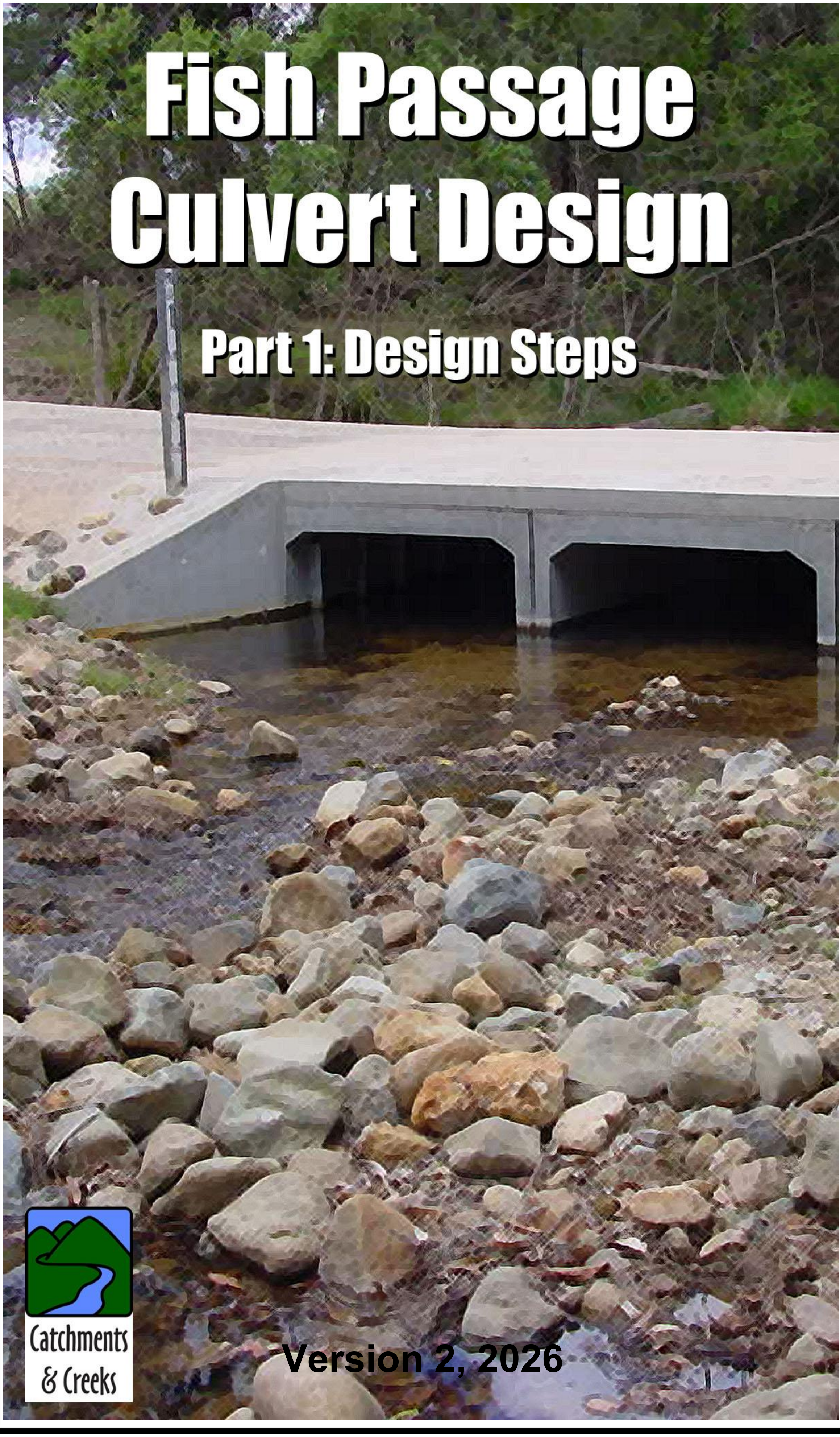
Fish Passage Culvert Design

Part 1: Design Steps



Version 2, 2026

Catchments & Creeks

Fish Passage Culvert Design – Part 1: Design Steps

Version 2, February 2026

Prepared and illustrated by: Grant Witheridge, Catchments and Creeks, Bargara, Queensland

Published by: Catchments and Creeks, Bargara, Queensland

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Cover image: Ewingar Creek culvert upgrade, North Ewingar Rd, Ewingar, NSW.

Note to Reader:
Readers should note that this document has been prepared by a civil engineer, with the focus being on the engineering aspects of fish passage at culvert crossings. The document has not been reviewed by a fisheries biologist, and as such does not present the complete picture.

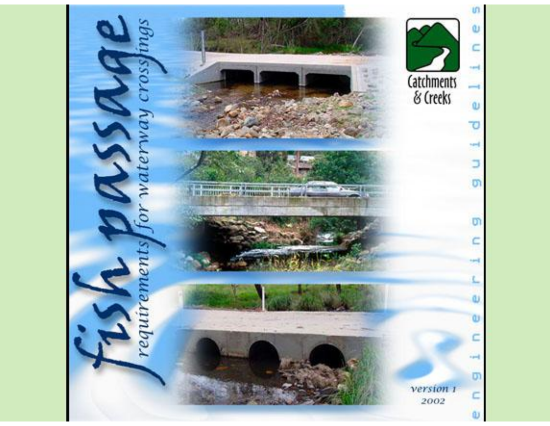
Disclaimer

To be effective, fish passage requirements at waterway crossings must be appropriately investigated, planned, and designed in a manner appropriate for the given work activity and site conditions.

Adoption of the recommendations and procedures presented within this document will not guarantee:

(i) compliance with any statutory obligations
(ii) compliance with fish passage outcomes
(iii) compliance with the structural or flood control requirements of the culvert
(iv) avoidance of environmental harm or nuisance
(v) appropriate outcomes for waterways located outside of Australia.

