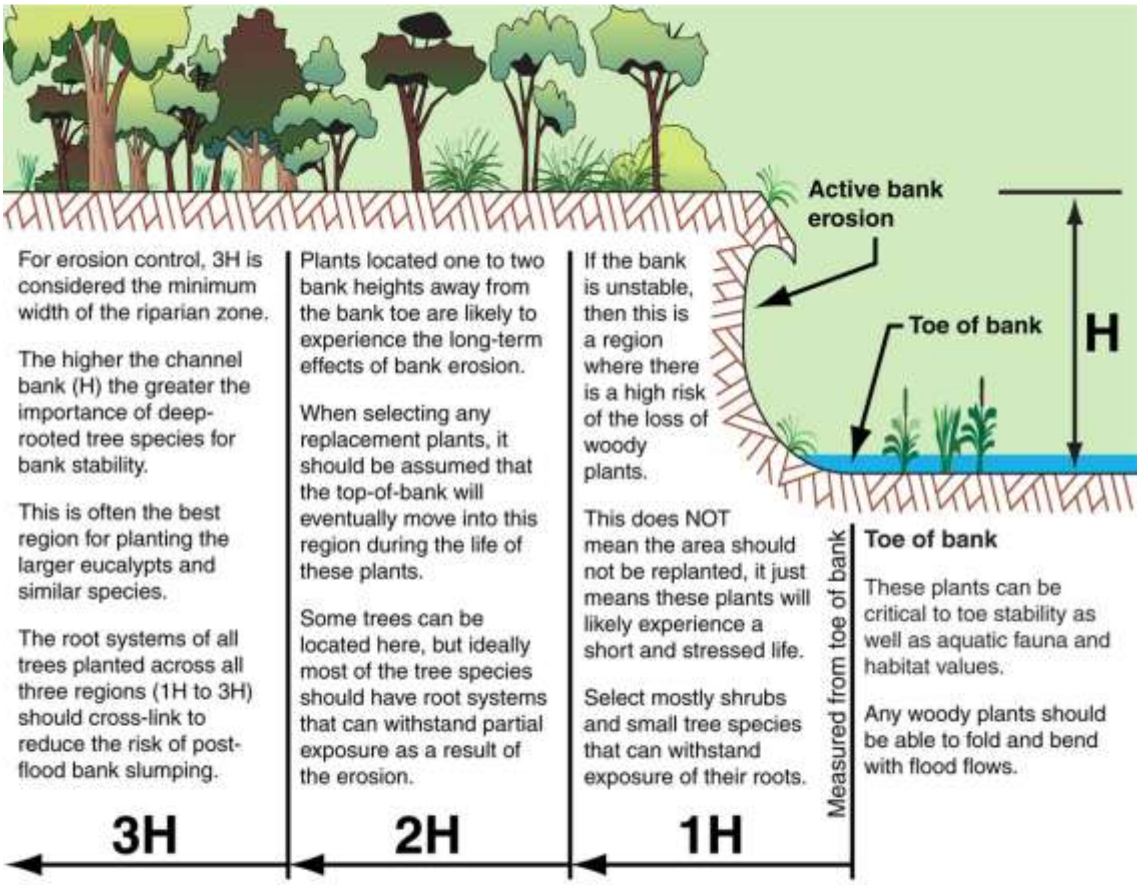
Overbank revegetation (Qld)

Introduction

- In cases of active bank erosion, the treatment options include:
  - allow the erosion process to resolve itself naturally (e.g. in cases where machinery access cannot be provided to the bank without causing damage to riparian areas), or
  - battering and revegetating the eroded bank, which may require the loss or modification of some riparian vegetation.

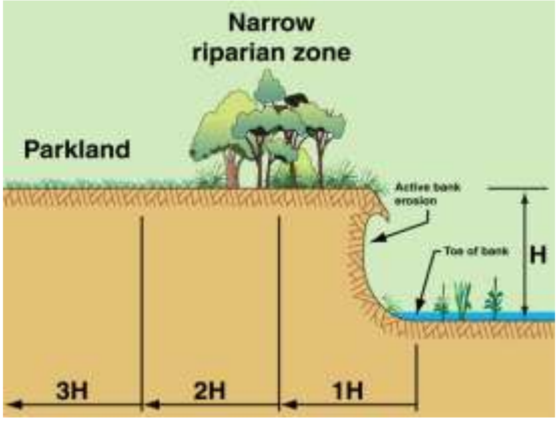
The use of sacrificial plants

- Many people struggle with the idea of 'sacrificial plants'—the concept of planting a tree knowing that it may never reach maturity.
- However, if we know that the bank erosion will be ongoing, then we must accept that new plants placed near the edge of the bank will likely be lost, while other plants located well away from the bank may have sufficient time to reach maturity (see over page).



Rehabilitating riparian zones adjacent to active bank undercutting

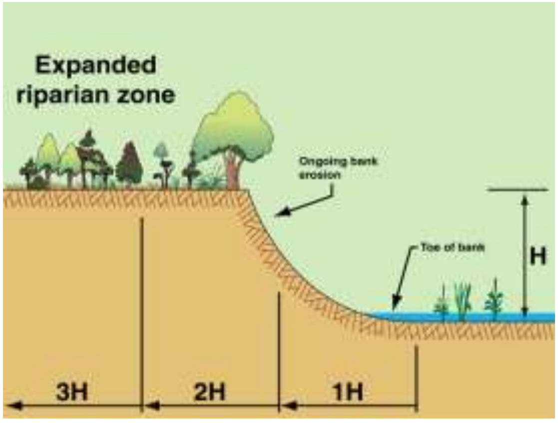
Planting in an area of active bank erosion



Existing site conditions

Introduction

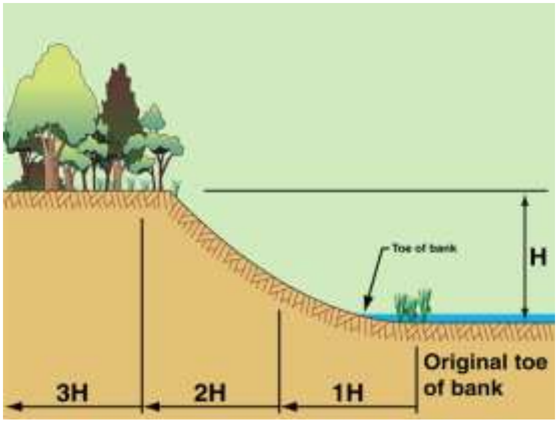
- In some cases, the only remaining habitat and wildlife corridor trees are those that exist within a narrow riparian strip located along the edge of the creek bank.
- If the eroding creek bank were to be 'battered and revegetated', then the creek would lose its wildlife habitat values for a period of time while new trees are establishing along the creek bank.
- This assumes that imported fill cannot be used to rebuild the bank.



Establish new overbank vegetation

Planting for a future bank condition

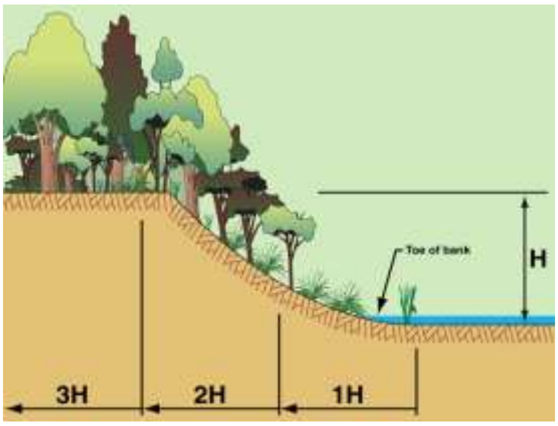
- The alternative approach to dealing with the creek erosion is:
  - to allow the bank erosion to progress naturally, and
  - to focus on establishing new riparian vegetation further inland.
- Depending on the height and gradient of the creek bank, some of these new trees may eventually succumb to the bank erosion (i.e. sacrificial plants).



Effects of ongoing bank erosion

Creek erosion finally forms a stable bank

- Retaining the existing riparian vegetation should slow down the progression of the bank erosion, giving additional time for the new plants to establish.
- It is noted that the final bank slope of around 1 in 2 (shown in the diagram) is not absolute, and will vary from location to location—in some cases a stable bank slope may never be reached without human interference.



Final stabilisation of the eroded bank

Final stabilisation of the creek bank

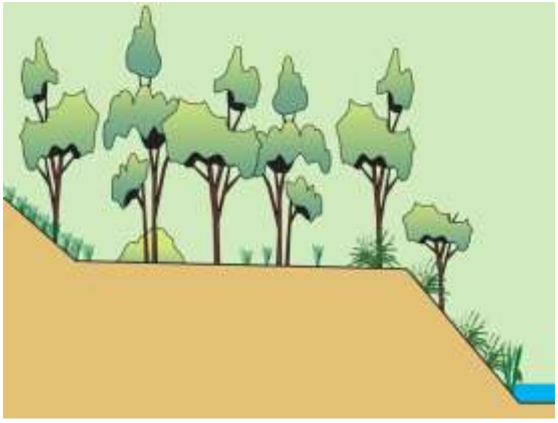
- Once the creek bank has established a stable slope, and the root systems of the new riparian vegetation have penetrated deep into the bank, the rest of the creek bank can be revegetated.
- Benching the creek bank at this stage can:
  - allow better access for bank revegetation, and
  - increase the stability of the final bank.
- Benching is not essential, just a design option.

Planting in flood hazard areas

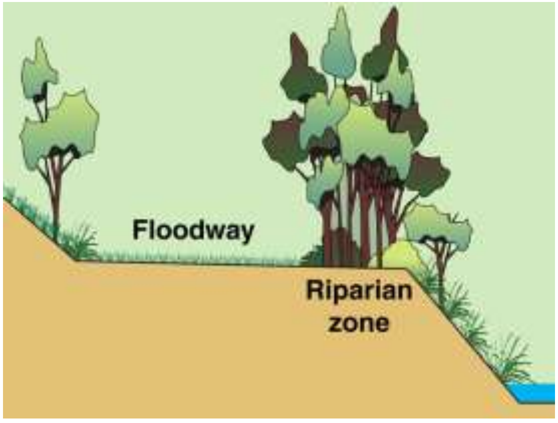
Sparsely treed floodplain (Qld)

Increasing the ecological 'value' of a riparian zone without causing adverse impacts on flood levels

- In many urban creeks, flooding is a significant community concern, and as a result, middle storey plants are often removed from floodplains in order to reduce flood levels.
- It is possible that a better ecological outcome could be achieved (without raising flood levels) by simply reorganising the layout of the riparian vegetation to make room for an open floodway.



Existing sparsely treed floodplain

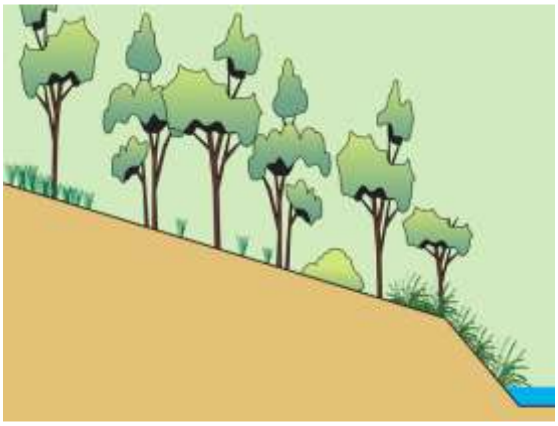


Creation of an open floodway

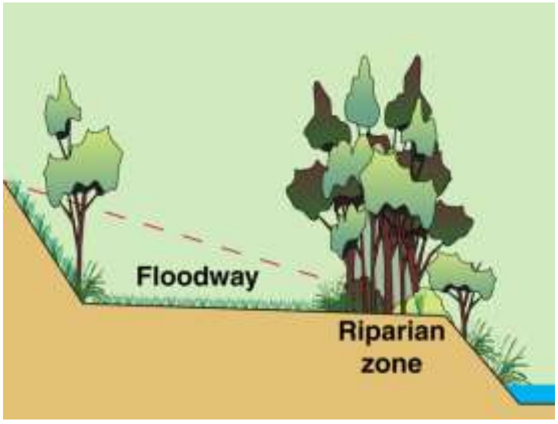
Constructed floodway (Qld)

Increasing the ecological 'value' of a riparian zone without compromising flow capacity

- In cases where a floodplain does not currently exist adjacent to the urban creek, an open floodway can be created by benching the creek bank.
- Benefits include:
  - enhanced ecological values
  - improved public access
  - improved maintenance access.

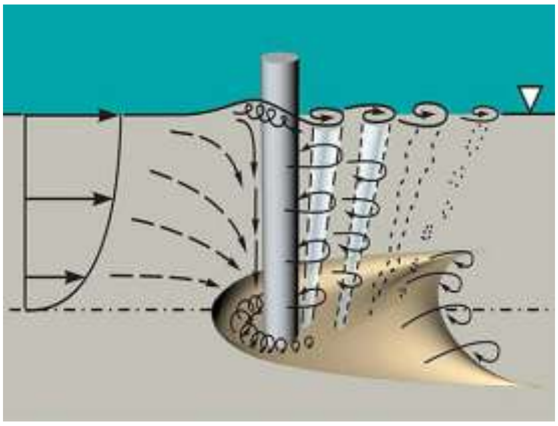


Existing sparsely treed floodplain



Excavation of a floodway

Planting in areas of high flow velocity



Pier scour flow patterns

Scour at bridge piers

- The flow field and maximum scour depths around bridge piers are dependent on three main variables:
  - effective pier width
  - flow depth, and
  - erodibility of the bed material.
- Flow fields around piers vary depending on the effective width of the pier in relation to the water depth.

Floodwater passing around a tree

Scour patterns around floodplain trees

- In hydraulic terms, isolated single trunk trees operate in a manner similar to bridge piers.
- Unfortunately, the same scour protection measures used on bridge piers cannot be applied to trees because of the potential damage to the underlying root system.

Scour pattern

Scour holes

- Scour holes can be formed on each side of the tree.

Alternative scour pattern

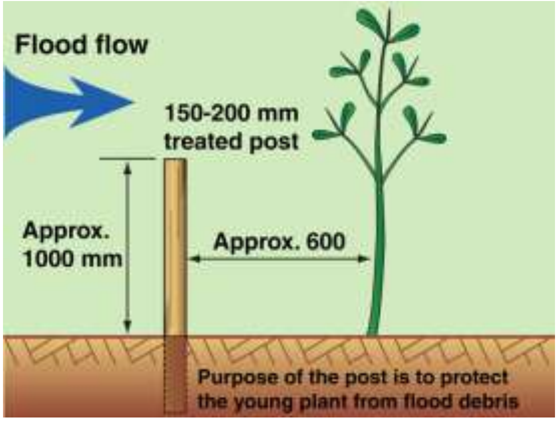
Alternative scour hole

- Alternatively, a single scour hole can form immediately downstream of the tree, which can aid in the tree collapsing under the force of the flow.

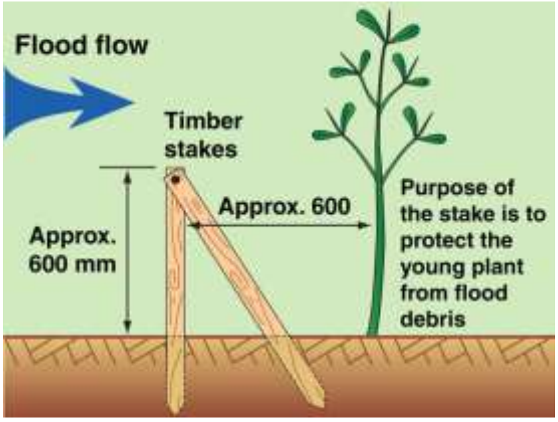
Planting in areas of high flow velocity

Riparian floodways

Flood damage to a sapling



Protecting plants from flood debris



Protecting plants from flood debris

Terminology

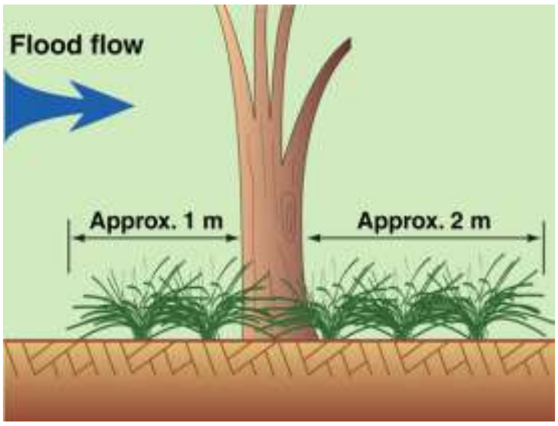
- A floodplain is any area that experiences flood inundation as a direct result of creek or river flooding.
- A floodway is that part of a floodplain where the floodwaters have an obvious forward velocity (i.e. not part of an area of land or water known as a 'backwater').
- A riparian floodway is a section of the riparian zone where floodwaters either pass across the waterway, or pass between the waterway and the floodway.

Difficulties of planting in floodways

- Newly established vegetation can be damaged by flood events in three ways:
  – plants are pushed over by high velocity flows
  – plants are pushed over as a result of flood debris (typically organic matter) wrapping around the plant
  – turbulence around the base of the plant causes a localised loss of soil (a scour hole).

Planting in floodways

- Saplings can be protected from high velocity floodwater by:
  – staking the plant
  – forming a triangular flow screen
  – adopting long-stem planting.
- Saplings can be protected from flood debris by placing a debris trap (post) upstream of the plant.
- Isolated trees can be protected from soil scour around their base by planting stiff grasses (e.g. *Lomandra*) around the tree.



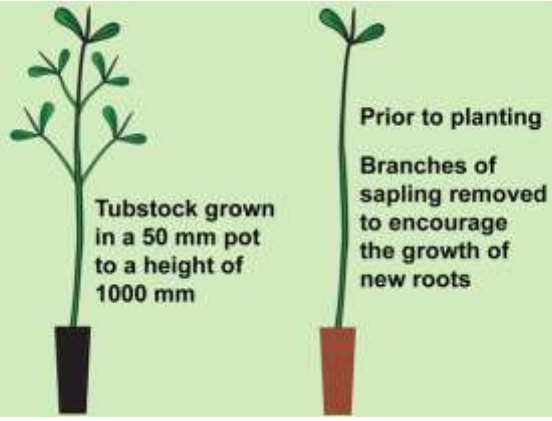
Protection of isolated trees in floodways

Planting within a floodway – Long stem planting

Exposure of roots by severe bank erosion

Introduction

- Depending on the plant species and the environmental conditions:
  - an exposed root system may begin to function as part of the tree's trunk system, and
  - a buried section of a sapling's stem may transform into part of the plant's root system (adventitious roots).
- Long stem saplings make use of the latter condition, but only for selected species in appropriate situations.



Establishment of long stem saplings

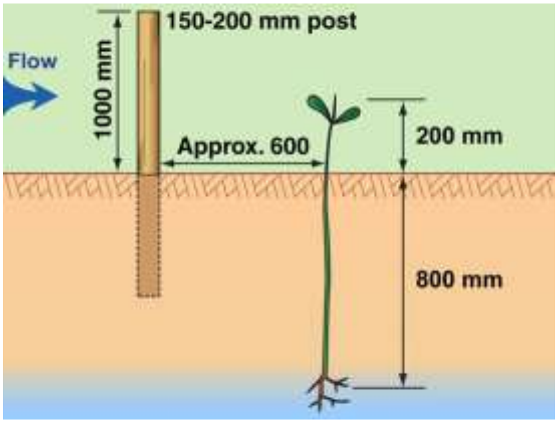
Initial growth stage

- The benefit of long stem planting is the enhanced anchorage of the sapling, which reduces the risk of the young plant being washed from the soil during a flood.
- In order to achieve this enhanced anchorage, the sapling must be planted deep into the soil, which means suitable tubestock need to be prepared:
  - grown in 50 mm pots
  - grown to a height of 1 metre.

Pre-planting preparation

Preparation prior to planting

- Branches of the sapling are removed to encourage the growth of roots.



Planting of long stem plant

Planting of long stem saplings

- Holes dug to a depth of 800 mm.
- Fertiliser pellet placed at the rootball.
- Placing the rootball deep in the soil allows these roots to be beyond the competition zone of other plants (weeds), and closer to a source of water.
- A stake/post can be placed upstream of the sapling to protect the plant from flood debris (in addition to staking the plant).

The hydraulic properties of stiff grasses

Grasses flattened by floodwater (Qld)

Mat-forming grasses

- Domestic, mat-forming grasses are likely to fold flat when subjected to significant surface flows (thus forming a 'mat').
- These plants act as a 'community' and in doing so can help to control soil scour.

***Lomandra* in deep water (Qld)**

Stiff grasses in <u>deep water</u>

- When subjected to deep water flows, many stiff grasses begin to act as community plants, helping to:
  - control soil scour
  - reduce flow velocities
  - help build a thick boundary layer of low-velocity water adjacent the creek's bed and banks.

***Lomandra* (Qld)**

Stiff grasses in <u>shallow water</u>

- When subjected to shallow water flows, stiff grasses begin to act as individual plants, which are likely to deflect flows rather than slow these flows.
- In general, stiff grasses should <u>not</u> be used on:
  - dam and basin spillways
  - narrow, high-velocity floodways
  - stormwater batter chutes.
- However, exceptions do exist if the hydraulic effects are fully understood.

Mass planting of *Lomandra* (Qld)

Stiff grasses used as a monoculture

- A mass planting of stiff grasses can be an effective way of dealing with very high flow velocities; however, ecological values can be diminished by such landscaping.
- The mass planting of stiff grasses can be useful in the following circumstances:
  - high-velocity channels
  - lower bank region on the outside of a channel bend
  - around the base of 'objects' located in floodways, such as isolated floodplain trees.

Use of vetiver grass in creek and gully engineering

Vetiver grass (full growth)

Introduction

- *Chrysopogon zizanioides* is commonly known as 'vetiver grass'.
- Vetiver grass grows in tall clumps, with tall, thin, and rather rigid leaves growing to a height of 2–3 metres, and a root system that grows to a depth of 2–4 metres.
- The plant can survive deep water flow conditions and temporary submergence.
- The most commonly used commercial genotypes of vetiver are sterile, meaning the plant can be propagated only by breaking the clumps.

Flow diversion barrier (Qld)

Use of vetiver grass as a flow diversion system

- Vetiver grass is one of a few grass-like plants that can be used to form a vegetative flow diversion barrier.
- Other species could include *Callide Rhodes*, *Katambara Rhodes* or *Molasses* can also be used; however, suitability and weed-potential of each species must be checked on a case-by-case basis.

Recent planting on a sandy soil bank

Use of vetiver grass in the stabilisation of sandy soils

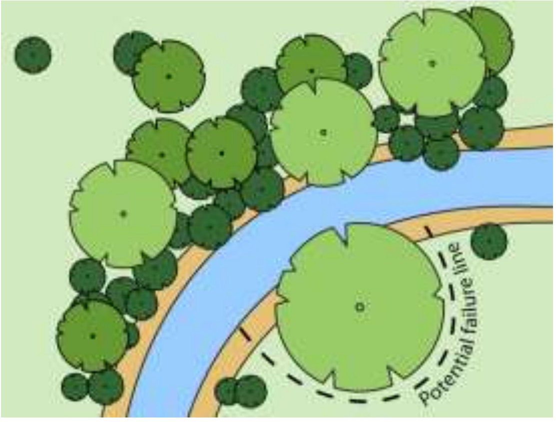
- The very deep, fibrous root system of vetiver grass means this plant can be used to stabilise sandy soils that are subjected to deep water flow conditions.
- Vetiver grass is not suitable for shallow water flow conditions, such as those found along overland flow paths, or down dam spillways (by-wash).

Gully stabilisation with vetiver grass (Qld)

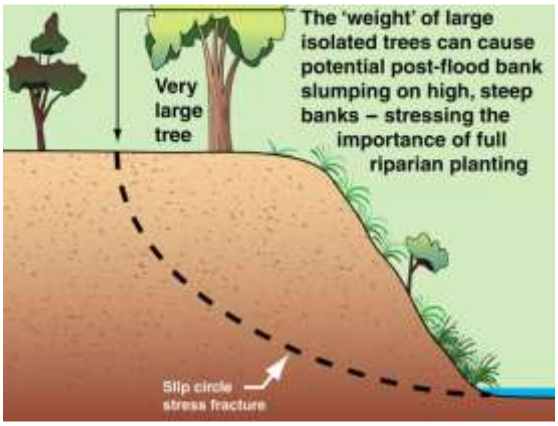
Use of vetiver grass in the stabilisation of gully erosion

- Vetiver grass has been used in the stabilisation of gullies that have formed within a slaking soil.
- Slaking soils are often very sandy, with minimal clay binder.
- Vetiver grass can be used as:
  - vegetative sediment traps spaced at regular intervals along the gully floor
  - revegetation of the gully banks.

Planting large trees on steep banks

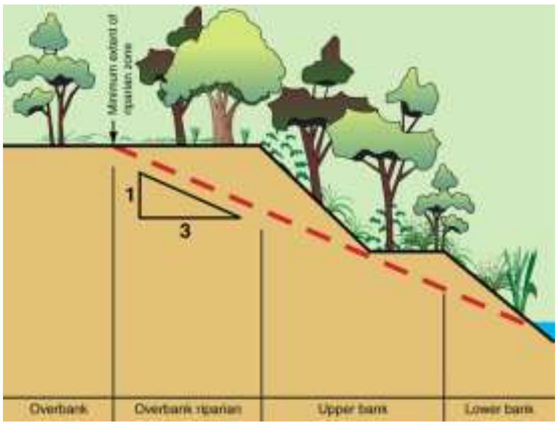


Isolated tree



Slip circle bank failure

Brisbane River, 2011



Minimum riparian width for bank stability

Introduction

- Trees and shrubs provide the anchoring system for earth banks through their root systems.
- In their natural environment, these plants typically exist in 'communities', which are termed 'riparian' when such plant communities have a direct link to the waterway.
- However, in some cases, large riverbank trees can find themselves isolated from their normal plant communities, and instead become surrounded by only ground covers, such as grasses.
- If these isolated trees are very large, and therefore very heavy, then they can pose a risk of causing post-flood bank slumping if they are located near the edge of a steep, high, river bank.
- The risk of such post-flood slumping is increased if the river is located downstream of a gated dam that is able to accelerate the falling period of a flood event by quickly raising its spillway gates.

The added effects of strong winds

- The risk of isolated riverbank trees falling increases if such trees are subjected to strong winds.
- Such flood-induced bank slumping is expected to have occurred at several locations along the Lockyer Creek, and Brisbane and Bremer rivers in 2011.

The risk of such bank slumping is low, and should not dominate the design of riparian zones, but instead should be just one of many issues that need appropriate consideration.

Reducing the risk of bank slumping

- The risk of such bank slumping can be reduced by:
  - benching steep and/or high banks
  - planting middle storey trees around isolated trees
  - restoring riparian areas to their natural condition.
- A geotechnical investigation into the river bank can determine if a risk of bank slumping exists.

Planting on steep banks – jute bagging

Jute bagging (Qld)

Jute bagging

- In the planting technique known as 'jute bagging', small 'bags' are made from thick jute blankets.
- These jute bags are then filled with soil and a single seedling, then pinned to the exposed creek bank.

Weed removal (2005)

Site preparation

- The creek bank should first be cleared of weeds and their roots (as appropriate).
- Unlike for the placement of an erosion control blanket, the bank does not need to be cleared of surface irregularities.
- However, if the bank is likely to be subjected to strong sunlight that is likely to cause excessive drying of the soil, then the bank could be covered with a light mulch, which could be anchored with a well-anchored jute mesh—this may require some further bank preparation.

Planting procedure (2005)

Planting

- The jute bags are then filled with soil and a single seedling, then pinned to the bank.
- The underside of the jute back must have good contact with the bank to allow plant roots to extend (grow) from the jute bag into the bank.
- This technique allows plants to be established on steep earth banks that are likely to be subject to occasional stream flows.

Fully established creek bank (2010)

Long-term outcomes

- As is the case on most creek sites, the long-term outcomes depend on:
  - site preparation
  - plant selection
  - initial plant watering and maintenance
  - weed control
  - 'luck' (in regards to flood damage).
- Stormwater runoff must be able to infiltrate the soil within the immediate overbank area (i.e. no impervious surfaces immediately adjacent to the creek bank).

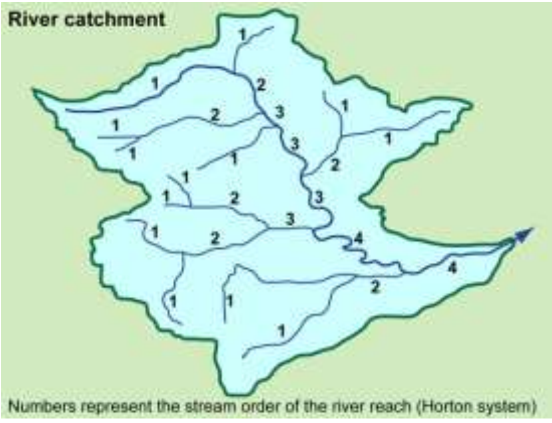
8. Hydraulics of Natural Waterways

River systems

Bluff River (NSW)

Waterway classification

- Classifying waterways as either creeks or rivers is not always useful because these terms do not necessarily relate to waterway features that are uniformly recognised across all regions.
- What may be referred to as a river in southern Australia, may be considered a creek in northern parts of the country.
- Also, the uppermost reaches of most rivers may behave like a 'creek', but the local sign-post will (correctly) title it a river.



Example of the Horton stream order

Stream order

- Stream order is a system for ranking the individual reaches of a waterway.
- There are a number of ranking systems.
- In the Horton system a first-order stream has no contributing branches based on a specified mapping scale (the choice of map scale is critical).
- A second-order stream has at least two contributing first-order branches.
- A third-order stream has at least two contributing second-order branches, etc.

Riffle system on the Nive River (Tas)

Typical features of a river

- Rivers typically exhibit the following characteristics (but not always):
  - a near constant flow (generally these are not ephemeral waterways)
  - significant quantities of mobile bed sediment (known as the bed load)
  - wide pools and riffles that extend across the full width of the bed
  - a significant change in vegetation type from the bed to the banks (bed vegetation may consist only of aquatic plants).

Rock stabilisation of a river bank (NSW)

Controlling bank erosion in rivers

- It can be very difficult to control bank erosion within rivers on a long-term basis, other than through expensive, hard-engineering measures.
- Typically the focus is on controlling the types of bank erosion issues that arise in the periods between major floods.
- It is important to remember that the occurrence of bank erosion is not necessarily a sign that someone has done something wrong, and it is not necessarily a bad thing for the river.

River morphology

Meandering river channel (Qld)

Introduction

- There are numerous features common to both creeks and rivers, but there are also key differences.
- The science of river morphology generally involves the study of long-term geological processes, which typically occur over hundreds or thousands of years.
- Key topics in river studies often centre around sediment transport and channel mobility, while creek studies are more likely to focus on bed and bank stability.

Sediment flow along a riverbed (NSW)

Sediment flow

- Most river systems have a significant degree of loose bed sediment that slowly migrates down the waterway.
- The quantity of sediment flow (bed load) typically increases with the size of the catchment, thus small waterways often have minimal sediment flow.
- Due to the high sediment flow experienced in most rivers, slow-growing, woody plant species can find it difficult to establish across a riverbed.

Pool/riffle in the Queanbeyan River (NSW)

Pools, riffles and low-flow channels

- In rivers, pools and riffles typically extend across the full width of the channel bed.
- Deep pools most commonly exist at channel bends.
- Riffles are commonly located near the mid-point between channel bends.
- The rocks that make up the riffles constantly migrate down the river; however, the riffle itself often stays in the same location, with any displaced rocks being replaced by new rocks migrating down the river.

An artist impression of channel relocation

Impact of vegetation on channel stability

- Vegetation is always important for short-term *bank stability*, but possibly not for long-term *channel stability*.
- If a flood wants to cause a river to relocate or change its meander pattern, then it is unlikely that any existing vegetation will prevent this from occurring.
- Vegetation performs many important roles in river morphology, but rarely is it stronger than the destructive power of a major flood.

How <u>creek</u> morphology differs from river morphology

Urban clay-based creek (Qld)

Creek morphology

- In essence, the science of creek engineering is the same as river morphology—the differences lie in the relative importance of key features, such as vegetation.
- Creek engineering is most commonly focused on short-term processes, such as the impacts of urbanisation, bushfires and regular floods, because these are the factors likely to be of prime interest to the local community.

Unnatural sediment in an urban creek

Sediment flow

- Relative to rivers, most creeks experience minimal <u>natural</u> sediment flow, especially clay-based creeks.
- In the absence of significant sediment flow, slow-growing woody vegetation can establish close to, or even on, the channel bed.
- In many urban creeks, most of the bed sediment is likely to have resulted from unnatural processes, such as urban runoff.

Creek with a narrow low-flow channel

Pools, riffles and low-flow channels

- Not all creeks have pools and riffles—these features appear mostly in sand and gravel-based waterways.
- If pools and riffles do exist, then they are often contained within a narrow low-flow channel that behaves like a small channel existing within the wider main channel.
- In creeks, pools and riffles can be found anywhere along the channel, not just at channel bends and inflection points.

Restored urban creek (Qld)

Impact of vegetation on channel stability

- One of the main differences between creeks and rivers is the relative importance of vegetation with respect to providing channel stability during floods.
- In creeks, the type of vegetation, its health and density, can be the dominant factor in determining the size of the channel.
- If you change the vegetation, for example by suddenly removing all weeds, you can cause significant changes to the channel's size, meander pattern, or location—in creeks, plants rule!

Classification of creeks based on the dominant bed material

Clay-based waterway (Qld)

Clay-based waterways

- The bed and banks of clay-based waterways are primarily formed from clayey soils.
- These are 'fixed bed' waterways that typically have minimal natural sediment flow or bed movement—this allows mature woody vegetation to establish close to, or even on, the channel bed.
- Typically these waterways have a U-shaped or V-shaped channel profile (i.e. not a wide, flat channel bed).

Sand-based waterway (Qld)

Sand-based waterways

- Deep, loose sand dominates the make-up of the bed.
- The depth of the sand can exceed the depth of the root systems of much of the bed and bank vegetation.
- These are alluvial waterways that experience significant bed movement (sand flow) during both minor and major flood events.
- Bed vegetation (if any) typically consists of quick-response, short-lived, non-woody species.

Gravel-based waterway (NSW)

Gravel-based waterways

- Bed material is made-up mostly of well-rounded gravels, cobbles or boulders.
- These are alluvial waterways that often feature pools and riffles, which can completely reform during severe floods.
- The movement of the bed material during major floods means the channel bed is usually flat (similar to sand-based rivers).
- Woody vegetation can struggle to form on the channel bed if the bed movement is significant—which may not be the case in the upper reaches of the waterway.

Rock-based waterway (Tas)

Rock-based waterways

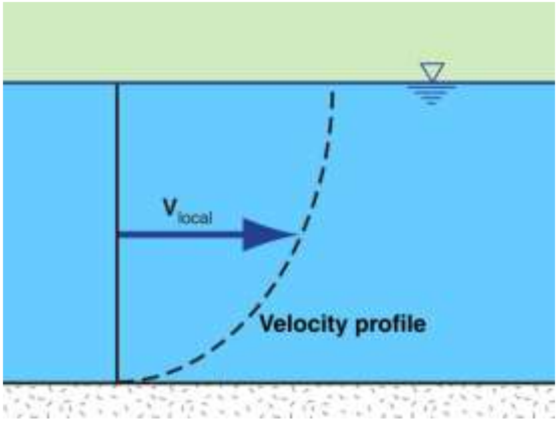
- The bed material of rock-based waterways is made-up of exposed rock outcrops, often separated by sections of clay, sand or gravel-based channels.
- These are fixed-bed, 'spilling' waterways usually containing waterfalls or riffles followed by deep pools within which energy dissipation occurs.
- These waterways are sometimes referred to as 'rocky-spilling' or 'steep pool-fall' waterways.

Defining flow velocity

High-velocity stream flow (Qld)

Flow velocity

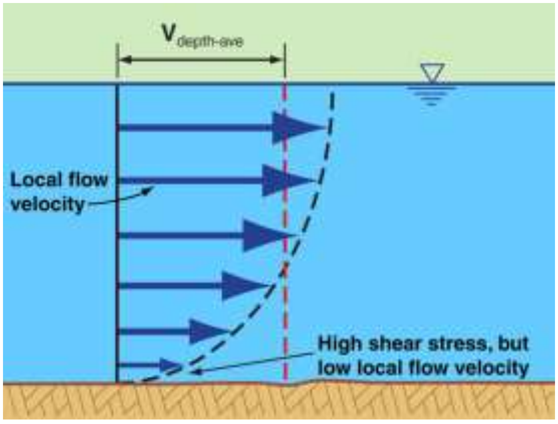
- There are several different ways to measure flow velocity, including:
  - local flow velocity (measured at a point)
  - depth-average velocity
  - average velocity (full cross-section)
  - critical velocity (special flow condition)
- Flow velocities can vary significantly across the depth and width of a stream, consequently the ‘average flow velocity’ is often much less than the maximum flow velocity within a waterway.



Local flow velocity

Local flow velocity

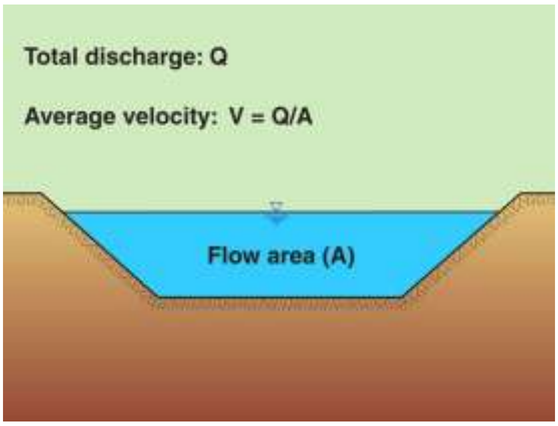
- The local flow velocity is the flow velocity at a specific point within a cross-section.
- The local flow velocity is the velocity of most importance to fish because it is this velocity that they confront when swimming upstream.
- In creek engineering, the local flow velocity is rarely used because it is so hard to calculate mathematically, even though it is relatively easy to measure in a creek.



Depth average flow velocity

Depth-average flow velocity

- The depth-average velocity is the average of the local flow velocities measured down through a vertical plain.
- The depth-average velocity typically varies across the width of a channel.
- This flow velocity is used by creek engineers in the design of some scour protection measures, such as rock.
- It is noted that some engineers refer to the depth-average velocity as the ‘local velocity’ (which can cause confusion).



Cross-sectional flow parameters

Average flow velocity

- The average flow velocity is defined as the total discharge (Q) divided by the total flow area (A).

$$V = Q/A \quad [m/s]$$

- In complex cross-sections there may be areas of zero flow due to flow isolation; in such cases these areas may be excluded from the total flow area.
- The symbol for velocity is normally a lower case ‘v’, but an upper case ‘V’ is often used in publications to highlight its importance.

Allowable flow velocity

Soil scour (Qld)

Constructed rock riffle (Qld)

Vegetated channel (Qld)

Flood damage to a grass-lined channel

Introduction

- Research into creek erosion has naturally focused on determining the flow velocity that is likely to initiate soil erosion, or cause flood damage to a waterway.
- However, when designing erosion control measures our focus is not on designing these control measures so that they operate close to the point of failure, but to adopt a conservative design approach.
- Two design approaches can be used:
  - use of safety factors
  - use of an allowable flow velocity.

The use of safety factors

- Some design procedures, or design equations, incorporate a *safety factor* (SF), which either:
  - increases the forces acting on the creek, or
  - increases the dimensions or strength of the scour control measures.
- Many of the equations used to size rock incorporate a safety factor, which changes depending on where the rock is placed within a creek.

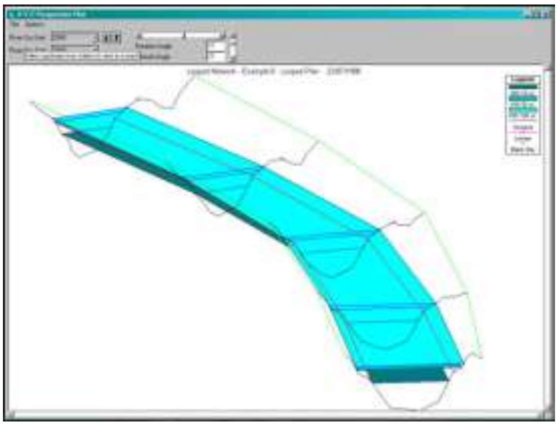
Allowable flow velocity

- An alternative design procedure is to size the erosion control measures based on an *allowable flow velocity* that is less than the critical (failure) velocity.
- An allowable flow velocity is typically used when designing vegetated channels.
- An allowable flow velocity is also used in the design of open soil drains (such as drains on farmland), or in the design of grass-lined drains.

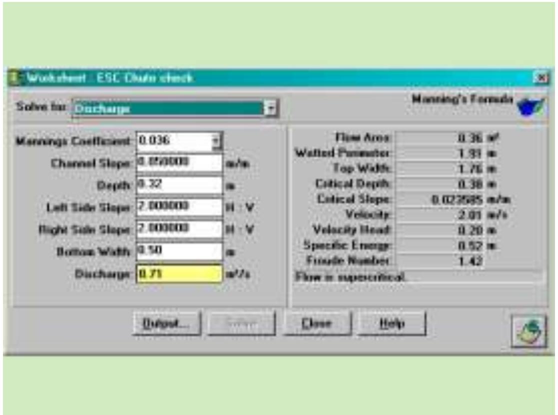
The allowable flow velocity for vegetated waterways

- Nominating an allowable flow velocity for vegetated waterways is complicated by the fact that:
  - the flow velocity that causes damage to the vegetation typically varies with the duration of the flow
  - the critical (failure) velocity varies as the flow depth varies.
- The allowable flow velocity for grass-lined channels depends on the flow duration.

Calculating the flow velocity

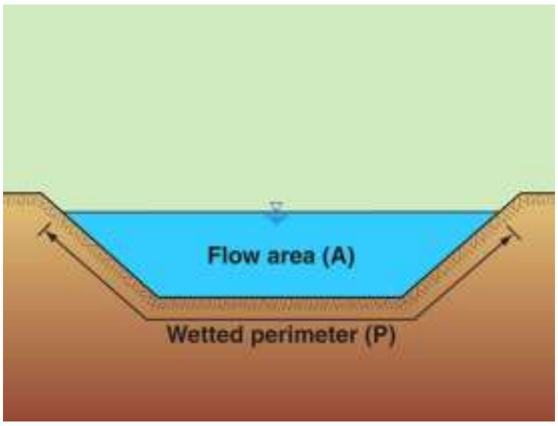


Numerical analysis (HecRas)



Spread sheet model (Flow Master)

Rainwater tank in a flooded river (Qld)



Channel cross-section

Numerical models

- On important projects it will be necessary to determine flow velocities through appropriate hydraulic analysis.
- There are various forms of numerical models that can be used to determine the average flow velocity within a channel.
- For very simple channels that have a near-uniform cross-section, a spread sheet analysis can be used (see below).