Principal reference documents

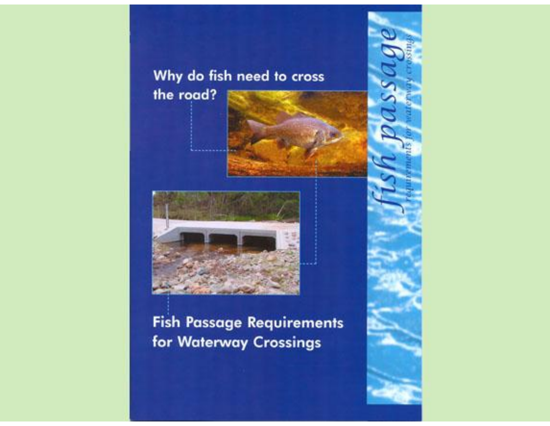


Catchments & Creeks Pty Ltd, 2002

Fish Passage Requirements for Waterway Crossings

Catchments & Creeks Pty Ltd. 2002 (CD-ROM).

[Discontinued](#) following the release of this Field Guide.

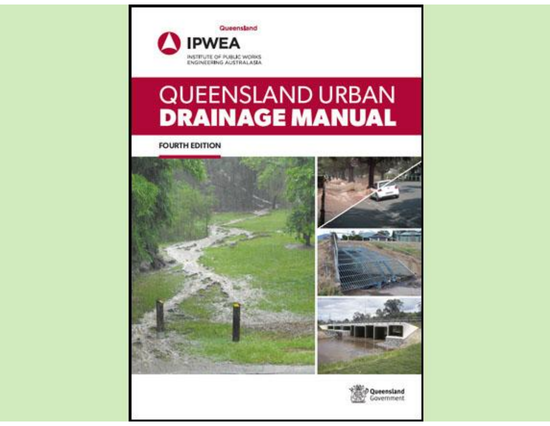


NSW Fisheries, 2003

Why do fish need to cross the road? – Fish Passage Requirements for Waterway Crossings

Fairfull and Witheridge, 2003, NSW Fisheries, Cronulla.

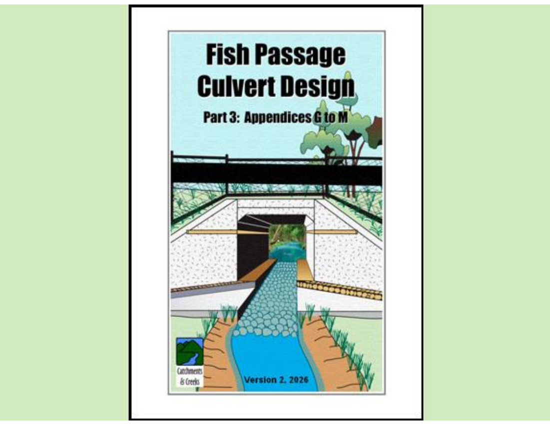
15 page colour booklet



Queensland Urban Drainage Manual

Queensland Urban Drainage Manual (QUDM)

Institute of Public Works Engineering Australia, Queensland Division and the Department of Energy and Water Supply. Brisbane, Australia, 4th edition, 2017.



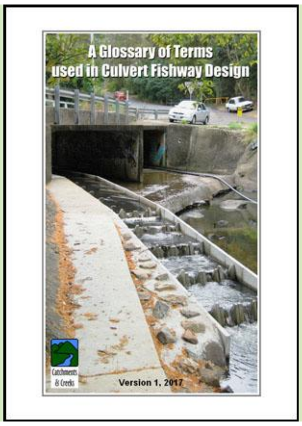
Fish Passage Culvert Design, Part 3

Fish Passage Culvert Design – Parts 2 & 3

Catchments & Creeks, Bargara Queensland.

Parts 2 and 3 of this three-part document, which was updated as Version 2 in 2026.

Related *Catchments and Creeks* field guides

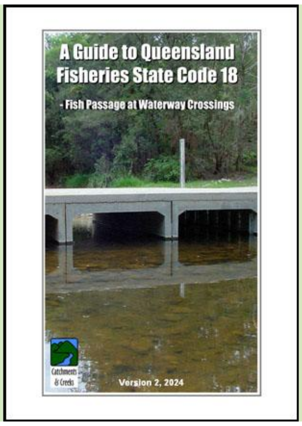


Glossary of Terms, 2017

A Glossary of Terms used in Culvert Fishway Design

Catchments & Creeks Pty Ltd, 2017, Brisbane Queensland.

This field guide provides photos and definitions of terms commonly used by engineers and fish biologists in the fish passage industry with specific reference to culvert design.

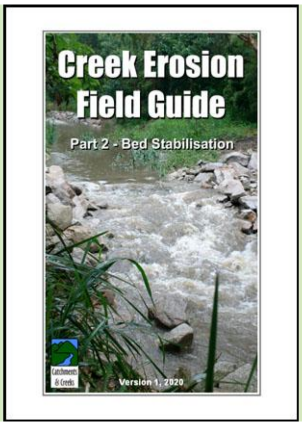


Queensland State Code 18, 2024

A Guide to Queensland Fisheries State Code 18

Catchments & Creeks, 2024, Bargara Queensland.

Published in October 2024.



Creek Erosion Field Guide, 2022

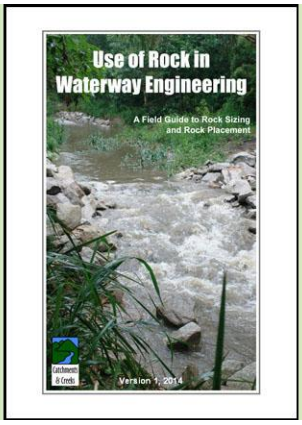
Creek Erosion Field Guide Part 2 – Bed Stabilisation

Catchments & Creeks Pty Ltd, 2022, Bargara Queensland.

Version 1, April 2021

Version 2, February 2022

Part 2 discusses the planning of creek erosion treatments, fish-friendly bed treatment, common properties of rock, the hydraulics of grade control structures, fish-friendly and non fish-friendly bed stabilisation techniques.



Use of Rock in Waterway Engineering

Use of Rock in Waterway Engineering

Catchments & Creeks Pty Ltd, 2020, Brisbane Queensland.

Version 1, 2014

Version 3, 2020

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

Contents

Purpose of field guide

This field guide has been prepared specifically to:

- provide educational information on fish passage at waterway culverts
- provide a quick reference guide to fish passage at culvert crossings
- provide a pictorial supplement to the various State Fisheries policies and design guidelines.

It is **not** the intention of this document to define the design standards for fish passage through waterway culverts. Such standards need to be set by Fisheries representatives from the various states and territories. This document is also **not** intended to be a detailed culvert design manual. Instead it is a 'supplement' to local Fisheries codes and engineering guidelines.

This document represents the opinions and recommendations of just one person, and a person without training in fish biology. As such, the document does not represent a holistic or balanced opinion. Readers should seek additional advice from their own experts.

The photos presented within this document do not necessarily represent current best practice, but are intended to represent the current topic of discussion. It would be near impossible to obtain a 'perfect' example for each 'topic'. No image (photo) presented in this document should be considered best practice without full knowledge of the site conditions.

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 had 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

A common mistake made by the writers of technical publications, particularly those with an environmental emphasis, is for the writer to use their document to convert the reader into a person that thinks like they do, or at least a person that has as much interest in the environment as they do.

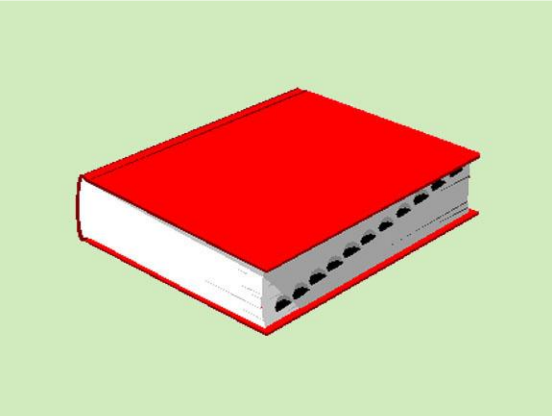
In my opinion, an engineer does not need to have a strong interest in roads in order to design a road, a strong interest in hydraulics in order to design a causeway, or a strong interest in fish in order to design a culvert. What designers need is knowledge of the design aims and standards, and respect for the key issues of public safety, crossing function, waterway hydraulics, financial issues, and the environment, which includes fish passage, terrestrial passage, and sediment control.

The aim of this document is not to change the 'interests' of the reader, or to provide detailed information on the biology of fish. The aim is to provide general waterway engineering information in order to explain the various engineering and hydraulics issues that can affect fish habitat and fish passage, and to assist engineers in designing fish-friendly waterway culverts.

In waterway design, the consideration of fish passage should not be viewed as an issue that may be required in some cases, but instead should be considered a normal part of best practice engineering design.

General note: This document adopts the hyphenated term 'fish-friendly' when it appears in front of a noun (e.g. 'fish-friendly culvert'), and the non-hyphenated term 'fish friendly' when the term stands in isolation (e.g. 'the culvert is required to be fish friendly').

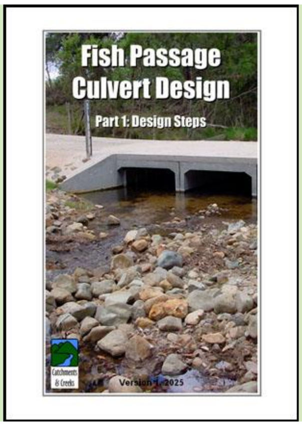
Layout of this three-part document



Document

Introduction

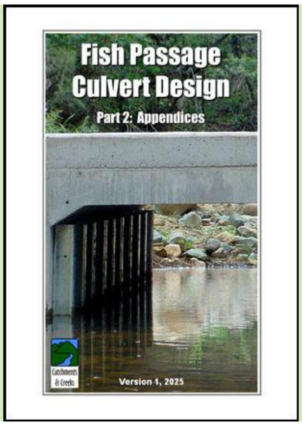
- For ease of use, this document has been split into three parts.
- Splitting the document into three parts allows Parts 2 & 3 to be open in separate windows while reviewing Part 1.



Fish Passage Culvert Design, Part 1

Part 1 – Design steps

- Part 1 introduces the topic of fish passage, and then provides a step-based procedure for the design of fish-friendly culverts.
- An expanded discussion on some of the design issues is provided in Parts 2 & 3.