Manning's equation

The average flow velocity may be estimated using Manning's equation:

$$V = (1/n)\ R^{2/3}\ .\ S^{1/2}$$

where:

V = average flow velocity (m/s)

n = Manning's roughness coefficient

R = hydraulic radius (m) = A/P

A = cross-sectional flow area (m^2)

P = wetted perimeter of flow (m)

S = channel slope (m/m)

On-site flow monitoring

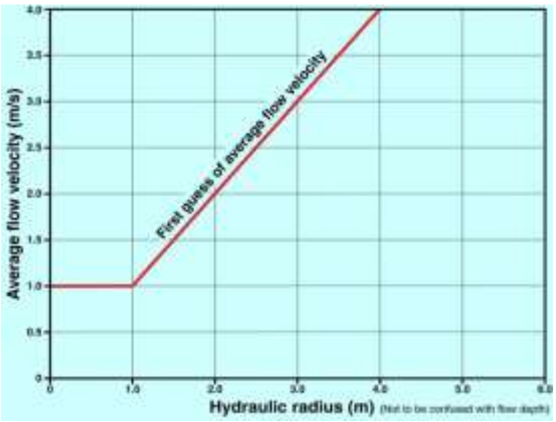
- If the waterway is flowing during the site visit, then an approximate flow velocity can be obtained by timing the movement of floating debris over a travel distance measured out along the edge of the channel.
- This is a very crude method for estimating flow velocity.

Estimating flow velocity based on the channel's hydraulic radius

- On low-risk projects it may be acceptable to determine just an estimate of the flow velocity.
- The charts presented on the following page can be used to determine a 'first guess' of the flow velocity based on the bankfull hydraulic radius (R) of the channel.

$$R = A/P$$

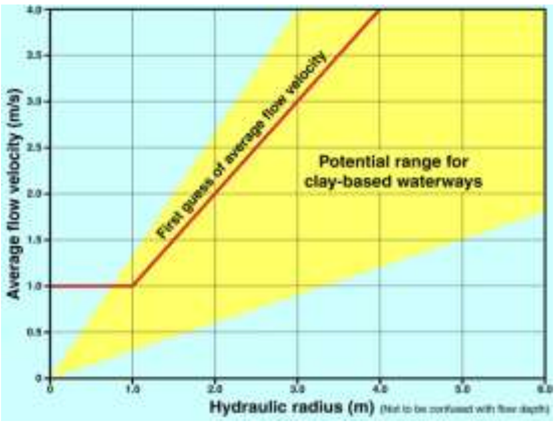
Estimating the average flow velocity



'First guess' flow velocity

Estimating the average flow velocity

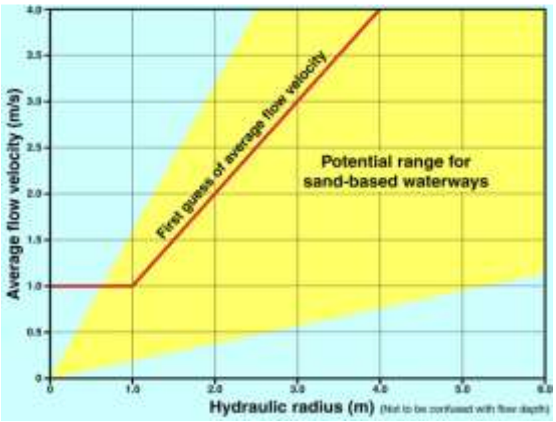
- If it is not feasible to use hydraulic analysis to determine a flow velocity, then as a first guess:
  - assume the average velocity (m/s) is equal to the hydraulic radius (m), but
  - do not choose a velocity < 1 m/s
- For design purposes, the flow velocity is typically based on bankfull flow conditions, but in some cases a lower water level is chosen, for example, in a deep gully.



Clay-based waterways

Clay-based waterways

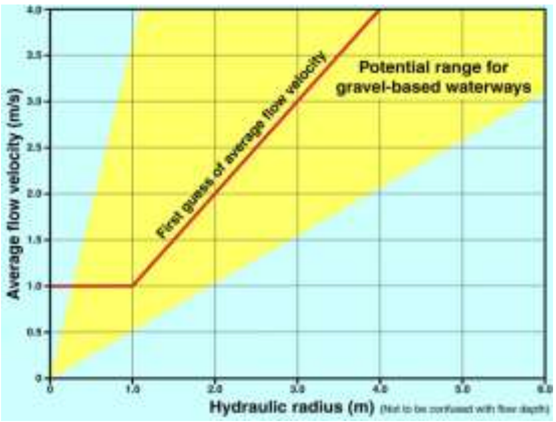
- The same 'first guess' line is used for all types of waterways.
- This means the first guess line is:
  - conservative for both clay-based and sand-based creeks; but is
  - representative of 'mean' values for gravel-based creeks.
- The 'yellow' highlight shows the typical range of values for clay-based waterways as determined from an analysis of New Zealand waterways.



Sand-based waterways

Sand-based waterways

- The 'yellow' highlight shows the typical range of values for sand-based waterways as determined from an analysis of New Zealand waterways.
- In many cases, loose sand can be more mobile than a cohesive clay soil, so the average flow velocity in a sand-based waterway can potentially be lower than in a clay-based waterway (but not always).



Gravel-based waterways

Gravel-based waterways

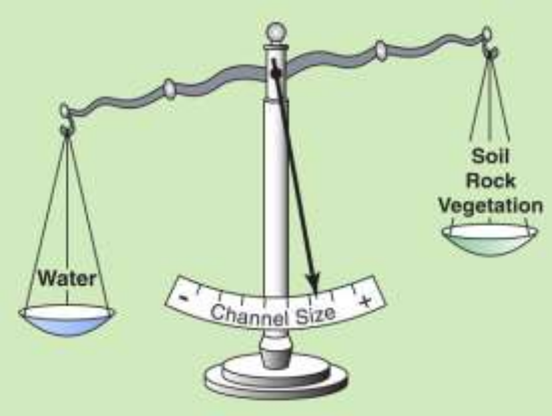
- Flow velocities in gravel-based waterways can be significantly higher than in sand or clay-based waterways.
- For experienced professionals, an estimate of the flow velocity can be determined by calculating the flow velocity that would move the largest bed rock.
- This means determining the threshold (critical) flow velocity:

$$V_{max} = (1/n).(d_{90}/1000/g)^{1/2}.D^{1/6}$$

where: 'd_{90}' = largest rounded bed rock (mm)

Actions followed by reactions

Brisbane River & Norman Creek in flood



A balancing act of opposing forces

Early stages of a meander being formed

Chess game

Introduction

- Most of the physical changes that occur within a waterway happen as a result of *pulsing* and *cyclic* actions.
- Floods can initiate a series of events to occur within a waterway (the action).
- But floods are infrequent (the pulse), which means there is time for the waterway to repair itself and thus resist future flood damage.
- In the periods between floods, the waterway will commence a rebuilding phase (the reaction).

Cyclic actions of expansion & contraction

- Floods regularly cause erosion within waterways:
  - which causes channels to expand
  - which causes flow velocities to reduce
  - which causes an increase in sedimentation
  - which causes channels to reduce in width or depth
  - which causes flow velocities to increase
  - which causes channels to expand (and the cycle repeats).

Waterways twist and turn

- In general, waterways do not like to exist as straight channels.
- At some point, sediment will deposit on one side of the channel:
  - which causes flows to move closer to the opposite bank
  - which causes an increase in erosion along that bank
  - which causes the channel flow to sightly change direction
  - which causes further bank erosion, etc.

For every ***action*** there is a ***reaction***

- The key to working with waterways is to be able to anticipate how a creek or river will respond to your actions, or to a recent flood event.
- It is like playing a game of chess with nature, you make your move only after you have considered the creeks next move, and if you are good, you will be planning several possible future moves.
- The real experts in creek erosion are those that can accurately predict the long-term consequences of creek works.

The importance of bankfull discharge

River flooding

Sediment transported by a flood (Qld)

Bankfull flow (Qld)

Urban waterway (NSW)

Introduction

- It should be obvious to most people that there is likely to be a mathematical relationship between the size of a waterway and the discharge passing down that reach of the waterway.
- The question is: which flow rate is the dominant discharge?
- Is it the:
  - 1-in-100 year discharge
  - most frequent discharge, or
  - bankfull discharge?

The dominant discharge

- It is only through the detailed comparison of many waterways, i.e. the science of river morphology, that an answer can be found to the above question.
- In large, alluvial rivers, the dominant discharge is claimed to be the flow that yields the *maximum sediment transport*.
- However for most waterways, the discharge that is likely to strongly influence the *size of the channel* is the bankfull discharge.

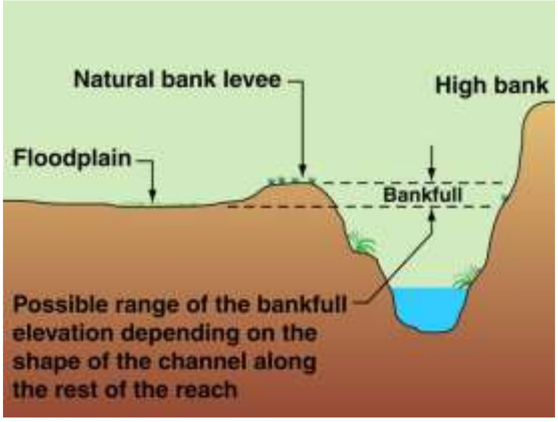
Treating the bankfull discharge as the dominant discharge

- Several studies have suggested that the bankfull discharge is the flow that yields the maximum sediment transport.
- However, in creek engineering, sediment transport may not be the primary concern, and in many clay-based waterways there may be minimal sediment transport.
- In such cases the focus returns to the flow condition that most strongly influences the size of the channel, which is likely to be the bankfull discharge.

The most frequent discharge

- Several publication focus on the importance of the *most frequent event* as being the dominant discharge.
- In heavily wooded, natural catchments, stream flows may not be affected by minor storms because all of the rainfall is captured by the vegetation and soil.
- This means the most frequent event is likely to be around the 1-in-1 year to the 1-in-2 year flow.
- However this does not apply to most urban catchments.

Bankfull discharge



Elevation of bankfull flow

Bankfull flow conditions (Qld)

Flow conditions just below the bridge deck

Backwater effects of a culvert crossing

Defining bankfull flow conditions

- Often the top of the left and right banks of a waterway are at different elevations, so the bankfull condition is usually defined by the lowest bank that allows water to spill onto an adjacent floodplain.
- If the elevation of the bank varies significantly along a given reach of a waterway, then the bankfull flow condition is defined by the lowest bank height (within that reach) that allows water to spill onto the adjacent floodplain.

Why bankfull flow is so important

- In the previous discussion about *shear stress* it was noted that the scour velocity increases with increasing flow depth.
- This means that higher than normal velocities can exist during bankfull flow before soil erosion begins to occur.
- So why does bankfull flow represent the flow condition of greatest shear stress?
- The answer is all in the mathematics of water flow.
- We know from the Manning's equation that the average velocity in a channel is proportional to the water depth (D) to the power of two-thirds:

$$V = (1/n)\ D^{2/3}\ S^{1/2}$$

- We also known from our discussion about shear stress that the <u>critical</u> depth-average flow velocity is proportional to the water depth to the power of one-sixth.

$$V_c = (1/n).(\text{critical shear}/1000.g)^{1/2}.D^{1/6}$$

- Which means that even though the threshold velocity (V_c) increases with flow depth, the <u>actual</u> velocity (V) increases at a greater rate, meaning erosion is more likely to occur during bankfull flows.

The frequency of bankfull flows

- It is often claimed that bankfull flows occur at a frequency of one to two years.
- Some studies have shown that the frequency of bankfull flows varies according to the type of waterway.
- Many incised urban creeks have a bankfull flow capacity close to the 10 year flow.
- Also, in urban waterways the bankfull flow may be affected by the afflux from downstream bridges, which can alter the frequency and erosive power of these events.

The importance of rare floods

Colorado River (USA)

Flood gauge, Rockhampton (Qld)

Flood stage, Louisville, Kentucky (USA)

Extensive channel erosion, Buaraba Ck

Introduction

- Few people would suggest that the Grand Canyon and the greater Colorado River valley were shaped by the bankfull flow.
- There is the strongly held position that many waterways experience continuous minor changes over decades, or centuries, interlaced with dramatic changes that occur on rare occasions.
- Look for the largest rounded boulder in a valley, and ask yourself what flood event would it take to cause such a boulder to move.

What is classified as a rare flood

- What defines a rare flood depends on the purpose of your study.
- With respect to the possible occurrence of major changes to the plan-form of a waterway, a rare flood may be defined as a flood with a return period greater than 1-in-200 years.
- The following is a generalisation:

  (i) 1-in-1 yr to 1-in-10 yr; minor floods

  (ii) 1-in-10 yr to 1-in-200 yr; major floods

  (iii) > 1-in-200 year; rare floods.

Reasons why rare floods are so important

- One of the problems with using stream power or bankfull discharge as the key channel-forming parameters is that neither of these terms incorporates 'duration'.
- Discharge (m^3/s) times duration (seconds) gives you units of volume (m^3), and the volume of water within a given flood can influence the volume of sediment transported by the flood, as well as the degree of erosion.
- Rare floods not only have high discharges, they usually have very large volumes.

The potential impact of rare floods on gravel, cobble and boulder-based channels

- Some cobble and boulder-based waterways can have relatively stable beds that experience very little disturbance during most flood events.
- However, these waterways can be 'sleeping giants' that can be awaken by extreme floods, which can commence movement of the cobbles causing extensive damage to both the channel and any adjacent engineering structures.

The hydraulic roughness of vegetation

Grasses flattened by floodwater (Qld)

Flood damage to shrubs (Qld)

Flood damage to recently planted trees

Post bushfire riparian vegetation (Qld)

Introduction

- It has long been understood that the Manning's roughness of some surfaces varies with flow depth, i.e. Manning's roughness is not a constant.
- However, what is possibly less well appreciated is that the hydraulic roughness of vegetation can vary not only with flow depth, but also over time during a flood.
- This means that channel roughness can be different during the 'rising' and 'falling' limbs of a flood.

Variations in roughness with flow depth

- As the flow depth increases, the hydraulic drag force on the plant increases, which causes the plant to bend with the flow.
- Ultimately the plant will either:
  - bend until the point of breaking
  - fold flat over the ground
  - fold flat to form a hydraulically-smooth 'mat' (typical for grasses).
- For grasses, this change in roughness also depends on the height of the grass prior to the flood.

Variations in roughness over time

- During the initial stages of a flood (i.e. the rising limb of the flood hydrograph), most of the vegetation will remain near vertical resulting in high channel roughness.
- At various stages during a flood different plants will either fold flat, or break, resulting in a significant reduction in the hydraulic roughness of the channel.
- During the falling limb of a flood, much of the vegetation will remain bent, or laying flat over the ground, resulting in continued low roughness values.

Variations in roughness with seasons

- In some regions, the density, and therefore the hydraulic roughness of vegetation, can vary from season to season.
- This means the peak flow velocities during a winter flood can be different from those experienced during a summer flood.
- In addition, the hydraulic roughness of riparian vegetation can significantly reduce for several years following a major bushfire.

The domino effect

Flow just submerging a Lomandra plant

Introduction

- Even while plants are bending with the flow, they can still provide significant flow resistance.

Flood damage to Lockyer Creek, 2011

The domino effect

- However, once the plants break, or fold flat over the soil, their hydraulic roughness can suddenly reduce.
- This sudden reduction in channel roughness can result in a rush of floodwater that damages both upstream and downstream plants.
- Under certain conditions, in-bank plants can fold flat like dominos.

Vegetation damage, Brisbane River, 2011

Flash floods

- It seems that almost every flood these days is called a *flash flood*.
- But a flood that has a very 'aggressive' rising limb (i.e. a flood that has a sudden and rapid rise in water levels), can result from the following circumstances:
  - a severe thunder storm over a small drainage catchment, or
  - a flood wave being formed during a flood as a result of a sudden mass failure of in-bank plants.

Vegetation damage, Lockyer Creek, 2011

A flood wave

- Flood waves are rare, but many residents have reported seeing a 'wall' of water passing down a flooded waterway.
- The hydraulic conditions that produce a flood wave are similar to the conditions that cause river bores—high velocity floodwater catching up with lower velocity floodwater further down the catchment, ultimately causing the formation of a wave-like flood event.

9. Properties of Rock

Introduction

Bank stabilisation with rock (Qld)

Introduction

- Rock is one of the most common materials used in the repair of creek.
- Rock is successful because it works well with the dynamics of most waterways.
- The purpose of this chapter is to present much of the design information on rock selection and placement, thus avoiding having to repeat the same information each time rock is discussed in the following chapters.

Round river rock (NSW)

Types of rock

- Common types of rock, including:
  - sandstone
  - granite
  - limestone
  - basalt
- The shape of the rock can either be:
  - 'round' typically originating from instream or floodplain extraction, or
  - 'angular' which is fractured quarry rock.

Sizing rock for use in straight channels

$$d_{50} = 40\ V^2$$

where:

d_{50} = mean rock size (mm)

V = average flow velocity (m/s)

Note: this equation gives d_{50} in millimetres

Specifying a required rock size

- The good thing about rock-sizing equations is that they can be programmed into design spreadsheets.
- The bad thing about rock-sizing equations is that they can present values to the nearest millimetre, which is simply unrealistic.
- There is little point in determining rock size to the nearest millimetre or centimetre given the natural variation in flow conditions.

Large fractured rock (Qld)

Quarry face or selected rock sizing

- Some quarries only sell a limited range of rock sizes, such as:
  - quarry face (or first blast), which often includes rock sizes from 300 mm to over 1000 mm
  - selected rocks larger than 1000 mm
  - rocks of around 600 mm
  - rocks of around 450 mm
  - graded rocks (50, 100, 200 & 300 mm) of a near uniform size that have passed through a sieving process.

Design parameters

Bank stabilisation (NSW)

Introduction

- The following pages present an overview of the various properties of rock, including:
  - equation safety factors
  - rock shape
  - method of placement
  - use of an underlying filter system
  - Manning's roughness
  - rock density
  - effective thickness of a rock layer.

Bank stabilisation (SA)

Safety factor (SF)

- For low risk sites, a safety factor of 1.2 is recommended.
- Examples of low-risk structures include:
  - most bank stabilisation measures
  - riffles and chutes in low-gradient creeks
- For high risk sites, a safety factor of 1.5 is recommended, for example:
  - bed stabilisation in steep creeks
  - areas of very high turbulence.

Fractured rock (Qld)

Effects of rock shape (K_1)

- Fractured rock is generally more stable than rounded rock.
- Most rock sizing equations, including those presented within this document, are based on the use of fractured (angular) rock.
- A correction factor (K_1 = 1.36) must be applied if rounded rock is used.
- This means rounded rock needs to be 36% larger than angular rock.

Individual placement of rocks (Qld)

Effects of rock placement on rock stability

- Rock-lined surfaces formed by the individual placement (stacking) of rocks are generally more stable than rock-lined surfaces produced by dumping the rock from a truck or bucket.
- Rocks dumped from a height, such as being dumped from a truck, will fall to a lower bank slope (angle of repose) than selectively placed rock.
- However, both methods of placement can fail if the foundations (toe) of the rock are disturbed.

Use of filter layers and filter cloth

Filter cloth (Qld)

Voids filled with soil prior to planting (Qld)

Rock filter layer (blue) under surface rock

Erosion under rocks on a dispersive soil

Conditions where filter cloth should be used

- Filter cloth is typically incorporated into the following structures:
  - some batter chutes
  - some drainage channels
  - non-vegetated bank stabilisation
  - energy dissipaters & outlet structures.
- The filter cloth must have sufficient strength (minimum 'bidim A24'), and must be suitably overlapped to withstand any disturbance during rock placement.

Conditions where filter cloth should not be used

- The 'old rule' was that rock must always be placed over a filter layer made up of either smaller rocks, or filter cloth.
- However, an underlying filter layer is usually not required **IF** the voids are filled with soil and pocket planted (which is the preferred outcome).
- Therefore, fully vegetated, rock-lined banks usually do not require filter cloth to be placed under the rock.

The use of aggregate filters

- An alternative to the use of filter cloth is the use of an aggregate.
- Two or more layers of aggregate may be required depending on the size of the primary armour rock.
- Recommended rock size grading is:

$$d_{15c}/d_{85f} < 5 < d_{15c}/d_{15f} < 40$$

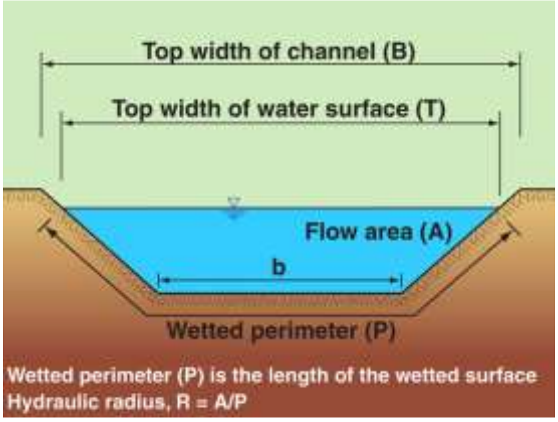
where:

- 'c' and 'f' refer to the coarse layer and fine rock underlay respectively.

Filter cloth cannot be placed directly on a dispersive soil

- Dispersive soils contain highly mobile clay particles.
- Clay particles are so small in size that they readily pass through **all** forms of construction-grade filter cloth.
- Dispersive soils **must** be sealed by a layer of non-dispersive soil prior to placement of a filter cloth, or aggregate filter layer.

Manning's roughness of rock



Channel geometry and flow conditions

Gravel-based alluvial waterway (Tas)

Deep water flow conditions (Qld)

Shallow water flow conditions (Qld)

Manning's equation

- The **average** channel flow velocity may be calculated using Manning's equation:

$$V = (1/n) \cdot R^{2/3} \cdot S^{1/2} \qquad (9.1)$$

where:

V = average flow velocity (m/s)
n = Manning's roughness coefficient
R = hydraulic radius (m) = A/P
A = effective flow area of channel (m^2)
P = wetted perimeter of flow (m)
S = channel slope (m/m)

Factors affecting the hydraulic roughness of rock-lined surfaces

- The Manning's roughness of rock-lined surfaces depends on:
  - the average rock size (d_{50})
  - the distribution of rock sizes, defined in this case by the ratio: d_{50}/d_{90}
  - the depth of water flow, usually defined by the hydraulic radius of flow (R)
  - the existence of vegetation
  - the occurrence of aerated water (e.g. whitewater flowing down rapids).

Manning's roughness in deep water

- The Strickler formula for deep water may be presented as:

$$n = ((d_{50})^{1/6})/21.1 \qquad (9.2)$$

- An alternative equation was developed by Meyer-Peter & Muller:

$$n = ((d_{90})^{1/6})/26.0 \qquad (9.3)$$

where:

– d_{50} = rock size for which 50% of rocks are smaller [m]

– d_{90} = rock size for which 90% of rocks are smaller [m]

Manning's roughness in shallow water

- The Manning's roughness (n) of rock-lined surfaces in both shallow water and deep water flow conditions is provided by:

$$n = \frac{d_{90}^{\;1/6}}{26(1 - 0.3593^{m})} \qquad (9.4)$$

  - $m = [(R/d_{90})(d_{50}/d_{90})]^{0.7}$
  - R = hydraulic radius of flow [m]

- The relative roughness (d_{50}/d_{90}) of rock extracted from streambeds is typically in the range 0.2 to 0.5; while quarried rock is commonly in the range 0.5 to 0.8.

Manning's roughness of rock

The Manning's (n) roughness for rock-lined surfaces can be determined from Table 9.1 or Equation 9.4.

Table 9.1 – Manning's (n) roughness of rock-lined surfaces

	d_{50}/d_{90} = 0.5				d_{50}/d_{90} = 0.8			
d_{50} =	200mm	300mm	400mm	500mm	200mm	300mm	400mm	500mm
R (m)	Manning's roughness (n)				Manning's roughness (n)			
0.2	0.10	0.14	0.17	0.21	0.06	0.08	0.09	0.11
0.3	0.08	0.11	0.14	0.16	0.05	0.06	0.08	0.09
0.4	0.07	0.09	0.12	0.14	0.04	0.05	0.07	0.08
0.5	0.06	0.08	0.10	0.12	0.04	0.05	0.06	0.07
0.6	0.06	0.08	0.09	0.11	0.04	0.05	0.05	0.06
0.8	0.05	0.07	0.08	0.09	0.04	0.04	0.05	0.06
1.0	0.04	0.06	0.07	0.08	0.03	0.04	0.05	0.05

Equation 9.4 is considered to produce significantly better estimates of the Manning's roughness of rock-lined surfaces in shallow water flow compared to the use of traditional deep water equations of Strickler, Meyer-Peter & Muller and Limerinos.

Given the high variability of Manning's n, and the wide range of variables that are believed to influence the hydraulic roughness of a rock-lined channel, Equation 9.4 is considered well within the limits of accuracy expected for Manning's n selection.

Data analysis during the development of Equation 9.4 indicated that the Meyer-Peter & Muller equation (Eqn 9.3) produced more reliable estimates of the deep water Manning's roughness values than the Strickler equation (Eqn 9.2). Possibly the choice between the two equations would come down to how reliable the determination of the d_{50} and d_{90} values are. If the estimate of d_{90} is not reliable, then it would be more appropriate to rely on the Strickler equation for the determination of the deep water Manning's n value, and vice versa.

Table 9.2 provides the range of data values used in the development of Equation 9.4. This table also contains the data range for the selected variables for which the calculated Manning's n value within +/-10% of the observed Manning's n.

Table 9.2 – Data range used in determination of Equation 9.4

	d_{50} (mm)	d_{90} (mm)	R/d_{50}	R/d_{90}	n_o/n	d_{50}/d_{90}
Min (+/-10%)	16	90	2.31	0.73	0.284	0.080
Max (+/-10%)	112	350	55.6	12.0	1.080	0.661
Min (All data)	16	90	1.17	0.31	0.097	0.080
Max (All data)	397	1080	66.9	12.9	1.120	0.661

Maximum bank gradient

The recommended maximum desirable side slope of a large rock-lined chute is 1:2 (V:H); however, side slopes as steep as 1:1.5 can be stable if the rock is individually placed rather than dumped. Typical angles of repose for dumped rock are provided in Table 9.3.

Table 9.3 – Typical angle of repose for dumped rock

Rock shape	Angle of repose (degrees)	
	Rock size > 100 mm	Rock size > 500 mm
Very angular rock	41°	42°
Slightly angular rock	40°	41°
Moderately rounded rock	39°	40°

Typical properties of rock

Crushed rock is generally more stable than natural rounded rock; however, rounded rock has a more 'natural' appearance. A 36% increase in rock size is recommended if rounded rock is used (i.e. K_1 = 1.36, which is a coefficient used in several rock-sizing equations).

The rock should be durable and resistant to weathering, and should be proportioned so that neither the breadth nor the thickness of a single rock is less than one-third of its length.

Maximum rock size generally should not exceed twice the nominal (d_{50}) rock size, but in some cases a maximum rock size of 1.5 times the average rock size may be specified.

Typical rock densities (s_r) are presented in Table 9.4.

Table 9.4 – Relative density (specific gravity) of rock

Rock type	Relative density (s_r)
Sandstone	2.1 to 2.4
Granite	2.5 to 3.1 (commonly 2.6)
Limestone	2.6
Basalt	2.7 to 3.2

Table 9.5 provides a suggested distribution of rock sizes for waterway chutes. The distribution of rock size can also be described by the coefficient of uniformity, $C_u = d_{60}/d_{10}$, which usually falls in the range 1.1 to 2.7, but typically around 2.1. Witter & Abt (1990) reported that poorly graded rock (C_u = 1.1) has a critical discharge 8% greater than well-graded rock (C_u = 2.2).

Table 9.5 – Typical distribution of rock size for fish friendly structures (guide only)

Rock size ratio	Assumed distribution value
d_{100}/d_{50}	2.0
d_{90}/d_{50}	1.8
d_{75}/d_{50}	1.5
d_{65}/d_{50}	1.3
d_{40}/d_{50}	0.65
d_{33}/d_{50}	0.50
d_{10}/d_{50}	0.20

Effective thickness of a rock layer

The thickness of the armour layer should be sufficient to allow at least two overlapping layers of the nominal rock size. The thickness of rock protection must also be sufficient to accommodate the largest rock size. It is noted that increasing the thickness of the rock placement will **not** compensate for the use of undersized rock.

In order to allow at least two layers of rock, the minimum thickness of rock protection (T) can be approximated by the values presented in Table 9.6.

Table 9.6 – Minimum thickness (T) of two layers of rock

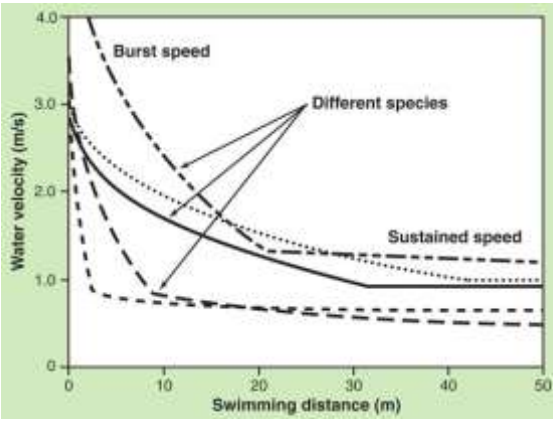
Min. thickness (T)	Size distribution (d_{50}/d_{90})	Description
1.4 d_{50}	1.0	Highly uniform rock size
1.6 d_{50}	0.8	Typical upper limit of quarry rock
1.8 d_{50}	0.67	Recommended lower limit of distribution
2.1 d_{50}	0.5	Typical lower limit of quarry rock

10. Design of Fish-Friendly Bed Stabilisation Structures

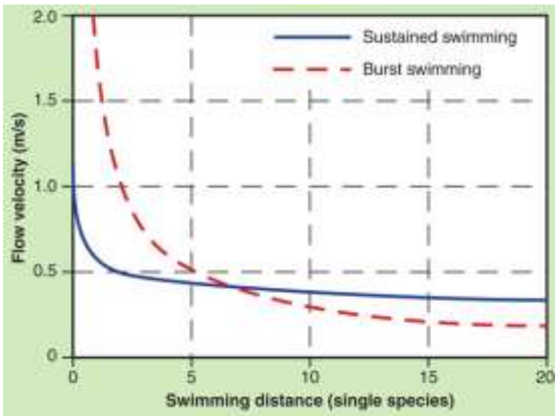
Introduction

Pygmy perch (NSW Fisheries)

Large fish in shallow water (SA)



Examples of fish swimming ability



Example of speed over distance

Modes of swimming

- The swimming ability of fish varies with each species, and the size of the fish.
- For any given fish (size and species) its swimming speed can be classified into three levels:
  - *Burst speed,* which is able to be maintained for short periods (seconds)
  - *Sustained speed,* a medium speed able to be maintained for minutes
  - *Cruising speed*, which allows fish to maintain continuous movement.

Swimming ability in shallow water

- The swimming ability of fish can also be affected by the depth of the water.
- If the body of the fish is partially exposed, then their swimming speed and endurance are likely to be reduced.
- Some engineering structures, such as flat-bed box culverts, can create shallow water conditions that are difficult for fish to negotiate.

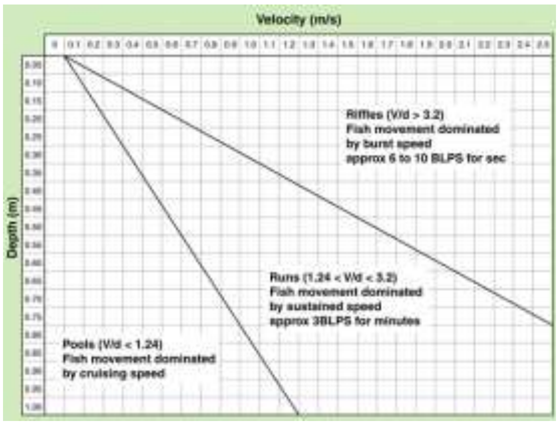
Approximate swimming speeds

- Fish use a combination of burst speed and sustained speed to negotiate waterway obstacles.
- In general terms, their swimming speed varies with the size of the fish, with:
  - burst speed being approximately 6 to 10 body lengths per second (BLPS)
  - sustained speed being approximately 3BLPS.

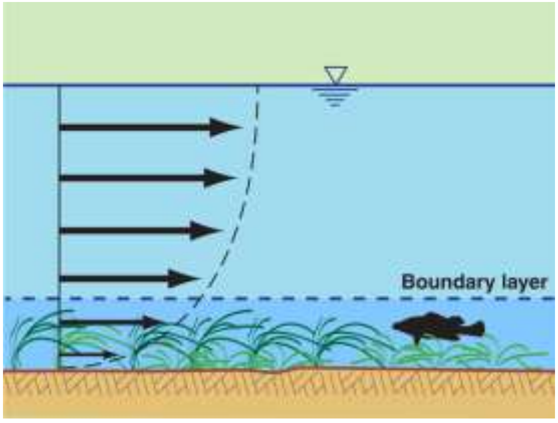
Swimming ability over long distances

- Fish use different muscle groups during different types of swimming.
- During burst swimming the initial speed can be high, but energy levels are quickly exhausted and eventually the swimming speed will fall below that which would have been achieved during sustained swimming.
- This means the effective 'length' of a waterway obstacle is critical in determining if the obstacle becomes recognised as a barrier to fish passage.

Waterway hydraulics and its interaction with fish passage



Typical flow conditions



Boundary layer flow conditions

Whirlpool in a flooded rural creek (Qld)

Gravel-based creek with boulders (Qld)

Natural obstacles

- Creeks are rarely uniform in their cross-section and bed conditions.
- Fish passage can be obstructed by natural features, such as riffles, rapids, waterfalls, dry creek beds, and disconnected pools.
- To negotiate these obstacles, fish can use:
  - burst speed
  - jumping from the water
  - crawling over damp rocks (used by a very limited number of species).

Variation in flow velocities within a channel

- Fish are aided in their movement by the fact that flow velocities are not uniform across the width or depth of most channels.
- Friction and turbulence alter the local flow velocity, with flow velocities being reduced close to the bed and banks of creeks as a result of friction.
- This 'layer' of lower velocity water is commonly referred to as the boundary layer.

The effects of turbulence

- Water turbulence can help to reduce flow velocities, but excessive turbulence can become a barrier to fish passage.
- Small-scale turbulence is most commonly associated with water flowing over rough or irregular surfaces.
- Large-scale turbulence (eddies and whirlpools) can be shed from large irregular objects, or from rapid changes in the direction of the water flow.

Small backwaters and shadow zones

- A key to good aquatic habitat and fish passage conditions is the existence of a diversity in bed conditions.
- The existence of a uniform channel cross-section means flow conditions across the channel will either be 'all good' or 'all bad'.
- Bed irregularities, such as exposed boulders, can provide fish with areas to rest and rebuild their energy prior to continuing their migration, or their search for food.

Fish-friendly bed stabilisation measures

Gravel-based creek (Qld)

Desirable creek bed features

- Within fish habitats, bed stabilisation measures should generally aim to provide the following features:
  - bed roughness that simulates the natural bed roughness
  - a diversity of surface conditions that produce a diversity of flow conditions
  - random objects that can provide fish with protection from high-velocity flows
  - a suitable source of food.

Constructed rock ramp/chute (NSW)

Fish-friendly rock ramps

- Rock ramps (rock chutes) are often used to stabilise bed scour problems.
- In order to be fish friendly, these structures need to comply with certain physical and hydraulic requirements:
  - a maximum gradient of around 1 in 20 to 1 in 30
  - a maximum fall of around 500 mm
  - stable outer flanks that provide suitable fish passage conditions during elevated flows (i.e. minor floods).

Constructed rock riffle (Qld)

Fish-friendly hydraulic steps

- Ideally, the ‘spill height’ between two layers of rocks, or any other part of a fishway, should not exceed 100 mm.
- Ideally, no hydraulic structure should be ‘uniform’ in its flow conditions across the full width of a channel.
- Minor variations in the positioning of rocks means fish can search for their preferred pathway during different flow conditions.
- Such diverse hydraulic conditions are commonly found in natural riffles.

Bed level falling downstream of culvert

Allowance for future changes in bed levels

- In waterways, nothing stays the same for very long, banks can move left and right, creek beds can move up and down.
- In order to be fish friendly, all waterway structures must be able to accommodate expected changes in bed level.
- This means:
  - extra rock may need to be placed below the current bed level, and/or
  - recessed rock check dams may need to be installed within some waterways.

Fish-friendly bed stabilisation measures

Habitats formed by placement of boulders

Random placement of boulders

- Rock riffles do not 'naturally' occur in all waterways.
- Similarly, rock boulders do not exist in all waterways.
- However, with the guidance of waterway and fisheries experts, the random placement of boulders can:
  - provide resting areas for fish
  - provide roosting areas for aquatic and terrestrial fauna.

Constructed pool-riffle system (Qld)

Use of pool-riffle systems

- The construction of a series of pools and riffles is one option for the rehabilitation of head-cut erosion within a waterway.
- However, a pool-riffle system is not a natural feature within all waterways.
- To be fish friendly:
  - the rocks must be stable during the expected flow range (unlike natural riffles which allow the rocks to move)
  - the total fall of the riffle should not exceed approximately 500 mm.

Constructed fishway (Qld)

Use of fishways

- Constructed fishways are often used as a component of the rehabilitation of existing non-fish-friendly waterway structures, such as culverts and weirs.
- To be fish friendly:
  - the spill height across any ridge should not exceed 100 mm
  - the design of the fishway must be compatible with the natural movement of bed material (i.e. sediment and gravels) during flood events.

Fish ladder on a river weir (USA)

Use of fish ladders

- A 'fish ladder' is a type of fishway that normally requires fish to 'jump' from pool to pool in order to ascend the fishway.
- In Australia, it is generally preferable for fishways to utilise the 'burst speed' of the fish in order to ascend the fishway, instead of the fish's jumping skills.
- Obtaining advice from fisheries experts is essential prior to the placement of any fishway within Australian waters.

10.1 Constructed Riffles

Constructed riffle (NSW)

Constructed riffles vs natural riffles

- Unlike natural riffles, most constructed riffles, rock chutes, fishway ramps, ridge rock fishways, and rock weirs, are required to be stable during a wide range of flow conditions.
- Constructed riffles usually contain rocks that are substantially larger than those found in natural riffles.
- This means their performance, especially with regards to fish passage, can vary significantly from natural riffles.

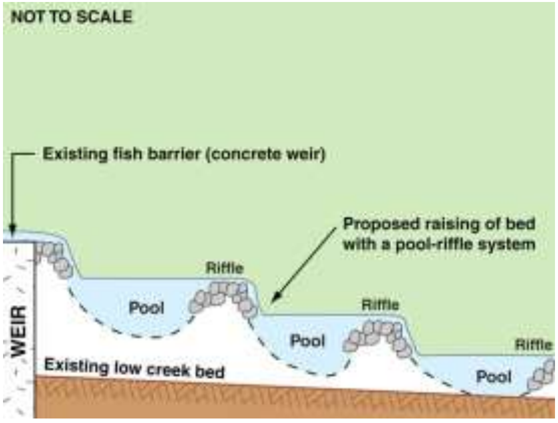
Constructed riffle (Qld)

Constructed riffles – Use of constructed riffles

Constructed pool-riffle sequence (Qld)

Introduction

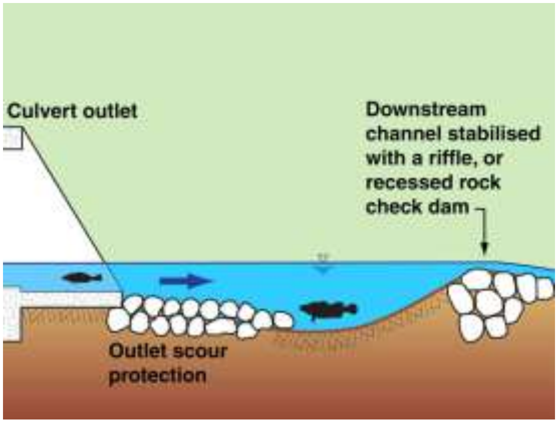
- Riffles, can exist in a wide variety of waterways.
- However, the waterway feature commonly known as 'pools and riffles' is most commonly found in gravel-based waterways.
- Waterway managers should not build a pool-riffle system in a clay or sand-based creek just because they think such a feature would look good within their waterway.



Bed raised using a pool-riffle system

Elevating a channel bed to drown out a fish barrier

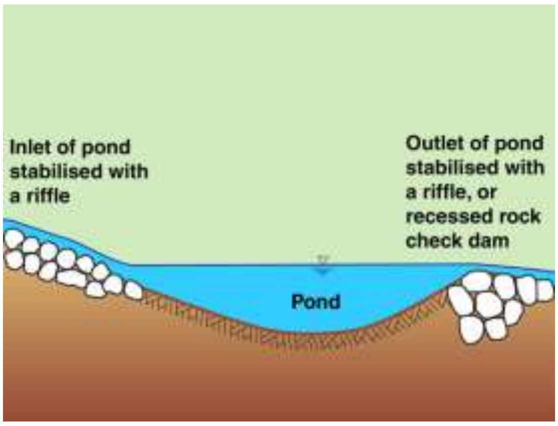
- A series of constructed pools and riffles can be used to elevate an existing creek bed in order to drown-out a recently formed barrier to fish passage, such as:
  - a small weir
  - a road causeway
  - a concrete-encased sewer pipe crossing.



Bed stabilised downstream of a culvert

Reconstructing a fish-friendly channel upstream or downstream of a culvert

- When a long culvert is installed on a steep creek, the flat gradient of the culvert bed usually means a steeper channel gradient is required at the upstream and/or downstream ends of the culvert.
- A series of pools and riffles can be used to make this steep channel gradient suitable for fish passage.



Stabilised inlet and outlet of a pond

Stabilising the channel bed upstream or downstream of an instream lake or wetland

- Creeks generally have a reasonably constant channel slope (within a given reach), but the water surface of a pool, lake or wetland is 'flat'.
- If a habitat pond, lake or wetland is constructed within a creek, there is usually a need to form a grade control structure at either the inlet or outlet of the water body.
- A constructed riffle can be used to form this grade control structure.

Constructed riffles – Use of riffles in different types of waterways

Constructed riffle in a clay-based creek

Clay-based waterways

- In an ideal world, pool-riffle systems would not be constructed within waterways where such features do not naturally exist.
- However, our waterways do not exist in an ideal world, and there are circumstances where a constructed pool-riffle sequence could benefit a clay-based waterway.
- In clay-based waterways there is no natural migration of bed rock; therefore, the rock used in a constructed riffle must be sized to be stable (i.e. not move).

Sand becomes 'unstable' after a flood

Sand-based waterways

- Constructing a rock riffle on the bed of a sand-based creek can be problematic.
- If the depth of the sand exceeds the foundation depth of the rock structure, then the rocks could simply 'sink' into the sand during a major flood.
- If the depth of the bed sand does <u>not</u> exceed the depth of the rock structure, then the structure could interfere with the natural migration of sand, or could simply become buried by the sand.