Fish Passage Culvert Design, Part 2

Part 2 – Appendices A to F

Appendix A – State by State Policies and Guidelines (2024)

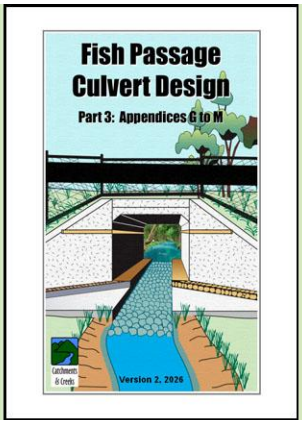
Appendix B – Organising a Design Team

Appendix C – An Introduction to Fish Passage and Fish Migration

Appendix D – The Importance of Boundary Layers

Appendix E – Baffle Selection and Design

Appendix F – Baffle Engineering and Hydraulics



Fish Passage Culvert Design, Part 3

Part 3 – Appendices G to M

Appendix G – Blockages

Appendix H – Safety Risks at Culvert Crossings

Appendix I – Culverts Located in High-Risk Soils

Appendix J – Terrestrial Passage Requirements at Culvert Crossings

Appendix K – Culvert Upgrades

Appendix L – Culvert Upgrade Case Studies

Appendix M – Terminology

The design team

Design team

Introduction

- In order to achieve a functional design, the design team must contain, or have access to, a range of professional inputs.
- A culvert design team would typically consist of:
  - local fisheries expert
  - engineers
  - terrestrial corridor expert.
- Local advice is essential if part of the design team is based at a distant location.

Fisheries biologist

Fisheries biologists

- Biologists (or other suitably trained professionals), are required to:
  - classify aquatic habitats
  - identify target species
  - identify feral species
  - identify migration triggers, timing, and likely movement pathways (i.e. along the bed, banks, or overbank)
  - identify potential conflicts between aquatic passage and terrestrial passage.

Engineer

Engineers

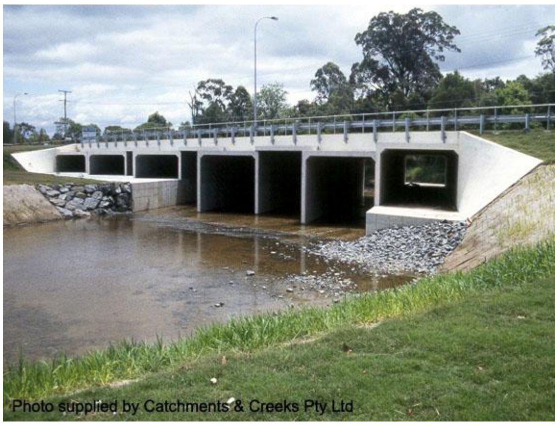
- Engineers and drafting personnel are required to investigate:
  - catchment hydrology
  - culvert hydraulics
  - pedestrian/road/rail design
  - foundation design
  - structural design
  - site revegetation (designers such as landscape architects).

Terrestrial ecologist

Terrestrial ecologists

- Wildlife officers (or other suitably trained professionals), are required to:
  - identify terrestrial movement corridors
  - identify terrestrial movement connectivity
  - identify target species
  - identify feral species
  - identify potential conflicts between aquatic passage and terrestrial passage.

Terminology



A culvert containing both wet and dry cells

Wet and dry cells

- Nominated 'wet' and 'dry' cells exist in order to promote the passage of both terrestrial and aquatic fauna.
- Wet cells have a floor level set below the normal dry-weather water level.
- Dry cells are designed to have a dry floor during low-flow conditions, which helps to promote native fauna movement.
- Each individual conduit in a culvert can be called a conduit, cell, barrel, or even a culvert.

Corrugated pipe culvert (NSW)

Box, pipe and corrugated culverts

- A box culvert contains rectangular conduits.
- A pipe culvert contains circular (pipe) conduits.
- A corrugated pipe culvert contains corrugated, circular, metal conduits.
- An arch bridge is not considered to be a 'culvert' because it is not a fully enclosed conduit (i.e. the structure does not enclose the channel bed).

Australian Smelt (Queensland Museum)

Fish

- With respect to fisheries legislation, the term 'fish' typically means any animal species that, throughout its life cycle, lives:
  - in water (whether freshwater or saltwater)
  - in or on foreshores
  - in or on land under water.
- Readers should refer to their local fisheries legislation for their State or Territory definition of 'fish'.

Waterway, watercourse, creek or stream

Waterway and fishways

- The term 'waterway' typically includes a river, creek, stream, watercourse, drainage feature, or inlet of the sea.
- Readers should again refer to their local fisheries legislation.
- The term 'fishway' refers to a constructed fish ladder, structure or device, by which fish can pass through, around, or over, a fish barrier—the term is more commonly associated with structures not defined as fish ladders.

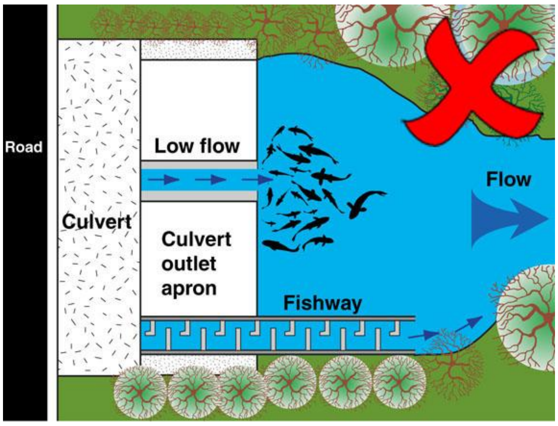
Fishway checklist

Design Checklist

Checklist

1. Does the culvert present an unacceptable safety risk to a person being swept through the culvert? Note: Safety issues take priority over fish passage, BUT these issues are <u>not</u> an excuse to ignore fish passage requirements.
2. Will fish find the entrance to the fishway, or are fish likely to swim past the fishway entrance as they continue to follow the dominant stream flow?
3. Will fish find the fishway during the full range of the expected fish-passage flow conditions?
4. Are suitable resting zones provided for fish within 'long' culverts?
5. Is the culvert suitable for fish moving along the bed, along the banks, and along the floodplain, as appropriate for the target fish species?
6. Is the fishway suitable for the expected range of target fish species and sizes?
7. Is the fishway free from excessive flow turbulence?
8. Are the levels of 'light' within the culvert appropriate for the target species?
9. Can fish bypass the culvert during overtopping flood events?
10. Are fish, to the maximum degree practical, protected from predators while passing along the fishway?
11. Will the culvert remain fish friendly if the downstream bed begins to lower from its current elevation?
12. Is the fishway compatible with the expected movement of bed sediments? This is typically an issue on alluvial (i.e. sand-based or gravel-based) waterways?
13. Is the culvert compatible with the expected movement of woody debris during flood events? Can woody debris become trapped inside the culvert? Can flood debris be easily removed by the asset manager?
14. Are the needs of the waterway being met?
15. Are the needs of the terrestrial wildlife being met?
16. Are all terrestrial pathways continuous from upstream to downstream (bank to bank)?
17. Are the needs of the local community being met?
18. Are flood flows and flooding conditions being appropriately managed?
19. Are the needs of the asset manager being met?
20. Does the asset manager have safe access to inspect the culvert?
21. Does the culvert discourage mosquito breeding?
22. Are the expected construction and maintenance costs affordable for the asset manager?

Fishway checklist



Poor fishway design

Floodwater overtopping a road culvert

Mary River Cod (Qld)

Sediment deposition within a fishway

Attracting flows

- Will fish find the entrance to the fishway?
- During periods of low flow, the fishway should either be the primary carrier of the base flow, or suitably integrated into the low-flow system such that fish will be attracted to the fishway entrance.
- Ideally, fish should not be able to swim past the entrance of the fishway as they swim towards the culvert.

A full range of expected flows

- Before anyone specifies that a fishway must be useable for a full range of flow conditions, they should think carefully.
- Remember, during a 1 in 100 year event, stream flows will likely operate below the 1 in 10 year (or even 1 in 2 year) flow rate for possibly 80% of the flood event.
- Designing for large flood events will only likely be required for critical habitats, and when fish migrate in response to flood events, and even then it is likely that a bridge will be used instead of a culvert.

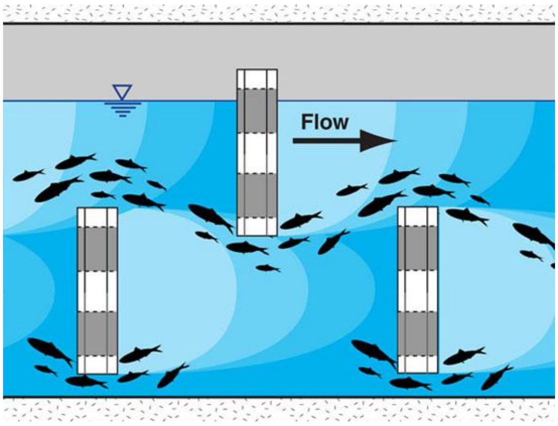
Understanding the needs of the fish

- So much of engineering design is based around understanding the needs of the client, or the target audience.
- The audience, or customers, may include:
  - road users
  - affected property owners, and
  - local fauna (aquatic and terrestrial).
- Designers need to know if fish passage is required during low flows and/or flood flows, and if fish passage is required along the sidewalls, and/or along the bed.

Understanding the characteristics of the waterway

- Different waterways have different characteristics, which interact differently to the fish passage features of a culvert.
- The critical difference is linked to the expected movement of bed material.
- Baffles located on the floor of a culvert must be compatible with the expected movement of bed material.
- A culvert must be compatible with the waterways as well as its aquatic fauna.

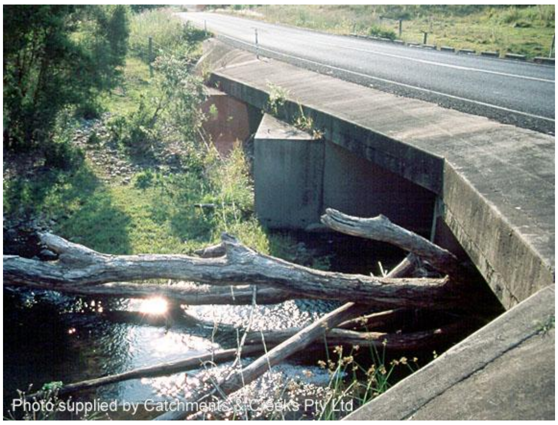
Fishway checklist



Fish swimming within the shadow zones

Baffles placed on wingwalls (Qld)

Rusted galvanised steel baffles (NSW)



Trapped woody flood debris (Qld)

Suitable resting areas

- Ensure the fishway has suitable resting areas.
- Where possible, design the fishway, and baffles, so that fish are able to swim the length of the culvert while remaining within a boundary layer, or within the shadow zones of the baffles.
- If fish need to enter high velocity flows in order to pass around a baffle, then this can limit fish passage to an average culvert flow velocity of less than 3.5 m/s.

Ensure connectivity

- Ensure:
  - fish swimming along the channel bed can pass over a suitably roughened culvert bed, and
  - fish swimming along the channel banks during elevated flows can swim along the wingwalls, and along the sidewall of the culvert, and
  - fish swimming over the floodplain can swim over the road, and through any floodplain culverts.

Understanding the service life of various materials

- The fish passage features of a culvert can be manufactured from various materials, including:
  - plastics
  - aluminium
  - galvanised steel
  - stainless steel
  - concrete.
- Each of these materials have a different service life, and maintenance costs.

Understanding the potential impacts of flood debris

- If you plan to recess a culvert in order to produce a 'pool' effect, then ask yourself if this 'pool' will simply fill with sediment during the first flood?
- If you plan to install baffles, will woody flood debris jam against these baffles and become trapped inside the culvert?
- Will the future manager of the culvert be willing and able to clean the inside of the culvert after each flood event?

Summary of design steps

Step 1: Site assessment

- Identify fish habitats.
- Identify the type of waterway: clay-based, sand-based, gravel-based, rock-based, or arid.