Unstable riffle in a gravel-based creek

Gravel-based waterways

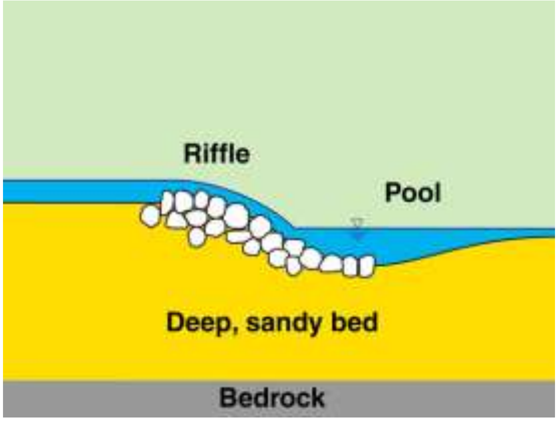
- If a new riffle needs to be constructed within a gravel-based waterway, then natural bed rock should be used in circumstances where the natural migration of bed rock and gravel can be maintained.
- However, if a riffle needs to be constructed downstream of a water feature that is likely to prevent the natural migration of bed rock (e.g. downstream of a constructed lake), then larger rock may be required (such as that recommended for constructed riffles).

Exposed bedrock (Qld)

Rock-based waterways

- It would be rare for constructed riffles to be required near sections of exposed bedrock.
- If constructed riffles are needed, then they are more likely to be associated with the sections of clay, sand or gravel-based channels found between the sections of exposed bedrock.
- If bed erosion results in the formation of an unnatural waterfall, then a riffle may be used to raise the downstream bed in order to maintain natural fish passage.

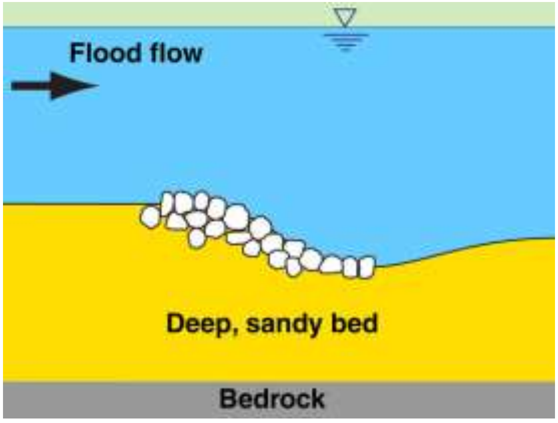
Caution the placement of rocks on a deep sandy bed



Recessed check dam in a sandy bed

Introduction

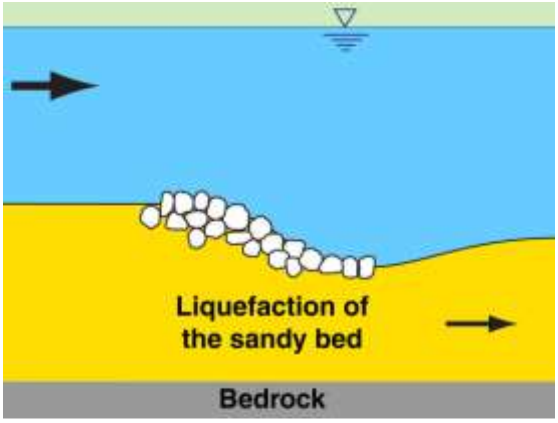
- These diagrams highlight the potential problem that can result when a rock riffle is formed on a deep, sandy bed.



Flood event

Major flood event

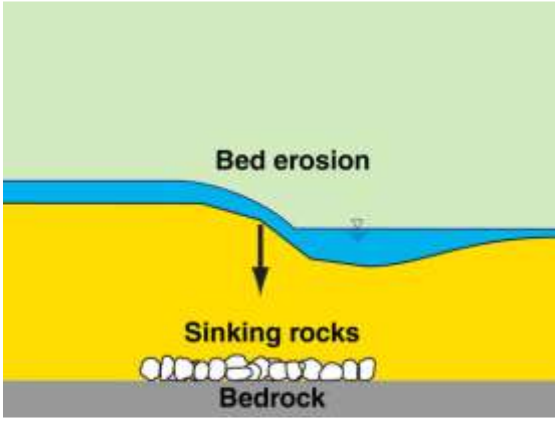
- During most floods, the sandy bed will begin to migrate down the channel, which can cause disturbance to the rocks.



Liquefaction of the sandy bed

Liquefaction of the sandy bed

- During a major flood, the sandy bed can liquefy, which can turn the sandy bed into a form of 'quicksand'.

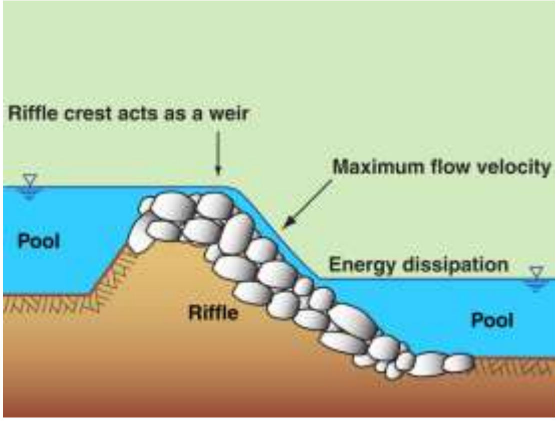


Rock sink into the sandy bed

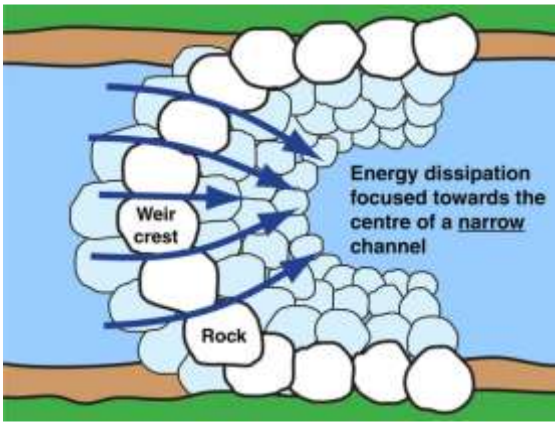
Sinking rocks!

- The riffle rocks can simply sink into the sand, which will leave the sandy bed subject to bed scour.

Constructed riffles – Hydraulics of the riffle

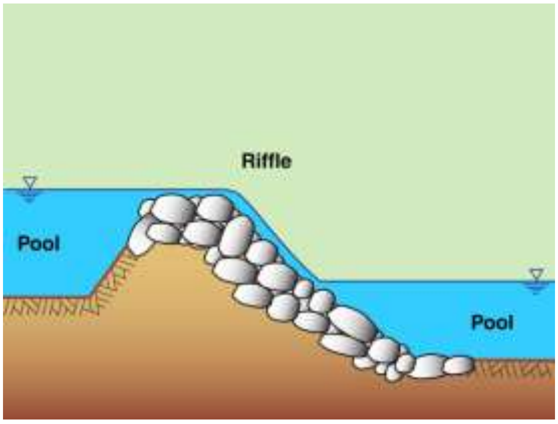


Riffle hydraulics



A curved riffle crest in a narrow channel

Constructed riffle (Qld)



Rock riffle profile

Riffle gradient

- There are three aspects to the hydraulics of a riffle:
  - crest hydraulics
  - riffle hydraulics
  - downstream energy dissipation.
- A survey of natural riffles found in South-East Queensland creeks found that riffles had a typical gradient of 1 in 30.
- In order to be considered fish friendly, it is recommended that constructed riffles have a maximum gradient of 1 in 20.

Weir crest in narrow channels

- A 'pool' must exist downstream of a riffle in order to facilitate energy dissipation.
- In narrow channels, the width of this pool can be a critical factor in some designs.
- The existence of a curved (concave) riffle crest helps to focus the flow energy towards the centre of the pool, thus reducing the risk of bank erosion.
- Hydraulically, the significance of the weir crest profile reduces as the length of the riffle increases.

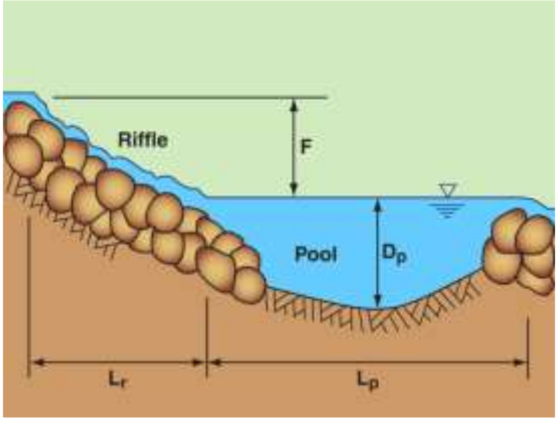
Weir crest in wide channels

- In wide channels it is normal for the crest of the riffle to be relatively straight and flat, and aligned at 90-degrees to the riffle's chute.
- If the pool-riffle sequence meanders across the bed of a wide channel, then 'changes of direction' can either occur:
  - within a long pool, or
  - at the crest of a riffle, but
  - the riffle's chute must remain straight.

Elevated weir crests

- Unlike some rock chutes, the crest of a riffle is normally elevated above the upstream channel in order to facilitate the existence of an upstream pool.
- Elevating the weir crest also helps to reduce flow velocities immediately upstream of the riffle, which helps to provide a rest area for migrating fish.

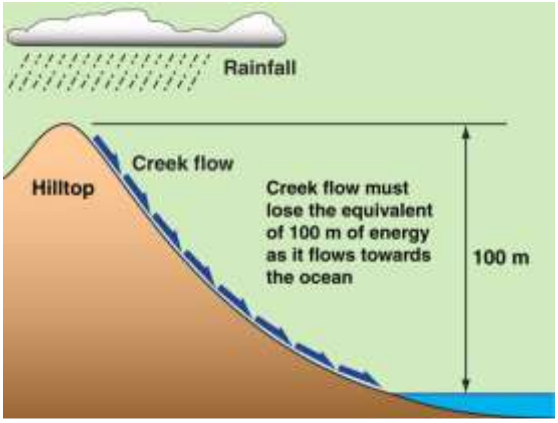
Constructed riffles – Hydraulics of the downstream



Profile of a pool-riffle system

Introduction

- The existence of both pools and riffles increases the habitat diversity and resulting biodiversity of the waterway.
- There is also an important hydraulic relationship that develops between a riffle and the downstream pool.
- This hydraulic relationship means that there are some attributes (dimensions) of a pool that can be linked back to the riffle.



Energy loss

Energy dissipation along creeks

- If a creek starts on a hilltop 100 m above sea level, then as the water travels the full length of the creek, it must lose the equivalent of 100 m of energy by the time the water enters the sea.
- Similarly, if the water descends a riffle that falls 500 mm, then the equivalent of 500 mm of energy must be consumed while the water passes down the riffle and through the downstream pool.

A pool-riffle type water slide (NSW)

Types of energy dissipation

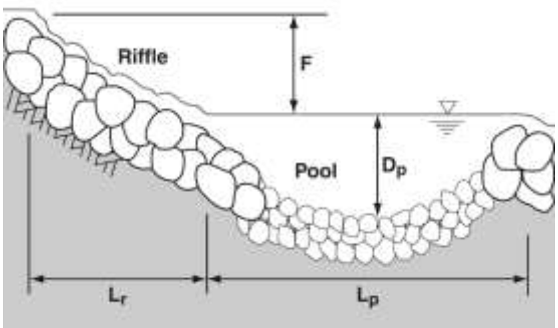
- In pool-riffle systems, energy loss can occur in two ways:
  - friction (down the chute)
  - turbulence (within the pool)
- As the flow enters the downstream pool, the jetting effects of the inflow cause turbulence within the pool, which contributes to energy loss.
- These same hydraulic principles exist within a wide range of hydraulic structures, including water slides.

Factors affecting the depth of a pool (D_P)

- A study of natural pool-riffle systems in South-East Queensland revealed that the depth of the downstream pool (D_P) was usually equal to, or greater than, the fall (F) of the upstream riffle.

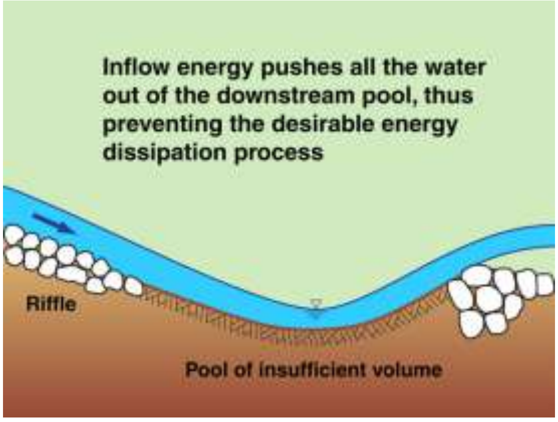
$$D_{P\,(min)} = F \text{ (typical)} \qquad (10.1)$$

- Waterfalls are different, however, the depth of the pool below a waterfall also increases with the height of the waterfall, but only to the point where the falling water reaches its terminal velocity.

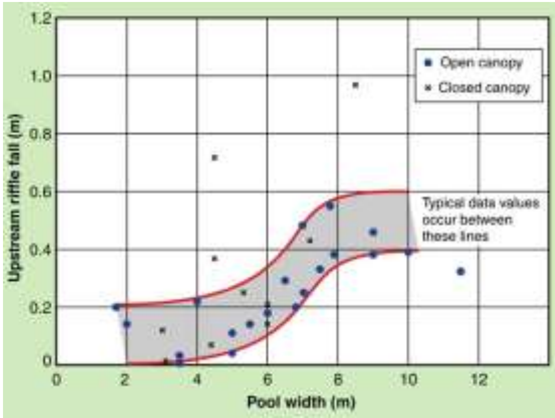


Profile of a pool-riffle system

Constructed riffles – Pool dimension in narrow channels



Outcome of insufficient pool volume



Relationship between 'fall' & 'pool width'

Pool downstream of a rock ramp (NSW)

Pool-riffle in a narrow channel (Qld)

Factors affecting the volume of a pool

- The volume of water contained within the downstream pool is important in order to maintain the correct operation of the pool.
- If the downstream pool has insufficient volume, then as the flow rate increases, the water energy passing down the riffle will eventually push the water out of the downstream pool causing the pool to act as a 'ski jump'.
- The volume of a pool is governed by its depth, width and length.

Factors affecting the width of a pool (W_P)

- Hydraulic factors mean that:
  - pool depth is linked to riffle fall (F), and
  - the minimum pool volume is linked to the riffle's fall (typically equal to D_P) and width (W_R).
- For relatively narrow channels (i.e. creeks) the pool width (W_P) should be taken as the greater of:

$$W_{P\,(min)} = 1.3 + 4.5\,D_P \qquad (10.2)$$

$$W_{P\,(min)} = W_R + 4.5\,D_P \qquad (10.3)$$

Factors affecting the length of a pool (L_P)

- The minimum length of a pool is in part governed by the minimum required volume of a pool in order to achieve efficient energy dissipation.
- A survey of pool-riffle systems in SE Qld creeks showed that the minimum pool length is around twice the pool width.

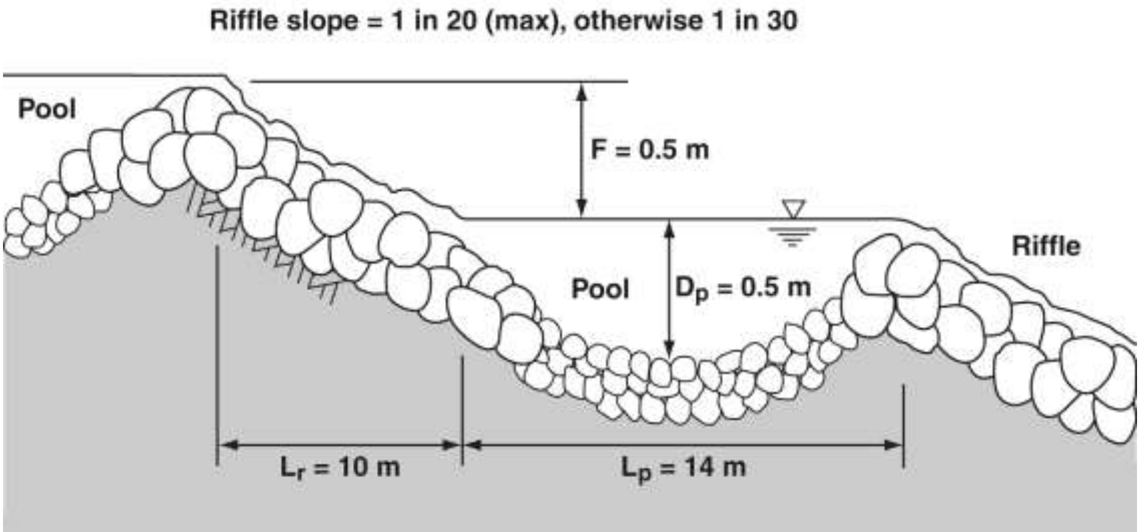
$$L_{P\,(min)} = 2 \text{ to } 4 \text{ times } W_P \qquad (10.4)$$

- However, the actual length of the pool is usually governed by the gradient of the creek, and the spacing of the riffles.

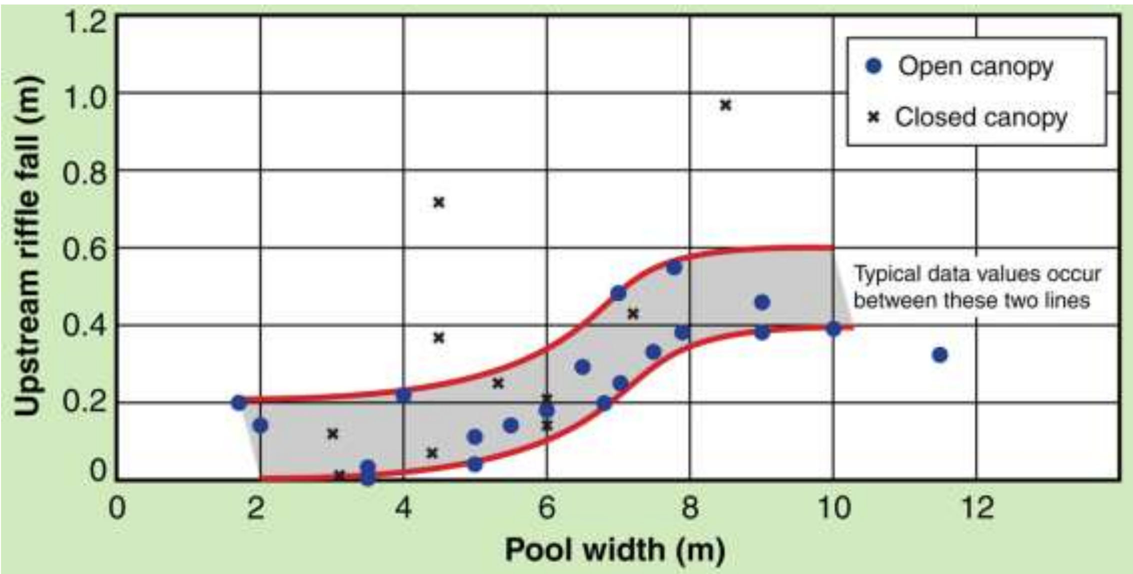
Use of rock to stabilise narrow pools

- In constructed channels, limits on the overall width of the channel may not allow the construction of the ideal pool width.
- In such cases, a narrower (but longer) pool can be constructed, but the sides of the pool will need to be stabilised with rock and hardy plants (e.g. *Lomandra*) in order to control potential bank erosion.
- The length of the pool should exceed the minimum length determined for the pond width (equations 10.2 or 10.3).

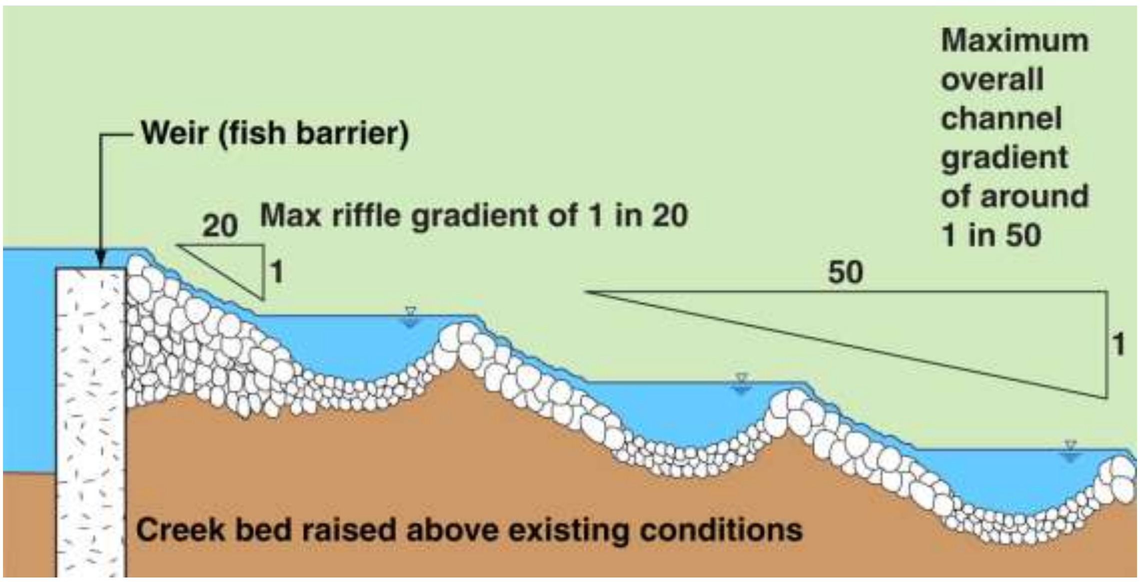
Constructed riffles – Pool dimensions in narrow channels



Dimensions of maximum possible pool-riffle gradient

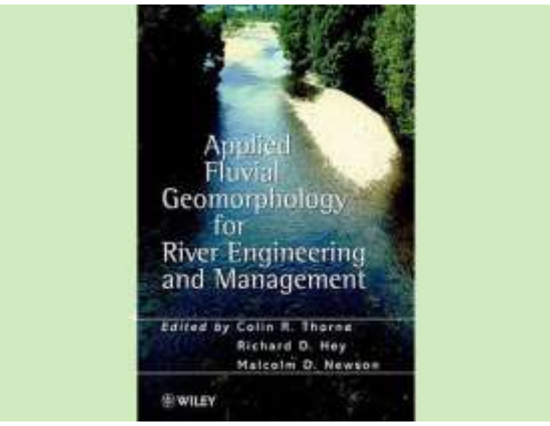


Relationship between the riffle fall (F) and the pool width (W_p) from creeks in SE Qld



Use of a pool-riffle system to raise the creek bed downstream of an existing weir

Constructed riffles – Pool and riffle dimensions in wide channels



Thorne, Hey & Newson, 1997

Riffle on the Gwydir River, NSW

Gwydir River, Moree, NSW

Pool-riffle system, Queanbeyan River, NSW

Introduction

- The previous discussion referred to the sizing of pool-riffle systems in narrow creeks based on a survey of creeks in South-East Queensland.
- It is not the intent of this field guide to provide sufficient information to allow the reader to design pool-riffles systems for larger waterways (i.e. rivers).
- Designing works in rivers requires the guidance of experts (river morphologists) and survey data from local river systems.

Width of riffles in wide channels

- In rivers, riffles are:
  - located at inflection points, midway between bends (but not always)
  - usually exposed across the full width of the channel bed, even though dry weather flows may only spill over a portion of the riffle.

$$W_R = 1.03\ b \qquad (10.5)$$

where:

- W_R = crest width of riffle (m)
- b = average width of channel bed (m)

Depth and width of pools in wide channels

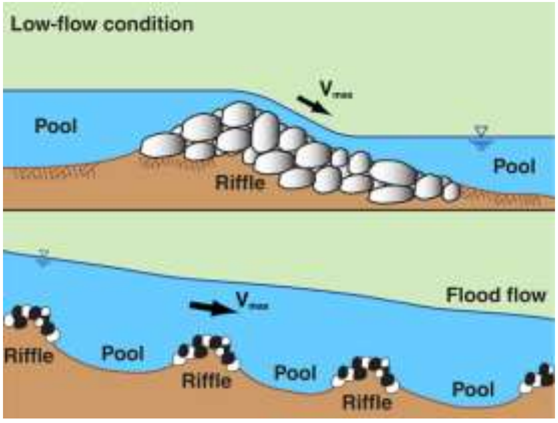
- In rivers, pools:
  - have a dry weather water surface width approximately equal to the channel width, and
  - typically extend from riffle to riffle, with the deepest part of the pool located at channel bends.
- The depth of pools at channel bends depends on the bed width (b) and the bend radius (refer to text books for typical relationships).

Length and volume of pools in wide channels

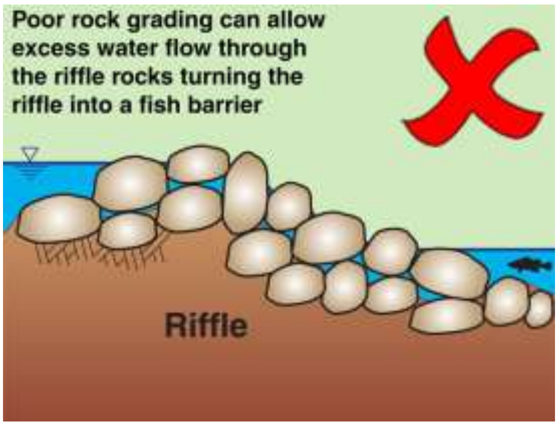
- The length of the pool is likely to relate solely to the spacing of the riffles.
- A pool of some type must exist at the base of a riffle in order to dissipate energy.
- The depth of the pool immediately downstream of a riffle will likely relate to the riffle's fall.
- The suggested minimum length of a pool is twice the pool width, but it would be better to survey existing pools in the river.

Constructed riffles – Rock sizing for riffles

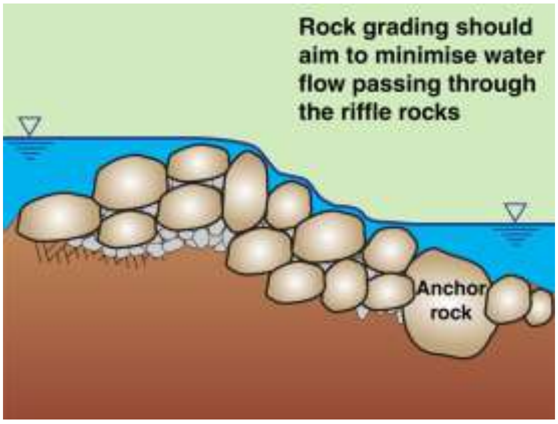
Rock sitting high with exposed edges



Design flow conditions



Consequence of poor rock grading



Optional use of anchor rocks

Critical design issues

- The size of the rock is generally governed by the following factors:
  - the maximum flow velocity during which the rock is required to be stable
  - the degree of exposure of the rock to direct river flow (i.e. does the rock sit flush with the adjacent rock, or does part of the rock extend into the flow)
  - the degree of turbulence within the water flow—this usually varies with water depth and flow velocity.

Design flow conditions

- Rock size usually needs to be checked for both low-flow (shallow flow) and high-flow (deep water) conditions.
- During low-flow conditions the water velocity is usually governed by the riffle slope.
- During high-flow conditions the water velocity is likely to be governed by the overall channel slope (i.e. the pools and riffles simply become part of the overall bed roughness).

Distribution of rock sizes

- There are many circumstances where a near-uniform rock size is desirable, but in constructed riffles this can result in fish passage problems.
- The rocks used in constructed riffles are usually larger than those found in natural riffles because it is usually necessary for these rocks to be stable (i.e. not migrate downstream during flood events).
- The use of large rock can result in excess water passing through the rocks during dry weather (low flow) conditions, which can block fish passage.
- To avoid such problems, there needs to be a certain percentage of smaller rocks in order to minimise the void spacing.
- The recommended distribution of rock sizes for constructed riffles is provided in Table 10.2 over the page.
- An option also exists for the placement of large anchor rock at the base of the riffle (i.e. below the normal pool water level) in order to increase the stability of the riffle rock during flood events.

Constructed riffles – Sizing rock for low-flow conditions

Low-flow condition (Qld)

Sizing rock for <u>low-flow</u> conditions

- In most cases, the required rock size will **<u>not</u>** be governed by the low-flow conditions.
- The low-flow hydraulic check requires the determination of the maximum flow velocity that occurs on the riffle prior to the riffle being drowned-out by backwater.
- This analysis usually involves numerical modelling of the stream for a range of flow conditions.

Flow approaching drowned conditions

Rock sizing equation for <u>low-flow</u> condition

$$d_{50} = \frac{SF.K_1.K_2.V^2}{(A - B.\ln(S_o)).(s_r - 1)} \qquad (10.6)$$

For SF = 1.2: A = 3.95, B = 4.97 (default)

For SF = 1.5: A = 2.44, B = 4.60

Tabulated rock sizes can be obtained from tables 10.4 to 10.7.

(Note: 'ln' means natural logarithm to base-e)

A & B = equation constants; typically adopt A = 3.95 and B = 4.97 based on SF = 1.2

d_{50} = nominal rock size (diameter) of which 50% of the rocks are smaller [m]

K_1 = correction factor for rock shape
= 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)

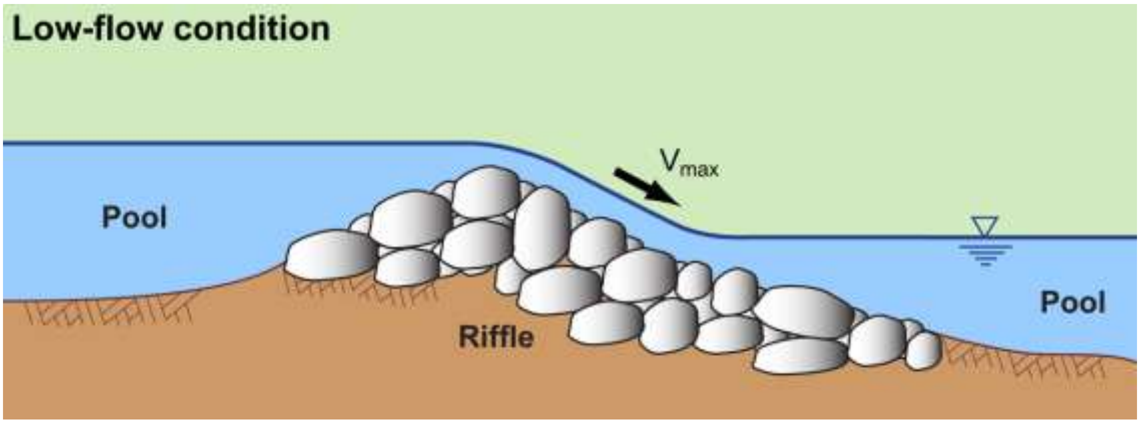
K_2 = correction factor for rock grading
= 0.95 for poorly graded rock ($C_u = d_{60}/d_{10} < 1.5$), 1.05 for well graded rock ($C_u > 2.5$), otherwise $K_2 = 1.0$ ($1.5 < C_u < 2.5$)

SF = factor of safety = 1.2 (recommended)

S_o = gradient of the riffle face [m/m]

s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, typically 2.6; limestone 2.6; basalt 2.7–3.2)

V = maximum depth-average flow velocity over the rocks during low flow [m/s]



Shallow water, low-flow design conditions

Constructed riffles – Sizing rock for <u>high-flow</u> conditions

The high-flow hydraulic check requires the nomination of the maximum flood event during which the riffle rock is required to be stable, e.g. the 1-in-10 year (10% AEP) or 1-in-50 year (2% AEP) discharge. This flow condition is then modelled to determine the maximum depth-average flow velocity passing over the riffle.

It is important that the calculated depth-average velocity is representative of the **actual** flow velocities above the riffle, **<u>not</u>** the flow velocity averaged across the full cross-section.

Minimum mean rock size for these high flow conditions may be determined from Equation 10.7.

$$d_{50} = \frac{K_1 . V^2}{2.g.K^2 (s_r - 1)} \quad (10.7)$$

where:

K = equation constant based on flow conditions

= 1.1 for low-turbulence, deep water flow, or 0.86 for highly turbulent flow; otherwise, refer to Table 10.1 for suggested vales of 'K' based on the flood gradient

V = nominated design flow velocity over the rocks [m/s]

g = acceleration due to gravity [m/s^2]

Table 10.1 – Suggested values of 'K' for various <u>flood</u> gradients

Flood gradient (%)	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**	**10.0**
K =	1.09	1.01	0.96	0.92	0.89	0.86	0.83	0.80
Flow conditions	Low turbulence □ □ □ □ □ □ □ □ Highly turbulent (whitewater)							

Specification of rock for constructed riffles

In circumstances where the constructed riffle is required to simulate 'natural' bed conditions, and the riffle is located in a waterway that contains natural pool–riffle systems, then the rocks used in construction of the riffle should match the size distribution of the natural riffle systems. However, for constructed riffles that are required to be stable during major flood flows, then the following rock specifications should be considered.

Crushed rock is generally more stable than natural rounded rock; however, rounded rock has a more 'natural' appearance and is considered more fish friendly. A 36% increase in rock size is recommended for rounded rock (i.e. $K_1 = 1.36$).

Broken concrete and building rubble should <u>not</u> be used.

The rock should be durable and resistant to weathering, and should be proportioned so that neither the breadth, nor the thickness, of a single rock is less than one-third its length.

The maximum rock size generally should not exceed twice the mean (d_{50}) rock size.

Table 10.2 provides recommended distribution of rock sizes for constructed riffles.

Table 10.2 – Recommended distribution of rock size for constructed riffles

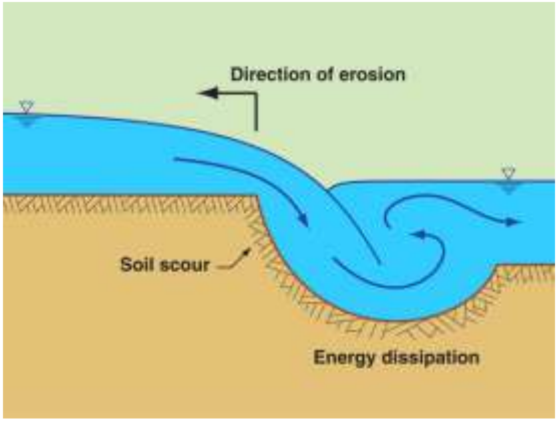
Rock size ratio	**Assumed distribution value**
d_{100}/d_{50}	2.0
d_{90}/d_{50}	1.8
d_{75}/d_{50}	1.5
d_{65}/d_{50}	1.3
d_{40}/d_{50}	0.65
d_{33}/d_{50}	0.50
d_{25}/d_{50}	0.45
d_{10}/d_{50}	0.20

Constructed riffles – Stabilisation of a head-cut with a plunge-pool

Head-cut erosion (Qld)

Head-cut erosion

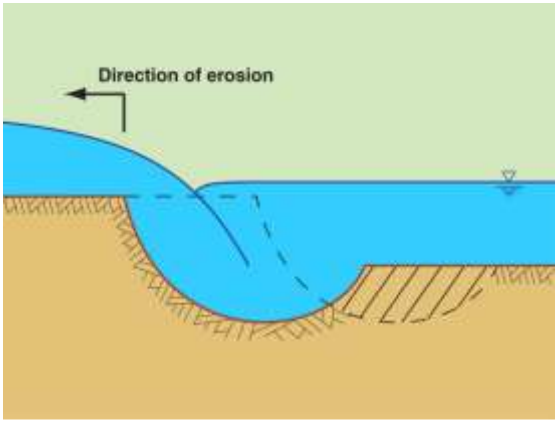
- A 'head-cut' is a sudden drop in the bed level, which migrates up the channel, usually during flood events, but the erosion can also grow slowly during regular dry weather flows.
- Immediately downstream of the head-cut there is usually a scour hole that also migrates up the channel.
- The existence of the scour hole is critically important for the dissipation of flow energy.



Head-cut erosion

Hydraulics of head-cut erosion

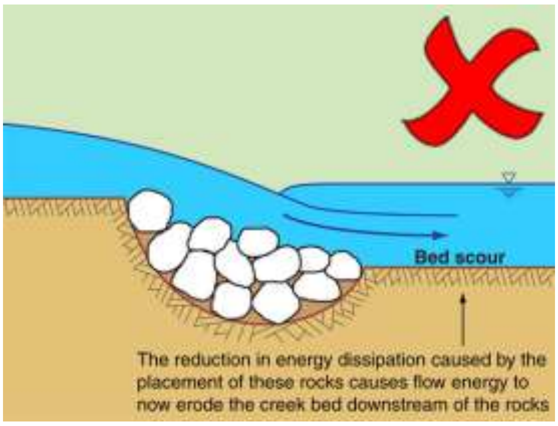
- The creek flow gains velocity and kinetic energy as it falls to a lower elevation.
- The increase in energy is then dissipated as it enters the downstream pool.
- The flow continues to erode the plunge pool until the pool achieves the 'volume' necessary to dissipate the excess kinetic energy.
- In effect, the erosion process forms a type of mobile pool-riffle system.



Migration of head-cut erosion

Migration of head-cut erosion

- Turbulence within the plunge pool causes ongoing soil scour to occur on the face of the head-cut.
- Over time the erosion migrates up the channel, and a new plunge pool is formed.
- The old plunge pool usually becomes backfilled with the sediment scoured from the new pool.
- The size of the plunge pool is related to the flow rate and the fall of the bed.

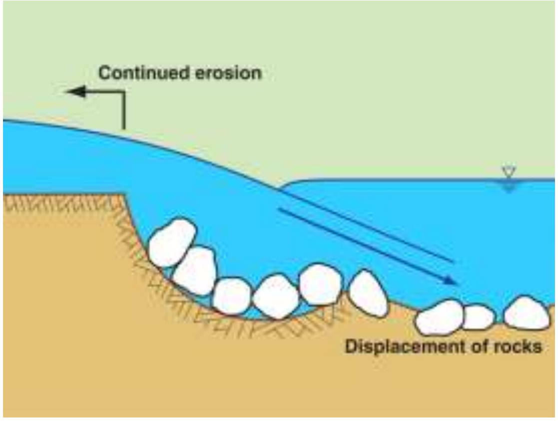


Problems caused by filling pool with rock

Inappropriate stabilisation with rock

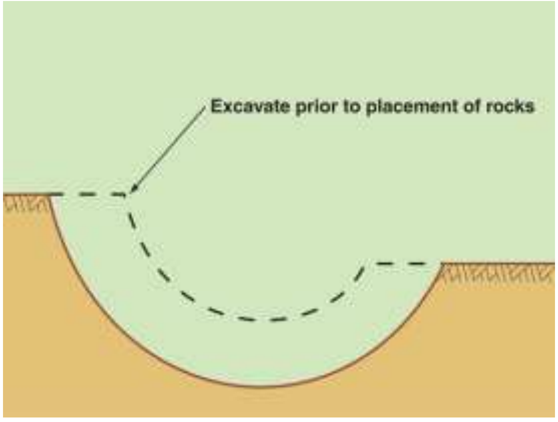
- Waterway managers can be tempted to simply fill the scour hole (plunge pool) with rock in an attempt to stabilise the erosion.
- Unfortunately, this bed condition needs the continued existence of a plunge pool in order to dissipate energy.
- Filling the plunge pool with rock will cause the flow energy to be directed downstream of the rock, where it will form a new energy dissipation pool.

Constructed riffles – Stabilisation of a head-cut with a plunge-pool



Problems caused by filling pool with rock

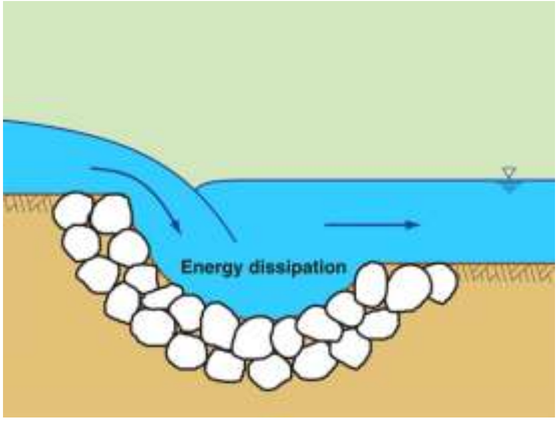
Failed placement of rock



Over-excavation of dissipation pool

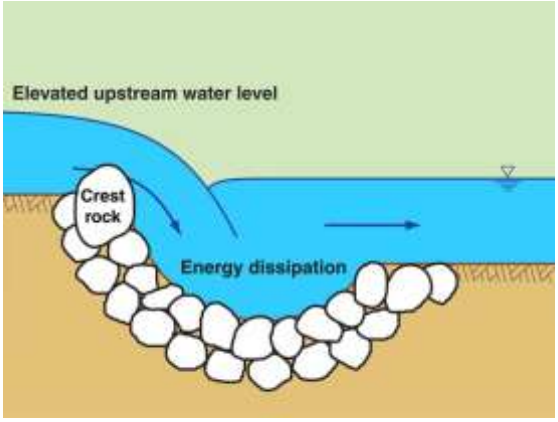
Appropriate placement of rock

- The correct approach to stabilising this type of erosion is to:
  - measure the dimensions of the existing plunge pool
  - enlarge the pool to allow placement of rock without loss of pool volume
  - line the enlarged pool with rock.
- Currently there are no equations specifically developed for sizing rock placed in plunge pools, so a best guess is required, usually 450 to 600 mm.



Placement of rock in downstream pool

Example of constructed plunge pool



Use of enlarged crest rock

Optional use of elevated crest rock

- Large rock can be placed along the crest of the plunge pool structure in order to:
  - further raise upstream water levels
  - slow upstream flow velocities
  - improve energy dissipation.
- This crest rock usually has a diameter in excess of 500 mm.
- Plunge pool designs may or may not be fish friendly depending on the fall height and design of the riffle.

10.2 Rock Chutes and Rock Ramps

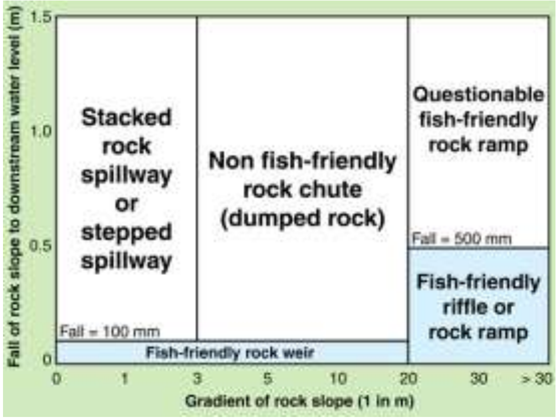
Rock chute stabilising gully erosion (Qld)

Rock chutes and rock ramps

- The term 'chute' is normally associated with something that descends a slope, such as water flowing down a chute.
- The term 'ramp' is normally associated with something that ascends a slope, such as fish migrating up a ramp.
- However, the terms 'rock chute' and 'rock ramp' are just different names for the same type of structure.
- Unlike 'riffles', chutes and ramps can exist in all types of creeks, but may be unstable if placed in a sand-based waterway.