Step 2: Fish passage requirements

- Identify fish habitat zoning from State Fisheries.
- Refer to local state/territory guidelines (refer to Appendix A in Part 2).

Step 3: Type of fish passage

- Obtain a fisheries report (fish expert) on the likely fish passage needs of the culvert.

Step 4: Preferred type of crossing

- Understand those conditions where a culvert can be used instead of a bridge.

Step 5: Location and alignment

- Consider the issues for and against a certain crossing location and alignment.

Step 6: Design flow rates

- Select either a High Flow, Medium Flow, or Low Flow design process.
- Select the design storm conditions for the culvert and the fishway.

Step 7: Required flow area

- Determine the flow area required for a High Flow, Medium Flow, or Low Flow design.

Step 8: Desirable culvert width

- Different States have different rules on the minimum required culvert width. Designers, however, should focus on achieving the best overall outcome for fish passage, the culvert, and the waterway. Don't unnecessarily damage the waterway just to meet a random State Government ruling—instead, seek further advice from the State.

Step 9: Use of low-flow channels

- A decision needs to be made about whether to form a low-flow channel in the bed of the nominated wet cell, or to fully recess one or more wet cells (simulating a 'pool'), or to design the culvert bed to function as a riffle.
- The low-flow channel may be designed to achieve the previously stated Low Flow design.

Step 10: Bed gradient and elevation

- Fish-friendly outcomes are usually best achieved with a flat bed culvert; however, this may require the formation of a grade control structure at the culvert inlet.
- Sloping bed culverts can be made fish friendly, but they need to follow a different design procedure.

Step 11: Culvert inlet (flow entry)

- Culvert inlet considerations include: safety issues, grade control structures, debris control structures, sediment control structures, and the special positioning of baffles on the wingwalls.

Step 12: Debris blockage and control

- Debris control structures can take many different forms. Debris screens are different from inlet safety screens, and thus follow different design standards. In general, all reasonable and practical measures should be taken to avoid the use of inlet screens.

Step 13: Design of nominated wet cells

- Determine the total width of the wet cells, typically equal to the channel bed width.
- Determine the surface conditions of the culvert floor.

Step 14: Design of nominated dry cells

- Determine the width and elevation of the dry cells, and their bed (floor) condition.
- Discussion is also provided on the design of floodplain culverts.

Step 15: Design of sidewall baffles

- Determine baffle location, position, spacing, type, and width.
- Refer to Appendix E for information on the different types of baffles.
- Refer to Appendix F for baffle width, spacing and positioning, plus hydraulic details (Manning's roughness) of sidewall baffles, if not provided in Step 15.

Step 16: Assess the need for improved lighting conditions (wet cells)

- If the road has more than two lanes, then consideration should be given to the inclusion of a skylight into at least one of the wet cells.

Step 17: Assess the terrestrial passage requirements

- The needs of all target fauna must be considered, aquatic and terrestrial. Specifications for sidewall baffles must take into account the need for terrestrial passage.

Step 18: Hydraulic analysis

- Hydraulic analysis can only be performed when the general layout of the culvert is known.

Step 19: Culvert outlet (flow exit)

- Consideration of outlet jetting.

Step 20: Erosion control at culvert outlets

- Design information on rock pad outlets.

Step 21: Safety issues

- Discussion of safety risks and potential mitigation measures.
- Design information on inlet safety screens.
- A risk assessment procedure is presented in Appendix H of Part 3.

Step 22: Landscaping and vegetation design adjacent to culverts

- Information provided on the critical landscaping zones.

Step 23: Culvert maintenance

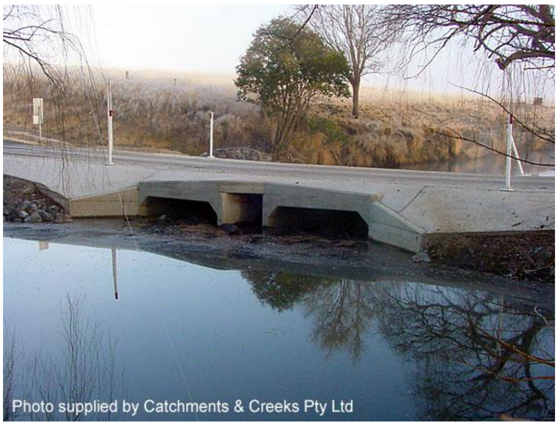
- Guidance on maintenance access ramps.
- Guidance on post-flood maintenance activities.

Design Steps

Design steps

Culvert design

Guyra, NSW



Tenterfield, NSW

Ewingar, NSW

Introduction

- The following design procedure is just one approach to the design of fish-friendly waterway culverts, but it is not the only acceptable approach.
- The procedure is based on the stream simulation method of fish passage design; however, the design procedure does not address:
  - structural design issues
  - flood control issues
  - detailed engineering plans.

Culvert design procedure

Step 1: Site assessment

Step 2: Fish passage requirements

Step 3: Type of fish passage

Step 4: Preferred type of crossing

Step 5: Location and alignment

Step 6: Design flow rates

Step 7: Required flow area

Step 8: Desirable culvert width

Step 9: Low-flow channels

Step 10: Bed gradient and elevation

Step 11: Hydraulic analysis

Step 12: Culvert inlet

Step 13: Design of nominated wet cells

Step 14: Design of nominated dry cells

Step 15: Design of sidewall baffles

Step 16 Assess the need for improved lighting conditions within wet cells

Step 17 Assess the terrestrial passage requirements

Step 18: Hydraulic analysis

Step 19: Culvert outlet

Step 20: Erosion control at outlets

Step 21: Safety issues

Step 22: Landscaping

Step 23: Maintenance access

Step 1 - Site Assessment

Small fish taking shelter in rocks (Qld)

Site inspection

Typical site observations include:

- Observations of existing aquatic life within the waterway.
- Observations of aquatic habitats within the waterway—this would include any permanent water bodies upstream of the crossing.
- The type of information that needs to be observed and recorded should be specified by a fisheries expert.

A natural barrier to fish passage (Qld)

Existing barriers to fish passage

Typical site observations include:

- Observations of existing barriers to fish passage upstream and downstream of the proposed crossing.
- The expected operational life of these barriers (if constructed), and the likelihood of their rehabilitation.
- Assessment of potential debris flows down the waterway, and the likely impacts of debris blockages on fish passage.

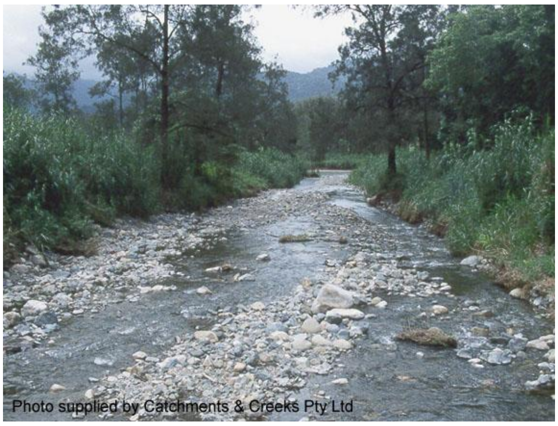
Gravel-based waterway (Qld)

Channel data

Typical site observations include:

- Description of the bed material, e.g. loose or fixed bed material; vegetated or non-vegetated; clay, sand, gravel or boulders.
- General dimensions (depth and width), spacing and location of any pool-riffle systems within the channel.
- Mean d_{50} and d_{90} (the rock size of which 90% of rocks are smaller) rock size on the bed, and within any riffle system.

Types of waterways



Gravel-based alluvial watercourse (Qld)

Alluvial waterways

- Alluvial waterways are formed from flood-laid deposits of silt, sand and gravel, but the term most commonly refers to sand-based and gravel-based waterways.
- These are moving bed waterways that experience significant natural substrate movement (as opposed to 'fixed bed' waterways).
- The term is generally not applied to clay-based creeks, even if these creeks contain significant quantities of introduced sediment.

Dry, ephemeral, semi-arid waterway (NSW)

Arid and semi-arid waterways

- Arid and semi-arid waterways are often treated as a separate waterway category due to the reduced influence of vegetation on the channel's size and stability.
- In arid regions it can be difficult to distinguish between a waterway and a drainage line.
- These waterways can share many characteristics with coastal waterways, including a wide flat channel bed, which is found in most sand-based and gravel-based waterways.

Well-vegetated drainage line (Qld)

Drainage lines

- A drainage line is a stormwater drainage pathway (or overland flow path) that carries concentrated flow (not sheet flow).
- These drains are likely to flow only while rain is falling, and possibly for short periods (hours) after rainfall has stopped.
- Drainage lines are generally not considered to be waterways, or fish habitats.

Ephemeral watercourse (Qld)

Ephemeral watercourses

- An ephemeral watercourse is a waterway that is expected to experience regular periods of zero-flow.
- In many locations, dry ephemeral waterways can look remarkably similar to drainage lines—even experts can disagree on what is a 'dry creek' and what is a 'drainage line'.
- An ephemeral watercourse may contain permanent pools that may, or may not, be considered as fish habitats (but they usually are fish habitats).

Types of waterways

Major waterway (Ipswich, Qld)

Major waterways

- Major waterways are most commonly referred to as rivers.
- In some regions of Australia, as well as within the upper regions of most rivers, these waterways can be so narrow that their behaviour is more closely aligned with the behaviour of minor waterways.
- In major waterways, bank vegetation can play a major role in providing post-flood bank stability, but during a flood, it is the floodwater that usually dominates over the vegetation.

Minor urban waterway (Brisbane, Qld)

Minor waterways

- Within this field guide, the term minor waterway is used to describe a narrow-bed waterway where vegetation type and density is often the dominant factor in determining the size and stability of the channel.
- 'Springs', 'brooks' and 'creeks' are the terms most likely to be used to describe minor waterways.
- These waterways normally have a low stream order classification (i.e. 1, 2, or 3).

Small rural stream (Guyra, NSW)

Springs, streams and brooks

- Springs, streams and brooks are minor waterways that experience a sustained base flow that may or may not be permanent.
- These waterways are typically sourced from well-established groundwater springs, or seasonal snowmelts.
- These waterways can be ephemeral, but a near-constant base flow (dry-weather flow) is a common occurrence.

Tidal waterway (Brisbane, Qld)

Tidal waterways

- Tidal waterways can be grouped under a variety of classifications including, creeks, rivers and estuaries.
- These waterways are usually classified as critical fish habitats.
- Strict rules apply to any disturbance of these waters and their associated vegetation.
- Regulations may also apply to the disturbance, or removal of, woody debris (refer to the local Fisheries office).

A waterway classification system based on 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.
- These waterways typically 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 of sand-based waterways.
- 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 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 re-form during flood events.
- 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 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 that usually contain 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.

Examples of Australian clay-based waterways

Albany Creek, Brisbane, Qld

Clay-based waterways

- Many of the urban creeks found in Adelaide, Brisbane, Melbourne and Sydney can be classified as clay-based waterways.
- Due to the clayey soils it can be difficult for vehicles to cross these waterways at bed level; thus making bed level vehicle crossings (fords) impractical.
- Correct plant selection and planting densities are critical for achieving long-term channel stability.