Constructed rock ramp (fishway) in Tamworth, NSW

Rock chutes and rock ramps



General classification of structures

Rock ramp (NSW)

An inflow batter chute (Qld)

Upstream and downstream pools (NSW)

Fish-friendly structures

- Rock chutes/ramps placed in creeks are normally required to be fish friendly, while rock chutes placed in gullies are not expected to be fish friendly.
- The conditions that make a structure fish friendly vary depending on the swimming ability of the target species.
- Typical fish passage requirements are:
  - a total fall not exceeding 500 mm
  - a gradient not steeper than 1 in 20.

Use of fish-friendly rock chutes/ramps

- Fish-friendly rock chutes and ramps are used to:
  - stabilise bed scour, including head-cut erosion, in waterways
  - form a constructed riffle
  - stabilise the entrance of a culvert
  - stabilise the outlet of a culvert
  - construct a bypass fishway around a fish barrier.

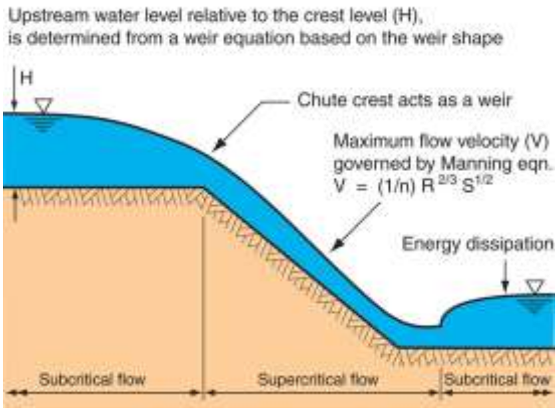
Use of non-fish-friendly rock chutes

- Non-fish-friendly rock chutes are used to:
  - stabilise head-cut erosion in a gully
  - stabilise the entrance of a culvert that crosses a gully
  - stabilise the outlet of a culvert that crosses a gully
  - stabilise stormwater inflows entering gullies and waterways (these structures are commonly referred to as 'batter chutes').

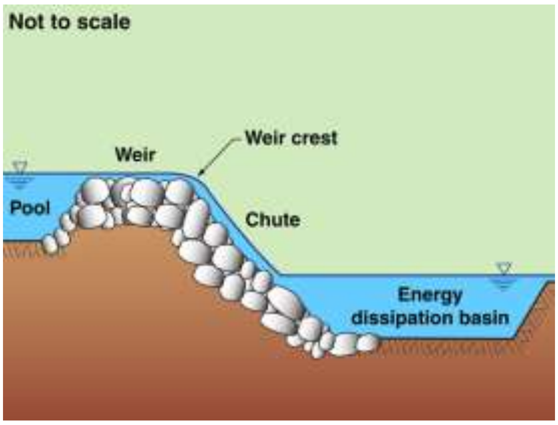
Existence of upstream and downstream pools

- In order for a rock chute to be fish friendly, not only does the 'chute' need to be fish friendly, but the channel upstream and downstream of the chute must also be fish friendly.
- This usually means that resting pools need to be positioned immediately upstream and downstream of the chute.
- Of course the downstream pool also acts as an energy dissipation basin.

Rock chutes and rock ramps – Weir crest

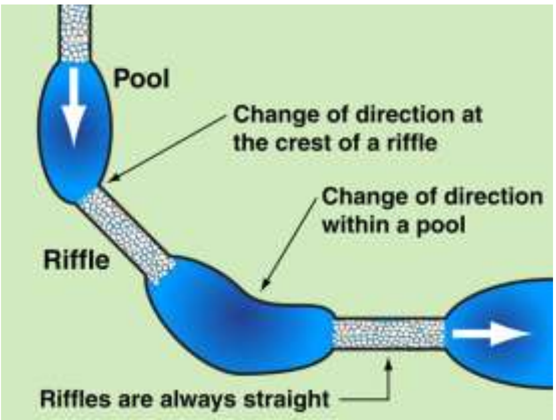


Chute hydraulics



Raised weir crest

Typical straight (trapezoidal) crest (Qld)



Straight chutes and changes of direction

Critical design issues for the weir crest

- Critical design issues include:
  - the choice of a 'flat' or 'raised' weir crest (with or without a low-flow)
  - the choice of a straight, flat, or slightly curved weir crest
  - the alignment of the weir crest and chute
  - the chute slope, fall, and rock size
  - the depth, width and volume of the energy dissipation pool (basin).

Benefits of a raised weir crest

- The benefits of a raised weir crest include:
  - formation of a pool upstream of the chute to allow migrating fish to recover their energy
  - lower flow velocities upstream of the chute, thus reducing the risk of erosion and vegetation damage.
- The disadvantages of a raised weir are:
  - more rock is required
  - potential stagnant water issues during periods of zero flow.

Choice of straight or curved weir crest

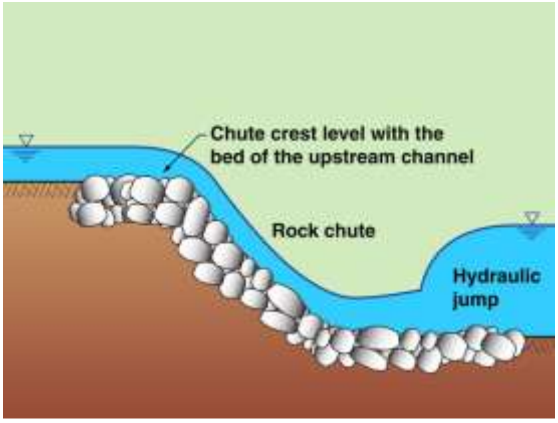
- The crest can be straight or slightly curved along the vertical and/or horizontal planes.
- The benefit of a straight crest is uniform hydraulic stresses down the chute.
- The benefit of slightly curving the crest is the production of variable flow condition, which can benefit fish passage, and a concentration of flow energy towards the centre of the downstream pool.
- A curved crest may be used on a narrow chute, but most rock chutes have a straight crest with a uniform chute profile.

The importance of a straight chute

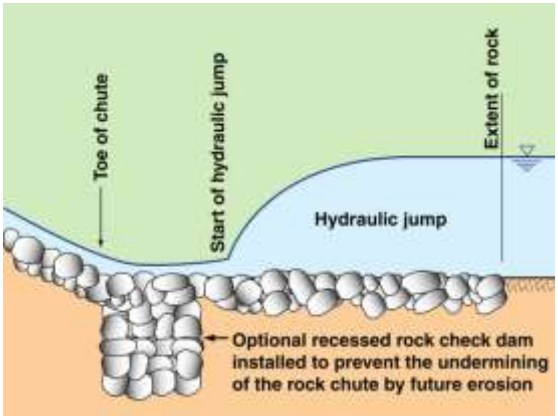
- It is essential that the alignment of the rock chute (in plan view) is 'straight'.
- This is because the flow down the chute is likely to be supercritical, and this type of flow does not like to change its direction.
- The upstream portion of the pool should also align with the direction of the chute so that energy dissipation can be fully contained within the pool (thus avoiding bank erosion along the edges of the pool).

Rock chutes and rock ramps – Energy dissipation at base of the chute

Energy dissipation basin at base of chute



Rock chute without a downstream pool



Extent of rock within the basin

Pool downstream of a rock chute (NSW)

Design of the chute outlet and energy dissipation

- Appropriate energy dissipation must occur within the 'pool' at the base of the chute.
- The design of this pool (basin) must be assessed on a case-by-case basis.
- The type and extent of scour control within the energy dissipater basin depends on:
  - the total fall of the chute (F)
  - the expected tailwater conditions, and
  - whether or not the energy dissipation basin can be recessed into the bed.

Rock chutes without downstream 'pools'

- Unlike a pool-riffle system, a rock chute can be designed with or without a downstream pool.
- However, fish-friendly structures are likely to incorporate upstream and downstream pools.
- In ephemeral waterways where fish migration is only likely to occur during periods of stream flow, the upstream and downstream channels effectively act as extended pools.

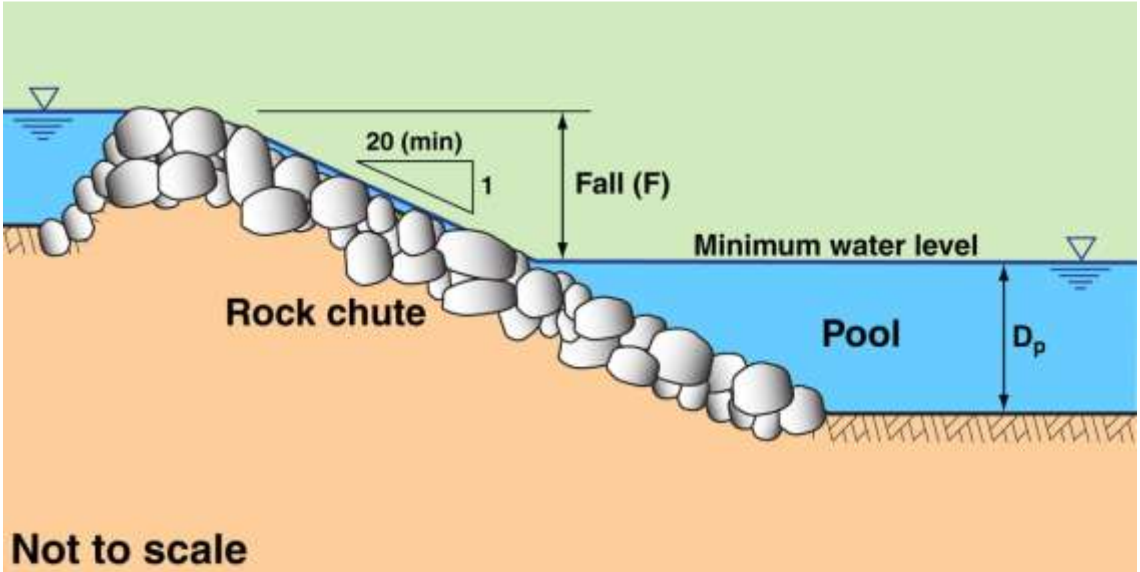
Design of rock chutes without a downstream pool

- If the rock chute does not have a recessed pool downstream of the chute, then energy dissipation must occur in the form of a hydraulic jump.
- The design of a hydraulic jump basin requires detailed hydraulic analysis in order to determine the size and location of the hydraulic jump.
- Rock scour protection normally needs to extend well-downstream of the hydraulic jump.

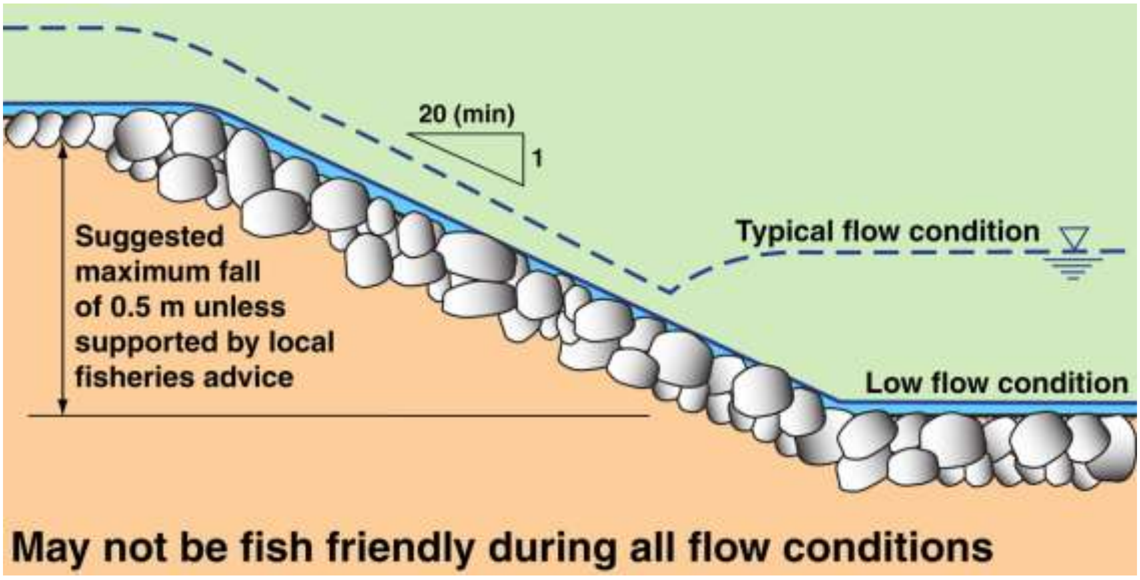
Design of chutes with a downstream pool

- The depth, width and length of the pool should be based on the same design requirements as for pool-riffle systems.
- The required length of the pool is likely to be longer than the specified minimum length (hydraulic analysis is required).
- The extent of rock protection depends on whether or not a hydraulic jump is generated within the downstream pool, which depends on the flow energy and tailwater conditions.

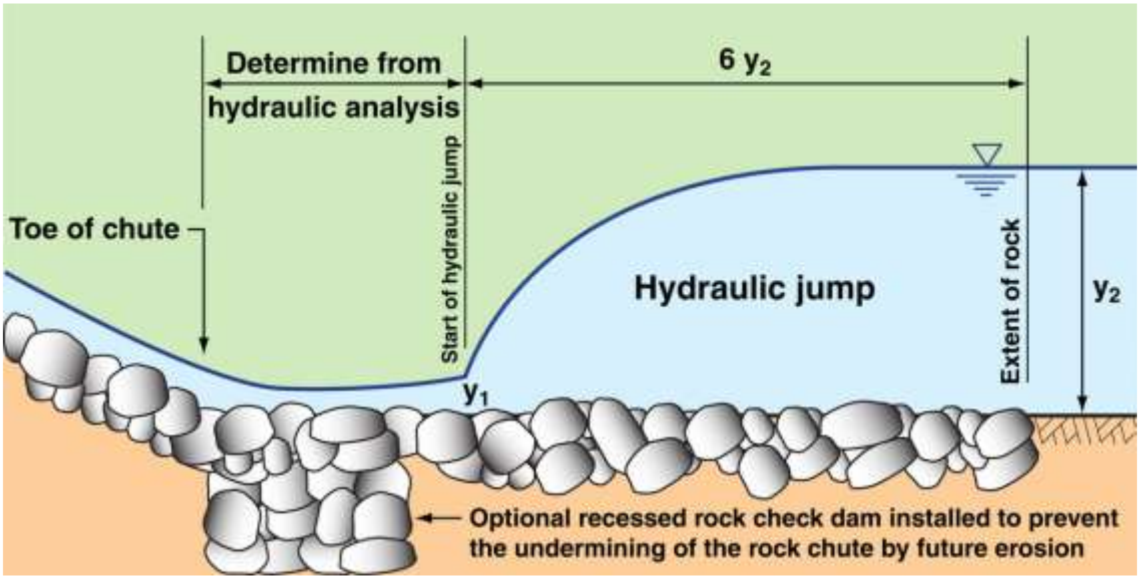
Rock chutes and rock ramps



Rock chute with raised weir crest and upstream/downstream pools

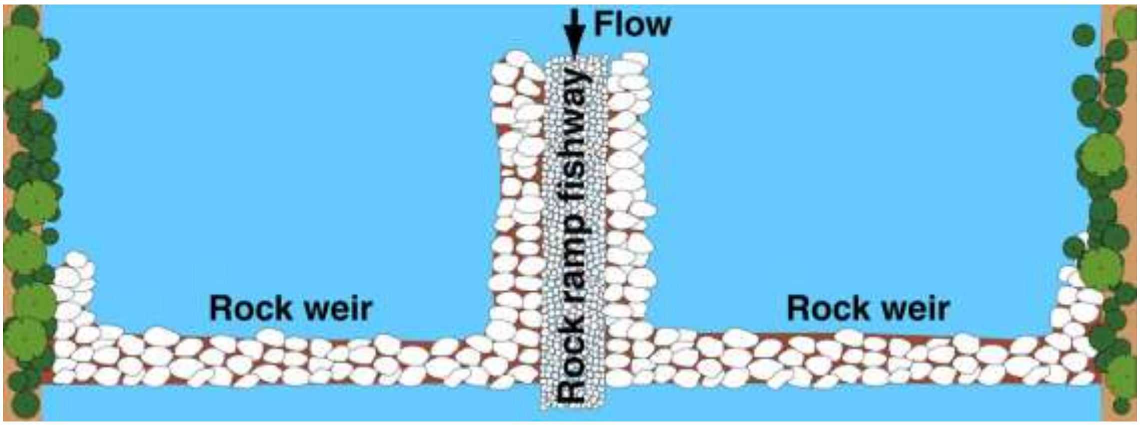


Rock chute with bed-level crest and no pools



Energy dissipater basin of a rock chute without a permanent downstream pool

Rock chutes and rock ramps – Rock ramp fishway, Tamworth, NSW



Layout of the rock ramp fishway

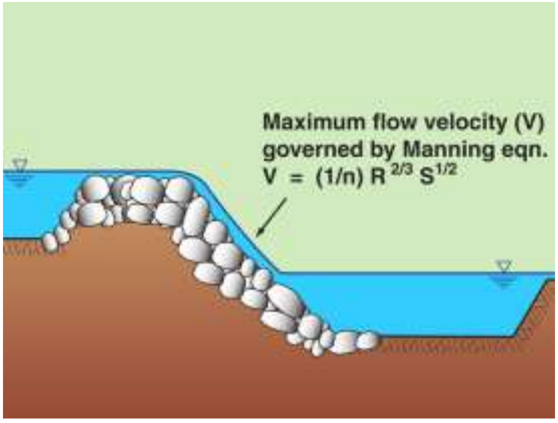
Rock ramp fishway viewed from the right bank (Tamworth, NSW)

Rock ramp fishway looking upstream from the base of the fishway (Tamworth, NSW)

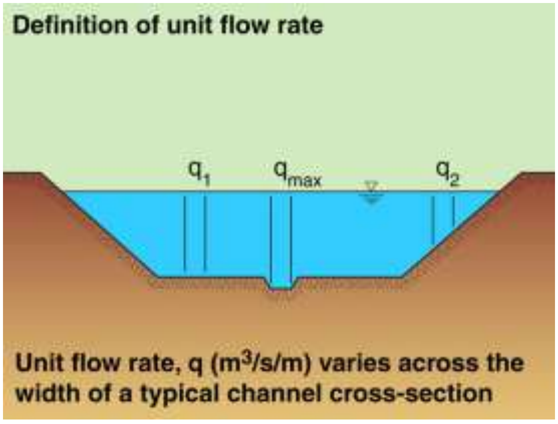
Rock ramp fishway looking downstream from the top of the fishway (Tamworth, NSW)

Rock chutes and rock ramps – Sizing of rock

Supply of rock to a work site (Qld)



Maximum flow velocity



Unit flow rate within an irregular channel

Low-flow channel set in grouted rock

Introduction

- Unlike natural riffles, the rock used in the construction of a rock chute must be stable during the nominated design storm.
- Hydraulic failures of rock chutes are relatively common compared to the failure of other waterway structures.
- It is suspected (by the author) that these failures are likely due to:
  - the use of undersized rock
  - the occurrence of flows in excess of the nominated design storm.

Problems associated with using flow velocity to determine rock size

- Using flow velocity (V) to determine rock size introduces unnecessary 'errors' into the design procedure due to the problems of determining the Manning's roughness.
- Unfortunately, there is disagreement in the industry regarding the determination of the Manning's roughness (n) of rock.
- Any 'errors' in the Manning's roughness will result in a similar errors in the flow velocity, which will result in errors in the sizing of the rock.

Use of unit flow rate (q) as the primary design variable

- Potential problems caused by variations in the choice of Manning's roughness can be reduced (but not eliminated) by using the unit flow rate (q) as the primary design variable instead of flow velocity.

The units of 'q' are [m^3/s/m] = [m^2/s]

$$q = (1/n) \,.\, D^{5/3} \,.\, S^{1/2} \qquad (10.8)$$

where:

D = water depth at a given location [m]

S = hydraulic gradient of flow [m/m]

Formation of a low-flow channel through the weir crest

- If a low-flow channel must pass through the rock chute (which is generally undesirable), then the depth of this channel should be minimised, especially at the crest of the chute.
- It can be very difficult to form a low-flow channel through any structure that has been formed from large, lose, rock.
- Grouting the rock can allow the formation of a low-flow channel, but this can cause other complications.

Rock chutes and rock ramps – Sizing of rock

Rock placement (Qld)

Introduction

- No single factor is more critical in determining the overall stability of a rock chute than the size of the rock.
- Rock size is normally presented in terms of the equivalent diameter of the mean rock size (d_{50}).
- However, the diameter of the rock is not the only factor that determines the stability of an individual rock.

Constructed rock chute (Qld)

Safety factor (SF)

- For low risk sites, a safety factor of **1.2** is recommended.
- Examples of low-risk structures include:
  - most bank stabilisation measures
  - riffles and chutes in low-gradient creeks
- For high risk sites, a safety factor of **1.5** is recommended, for example:
  - bed stabilisation in steep creeks
  - areas of very high turbulence.

Rounded river rock (USA)

Effects of rock shape (K_1)

- Fractured or angular rock is generally more stable than rounded rock.
- Most rock sizing equations, including those presented within this document, are based on the use of fractured (angular) rock.
- A correction factor ($K_1 = 1.36$) must be applied if <u>rounded</u> rock is used.
- This means rounded rock needs to be 36% larger than angular rock.


Gravel-based creek (Qld)

Exposure of individual rocks to high velocity flow

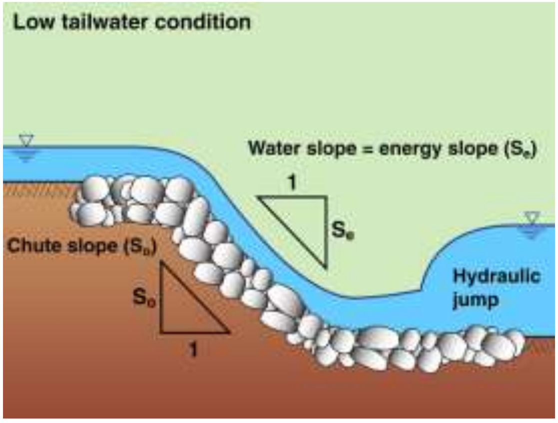
- The occasional exposed boulder can provide:
  - a more natural (random) appearance
  - resting areas for migrating fish.
- However, such exposure increases the potential hydraulic forces on the rock.
- Suggested sizing considerations include:
  - diameter > 2 d_{50} typical equal to d_{100}
  - diameter [mm] greater than 60 V^2.

Rock chutes and rock ramps – Design flow conditions

Partially drowned chute (Qld)

Introduction

- The hydraulic forces on the chute rock vary with:
  - flow velocity
  - the degree of turbulence.
- As the channel flow (Q) increases, it is normal for the tailwater level to also increase, which means the rock chute slowly becomes submerged.
- The rock size specified for the rock chute must be checked for three flow conditions: low, medium, and high tailwater.

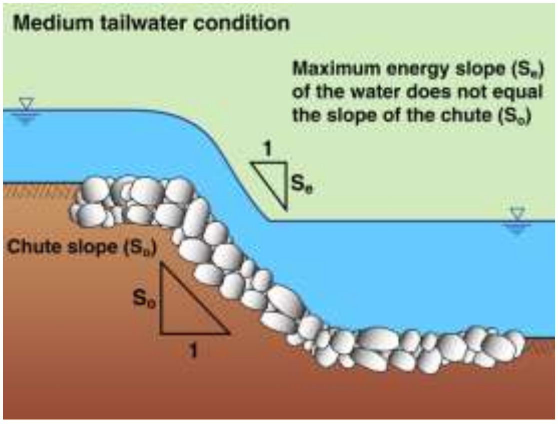


Low tailwater condition

Low tailwater condition

- In this condition, tailwater levels are so low that uniform flow conditions are usually developed down the chute (i.e. the water slope equals the energy slope equals the chute slope).
- Mean rock size should be checked against the following equation.

$$d_{50} = \frac{1.27 . SF . K_1 . K_2 . S_o^{0.5} . q^{0.5} . y^{0.25}}{(s_r - 1)}$$

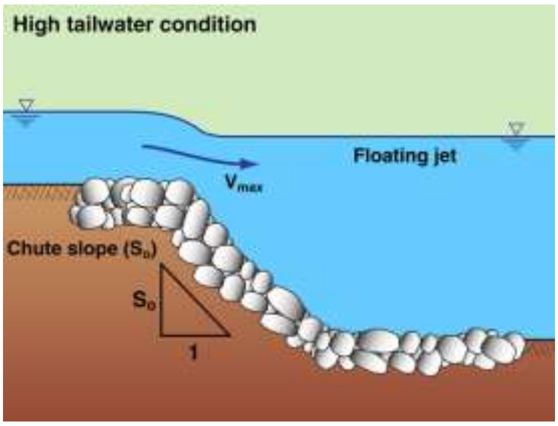


Medium tailwater condition

Medium tailwater condition

- In this condition, tailwater levels begin to drown out the chute, and the maximum energy gradient does not equal the slope of the chute.
- Mean rock size should be checked against the following equation.

$$d_{50} = \frac{1.27 . SF . K_1 . K_2 . S_o^{0.5} . V^{2.5} . y^{0.75}}{V_o^{2.0} (s_r - 1)}$$



High tailwater condition

High tailwater condition

- In this condition, tailwater levels are so high that the rock chute is fully or partially drowned out.
- The falling 'jet' is likely to separate from the rock chute and begin to float.
- Mean rock size for the <u>crest</u> rock should be checked to ensure that it exceeds the general rock sizing equation for normal stream flow, i.e. Equation 10.9.

$$d_{50} \text{ [mm]} = 40\, V^2 \qquad (10.9)$$

Sizing rock for the face of waterway and batter chutes

Application	Equation
Application of Equation 10.10 • The preferred design equation. • Applicable for uniform flow conditions only, $S_e = S_o$ • Batter slopes (S_o) flatter than 50% (1 in 2)	**Equation 10.10** $d_{50} = \frac{1.27.SF.K_1.K_2.S_o^{0.5}.q^{0.5}.y^{0.25}}{(s_r - 1)}$
Application of Equation 10.11 • A simplified equation independent of flow depth. • Applicable for uniform flow conditions only, $S_e = S_o$ • Batter slopes (S_o) flatter than 50% (1 in 2)	**Equation 10.11** $d_{50} = \frac{SF.K_1.K_2.S_o^{0.47}.q^{0.64}}{(s_r - 1)}$
Application of Equation 10.12 • A simplified, velocity-based equation. • Applicable for uniform flow conditions only, $S_e = S_o$ • Batter slopes (S_o) flatter than 33% (1 in 3)	**Equation 10.12** $d_{50} = \frac{SF.K_1.K_2.V^2}{(A - B.\ln(S_o)).(s_r - 1)}$ For SF = 1.2: A = 3.95, B = 4.97 For SF = 1.5: A = 2.44, B = 4.60
Application of Equation 10.13 • Suitable for use in the design of partially drowned waterway chutes. • Applicable for steep gradient, non-uniform flow conditions, $S_e \neq S_o$ • Batter slopes (S_o) flatter than 50% (1 in 2)	**Equation 10.13** $d_{50} = \frac{1.27.SF.K_1.K_2.S_o^{0.5}.V^{2.5}.y^{0.75}}{V_o^{2.0}(s_r - 1)}$

where:

- d_X = nominal rock size (diameter) of which X% of the rocks are smaller [m]
- A & B = equation constants
- K = equation constant based on flow conditions
  = 1.1 for low-turbulence, deep water flow; 1.0 for low-turbulence shallow water flow; and 0.86 for highly turbulent and/or supercritical flow
- K_1 = correction factor for rock shape
  = 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)
- K_2 = correction factor for rock grading
  = 0.95 for poorly graded rock ($C_u = d_{60}/d_{10} < 1.5$), 1.05 for well graded rock ($C_u > 2.5$), otherwise $K_2 = 1.0$ ($1.5 < C_u < 2.5$)
- ln = means natural logarithm to base-e
- q = flow per unit width down the embankment [m^3/s/m]
- s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, typically 2.6; limestone 2.6; basalt 2.7–3.2)
- S_e = slope of energy line [m/m]
- S_o = bed slope = tan(θ) [m/m]
- SF = factor of safety
- V = actual depth-average flow velocity at location of rock [m/s]
- V_o = depth-average flow velocity based on **uniform** flow down a slope, S_o [m/s]
- y = depth of flow at a given location [m]
- θ = slope of channel bed [degrees]

Table 10.3 provides suggested safety factor values. Tables 10.4 and 10.5 provide mean rock size (rounded up to the next 0.1 m unit) for angular rock, for a factor of safety of both 1.2 and 1.5. These tables are based on Equation 10.10, and are best used in the design of long chutes. Use of the 'unit flow rate' (q) as the primary design variable is preferred to the use of flow velocity (V) because it avoids errors associated with the selection of Manning's roughness.

Alternatively, tables 10.6 and 10.7 provide mean rock size for angular rock and a safety factor of 1.2 and 1.5, based on a modification of Equation 10.10, but with flow velocity presented as the primary variable. These tables are best used in the design of waterway chutes where uniform flow conditions are unlikely to be achieved down the face of the chute.

Table 10.3 – Recommended safety factor for use in determining rock size

Safety factor (SF)	Recommended usage	Example site conditions
1.2	• Low risk structures. • Permanent rock chutes with all voids filled with soil and pocket planted.	• Waterway chutes where failure of the structure is likely to result in easily repairable soil erosion.
1.5	• High risk structures. • Failure of structure may cause loss of life or irreversible property damage.	• Waterway chutes where failure of the structure may cause severe gully erosion or damage to important infrastructure.

Thickness and height of rock layer

The thickness of the armour layer should be sufficient to allow at least two overlapping layers of the nominal rock size. The thickness of rock protection must also be sufficient to accommodate the largest rock size. In order to allow at least two layers of rock, the minimum thickness of rock protection (T) can be approximated by the values presented in Table 9.6.

Generally, the minimum height of the rock protection placed on the banks should be equal to the critical flow depth (at the crest) plus 0.3 m.

Rock type and grading

Crushed rock is generally more stable than natural rounded rock; however, rounded rock has a more 'natural' appearance. A 36% increase in rock size is recommended for rounded rock (i.e. K_1 = 1.36). Typical rock densities (s_r) are presented in Table 9.4.

The rock should be durable and resistant to weathering, and should be proportioned so that neither the breadth nor the thickness of a single rock is less than one-third of its length. Maximum rock size generally should not exceed twice the nominal (d_{50}) rock size. On very steep grades, the maximum rock size should not exceed 1.25(d_{50}).

Backing material or filter layer

A geotextile filter is unlikely to be required (or desired) under the bed of a waterway chute.

However, in gullies, these chutes must be placed over a layer of suitably graded filter rock, or geotextile filter cloth (minimum 'bidim A24' or the equivalent). The geotextile filter cloth must have sufficient strength and must be suitably overlapped to withstand the placement of the rock.

If the rock is placed on a dispersive (e.g. sodic) soil (a condition **not** recommended), then prior to placement of filter cloth, the exposed bank **must** first be covered with a layer of non-dispersive soil, typically minimum 200 mm thickness, but preferably 300 mm.

Placement of vegetation over the rock

Vegetating rock chutes can significantly increase the stability of these structures, but can also reduce their hydraulic capacity. Obtaining experienced, expert advice is always recommended before establishing vegetation on waterway structures.

Table 10.4 – Uniform flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.2

Safety factor, SF = 1.2			Specific gravity, s_r = 2.4		Size distribution, d_{50}/d_{90} = 0.5			
Unit flow rate ($m^3/s/m$)	Bed slope = 1:10		Bed slope = 1:15		Bed slope = 1:20		Bed slope = 1:30	
	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}
0.1	0.10	**0.10**	0.10	**0.10**	0.10	**0.05**	0.11	**0.05**
0.2	0.15	**0.10**	0.16	**0.10**	0.16	**0.10**	0.17	**0.10**
0.3	0.20	**0.20**	0.21	**0.20**	0.21	**0.10**	0.22	**0.10**
0.4	0.25	**0.20**	0.25	**0.20**	0.26	**0.20**	0.27	**0.10**
0.5	0.28	**0.20**	0.29	**0.20**	0.30	**0.20**	0.31	**0.20**
0.6	0.32	**0.30**	0.33	**0.20**	0.34	**0.20**	0.35	**0.20**
0.8	0.39	**0.30**	0.40	**0.30**	0.41	**0.20**	0.43	**0.20**
1.0	0.45	**0.30**	0.47	**0.30**	0.48	**0.30**	0.50	**0.20**
1.2	0.51	**0.40**	0.53	**0.30**	0.54	**0.30**	0.56	**0.20**
1.4	0.56	**0.40**	0.58	**0.30**	0.60	**0.30**	0.62	**0.30**
1.6	0.62	**0.40**	0.64	**0.40**	0.65	**0.30**	0.68	**0.30**
1.8	0.67	**0.50**	0.69	**0.40**	0.71	**0.30**	0.73	**0.30**
2.0	0.72	**0.50**	0.74	**0.40**	0.76	**0.40**	0.79	**0.30**
3.0	0.94	**0.60**	0.97	**0.50**	0.99	**0.50**	1.03	**0.40**
4.0	1.14	**0.80**	1.17	**0.60**	1.20	**0.60**	1.25	**0.50**
5.0	1.32	**0.90**	1.36	**0.70**	1.40	**0.60**	1.45	**0.50**

[1] Flow depth is expected to be highly variable due to whitewater (turbulent) flow conditions.

Table 10.5 – Uniform flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.5

Safety factor, SF = 1.5			Specific gravity, s_r = 2.4		Size distribution, d_{50}/d_{90} = 0.5			
Unit flow rate ($m^3/s/m$)	Bed slope = 1:10		Bed slope = 1:15		Bed slope = 1:20		Bed slope = 1:30	
	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}
0.1	0.11	**0.10**	0.11	**0.10**	0.11	**0.10**	0.11	**0.05**
0.2	0.17	**0.20**	0.17	**0.20**	0.18	**0.10**	0.18	**0.10**
0.3	0.22	**0.20**	0.23	**0.20**	0.23	**0.20**	0.24	**0.10**
0.4	0.26	**0.20**	0.27	**0.20**	0.28	**0.20**	0.29	**0.20**
0.5	0.31	**0.30**	0.32	**0.20**	0.32	**0.20**	0.34	**0.20**
0.6	0.35	**0.30**	0.36	**0.30**	0.37	**0.20**	0.38	**0.20**
0.8	0.42	**0.40**	0.43	**0.30**	0.44	**0.30**	0.46	**0.20**
1.0	0.49	**0.40**	0.50	**0.30**	0.51	**0.30**	0.53	**0.30**
1.2	0.55	**0.50**	0.57	**0.40**	0.58	**0.30**	0.60	**0.30**
1.4	0.61	**0.50**	0.63	**0.40**	0.64	**0.40**	0.67	**0.30**
1.6	0.67	**0.50**	0.69	**0.50**	0.70	**0.40**	0.73	**0.30**
1.8	0.72	**0.60**	0.74	**0.50**	0.76	**0.40**	0.79	**0.40**
2.0	0.77	**0.60**	0.80	**0.50**	0.82	**0.50**	0.85	**0.40**
3.0	1.01	**0.80**	1.04	**0.70**	1.07	**0.60**	1.11	**0.50**
4.0	1.23	**1.00**	1.27	**0.80**	1.30	**0.70**	1.34	**0.60**
5.0	1.43	**1.10**	1.47	**0.90**	1.50	**0.80**	1.56	**0.70**

[1] Flow depth is expected to be highly variable due to whitewater (turbulent) flow conditions.

Table 10.6 – Velocity-based design table for mean rock size, d_{50} (m) for SF = 1.2

Safety factor, SF = 1.2			Specific gravity, s_r = 2.4			Size distribution, d_{50}/d_{90} = 0.5		
Local velocity (m/s)	Bed slope (V:H)							
	1:2	1:3	1:4	1:6	1:10	1:15	1:20	1:30
0.5	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.8	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.05
1.0	0.20	0.10	0.10	0.10	0.10	0.10	0.05	0.05
1.3	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10
1.5	0.30	0.30	0.20	0.20	0.20	0.20	0.20	0.10
1.8	0.40	0.30	0.30	0.30	0.20	0.20	0.20	0.20
2.0	0.50	0.40	0.40	0.30	0.30	0.30	0.20	0.20
2.3	0.60	0.50	0.50	0.40	0.30	0.30	0.30	0.30
2.5	0.70	0.60	0.60	0.50	0.40	0.40	0.30	0.30
2.8	0.80	0.70	0.70	0.60	0.50	0.40	0.40	0.40
3.0	1.00	0.90	0.80	0.70	0.60	0.50	0.50	0.40
3.5	1.30	1.10	1.00	0.90	0.80	0.70	0.60	0.60
4.0	1.70	1.50	1.30	1.20	1.00	0.90	0.80	0.70
4.5	2.10	1.90	1.70	1.50	1.20	1.10	1.00	0.90
5.0				1.80	1.50	1.30	1.20	1.10
6.0						1.90	1.70	1.60

[1] Based on uniform flow conditions, safety factor = 1.2, rock specific gravity of 2.4, and a rock size distribution such that the largest rock is approximately twice the size of the mean rock size.

Table 10.7 – Velocity-based design table for mean rock size, d_{50} (m) for SF = 1.5

Safety factor, SF = 1.5			Specific gravity, s_r = 2.4			Size distribution, d_{50}/d_{90} = 0.5		
Local velocity (m/s)	Bed slope (V:H)							
	1:2	1:3	1:4	1:6	1:10	1:15	1:20	1:30
0.5	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.8	0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05
1.0	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10
1.3	0.30	0.30	0.20	0.20	0.20	0.20	0.20	0.10
1.5	0.40	0.30	0.30	0.30	0.20	0.20	0.20	0.20
1.8	0.50	0.50	0.40	0.40	0.30	0.30	0.30	0.20
2.0	0.70	0.60	0.50	0.50	0.40	0.40	0.30	0.30
2.3	0.80	0.70	0.60	0.60	0.50	0.40	0.40	0.40
2.5	1.00	0.90	0.80	0.70	0.60	0.50	0.50	0.40
2.8	1.20	1.00	0.90	0.80	0.70	0.60	0.60	0.50
3.0	1.40	1.20	1.10	1.00	0.80	0.70	0.70	0.60
3.5	1.90	1.70	1.50	1.30	1.10	1.00	0.90	0.80
4.0			1.90	1.70	1.40	1.30	1.10	1.00
4.5					1.80	1.60	1.40	1.30
5.0						1.90	1.80	1.60
6.0								2.20

[1] Based on uniform flow conditions, safety factor = 1.5, rock specific gravity of 2.4, and a rock size distribution such that the largest rock is approximately twice the size of the mean rock size.

10.3 Ridge Rock Ramps

Ridge rock ramp (Qld)

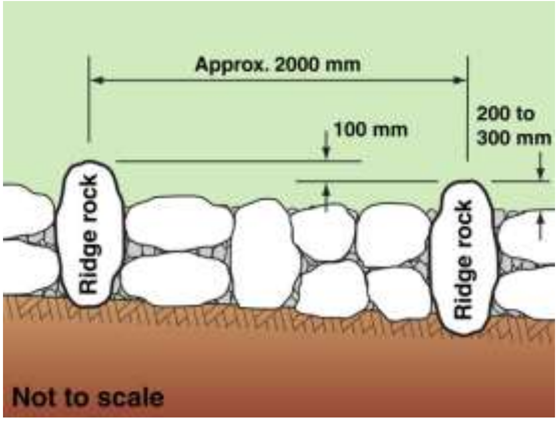
Description

- Ridge rock ramps consist of a series of rock weirs, each having a maximum water level fall of around 100 mm.
- Typically used on ephemeral waterways where water depths are around 100 to 300 mm during periods of low flow.
- Ridge rock ramps differ from traditional rock chutes and rock ramps in regards to how the rocks are arranged in the formation of each descending crest.

Rock fishway (NSW)

Ridge rock ramps

Ridge rock ramp (Qld)



Typical dimensions

Potential site for a ridge rock ramp (Qld)

Highly unstable gravel bed (Qld)

Introduction

- The author does not support the use of ridge rock ramps because he believes these structures are not durable.
- The durability of these structures depends on the stability of the 'foundations' of the structure, which in most cases depends on the stability of the waterway bed, which in most cases is unstable—because waterways are dynamic in their nature.
- To be effective, they need to be designed by the right people, and built with very close supervision.

General design parameters

- General design specifications are:
  - spacing of rock ridges = 2 m
  - fall across a rock ridge = 100 mm
  - overall gradient = 1 in 20
  - maximum total fall = 1000 mm.
- Each ridge is formed from rocks with a length of around 600–1000 mm, standing vertically, and recessed into a bed of tightly packed smaller rocks such that just 200–300 mm of the ridge rock is exposed.

Placement in fixed-bed creeks

- Both rock-based and clay-based creeks can be termed fixed-bed creeks, because in a catchment with stable hydrology, these creeks should be relatively stable.
- Rock-based creeks can provide a stable foundation, but may rely on grout to anchor the rocks to the bedrock.
- In clay-based creeks it is important to provide a stable downstream anchor (bookend) that can prevent any undermining of the structure (foundations mimic that of the old Roman road style).

Placement in alluvial creeks

- Alluvial waterways include sand-based and gravel-based creeks.
- Ridge rock ramps should not be constructed in deep sand-based creeks.
- The stability of a ridge rock ramp in a gravel-based creek depends on the frequency of major bed movement, which can totally destroy the structure.
- Natural bed gravels will eventually migrate over the ridge rock ramp, which can either enhance or diminish the ramp's fish passage attributes.

Baffled fishways

Precast concrete fishway (Qld)

Introduction

- Precast concrete units can be used as an alternative to ridge rock ramps.
- Such units can be used to form bypass fishways that are built to the side of, or separate to, the main waterway channel.
- These fishways have been used to provide fish passage through roadway culverts that have become 'elevated' as a result of downstream bed erosion.
- These structures do not repair the channel erosion, but they can help to return fish passage to the waterway.

Downstream end of fishway (Qld)

Directing fish to the fishway

- It is important that the design of the fishway allows fish to readily find the downstream entrance to the fishway.
- Ideally, flow conditions should not allow fish to swim past the entrance to the fishway as they migrate up the creek towards the fish barrier.
- Note: Birds collecting at the entrance to a fishway (as shown here) is a sign that fish are actually using the fishway.

Debris blockage of fishway (Qld)

Problems of organic and bed rock debris

- In natural riffles, the roundness of the riffle rock encourages flood debris to wash off the rocks.
- In precast baffle fishways, the baffles can (depending on their design) temporarily collect both organic debris as well as bed gravel.
- Subsequent stream flows can displace this debris, but in a long structure it only takes one blockage to stop all fish passage.

Upstream end of fishway (Qld)

Directing low flows into the fishway

- It is important that the design of the fishway allows low flows towards the upstream entrance of the fishway.
- If 100% of the low flows can be directed to the fishway, then this can improve the ability of fish to find the downstream entrance to the fishway.
- The images presented here are from a Walaman system installed on Enoggera Creek, Brisbane.