Little Cabbage Tree Ck, Brisbane, Qld

Roma, Queensland

Rapid Creek, Darwin, NT

Norman Creek, Brisbane, Qld

Kedron Brook, Brisbane, Qld

West of Cobar, NSW

Examples of Australian sand-based waterways

Ten Mile Creek, North of Mackay, Qld

Sand-based waterways

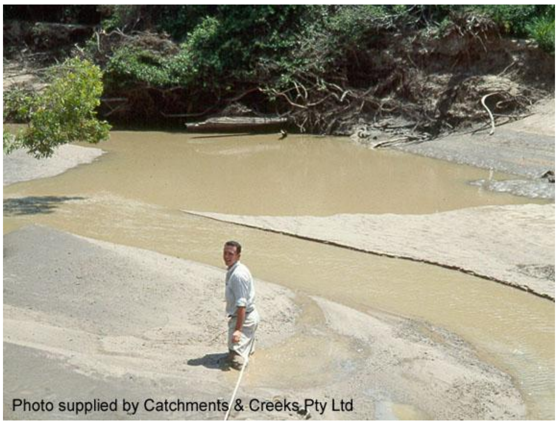
- Sand-based waterways are often found in landscapes dominated by granite rock (of course exceptions do exist).
- Geologists can point out the relationship that typically exists between the make-up of a waterway, and the parent rock that exists within the upper catchment.
- Sand-based waterways are also commonly found in catchments that contain dispersive or slaking soils—this can be a warning sign of soil issues when performing a site inspection.

Tributary of the Upper Burnett River, Qld

Ipswich, Queensland

Chinchilla, Queensland

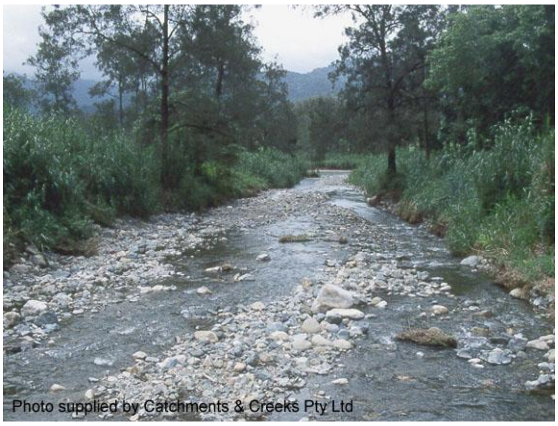
Fern Creek, Coffs Harbour, NSW



Oxley Creek, Brisbane, Queensland

Brogo River, Bega, NSW

Examples of Australian gravel-based waterways



Broken River, Eungella, Queensland

Gravel-based waterways

- Gravel-based waterways are the sleeping giants of our waterways.
- These waterways can look so calm and peaceful for decades; they are the waterways that people love to photograph and have as posters on their office walls.
- But when disturbed by a major flood, these waterways can be **very** destructive, causing significant bank erosion and damage to, or total loss of, long-established riparian vegetation.

Liffey Falls, Tasmania

Buaraba, Esk, Queensland

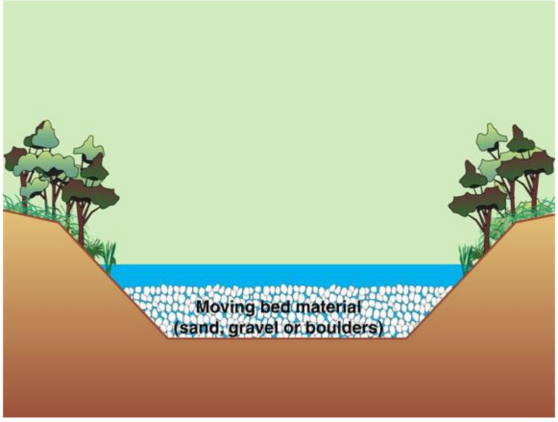
Samford, Queensland

Snowy Mountains NP, NSW

Marne River, South Australia

Upper South Pine River, Samford, Qld

Comparing alluvial waterways with clay-based waterways

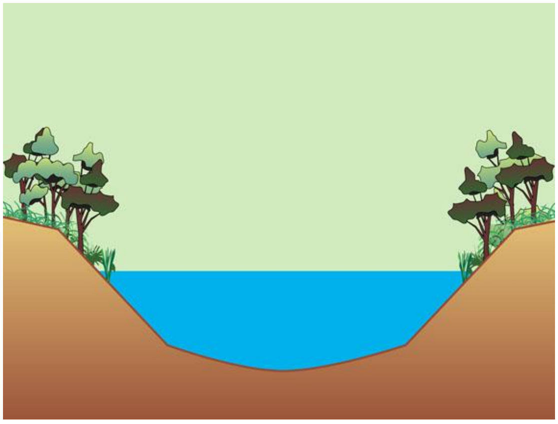


Flat-bed alluvial waterway

Alluvial (moving bed) rivers

- If you have ever watched a Western movie of wagon trains heading west, or the U.S. cavalry chasing down 'bad guys', then you would have probably seen horses, cattle and covered wagons, crossing rivers.
- If the river is wide, and the depth of the water is near-constant across the river bed, then this is almost certainly an alluvial waterway.
- A 'flat bed' indicates that the bed material is very mobile and self-levelling during flood events.

Crossing of a shallow-water alluvial river (USA)



V or U-shaped channel profile

Clay-based (fixed bed) rivers

- There can be times in these movies when horse riders were forced to take a barge ride across a river (e.g. the movie 'True Grit'), or where the water was so deep that horses and cattle were required to swim.
- These waterways are likely to be clay-based waterways that do not experience significant bed flow as part of their natural behaviour.
- Or maybe they could just be very deep alluvial waterways!

Raft crossing a deep-water river (USA)

Examples of Australian rock-based waterways

Naps Creek, Beaudesert, Qld

Rock-based waterways

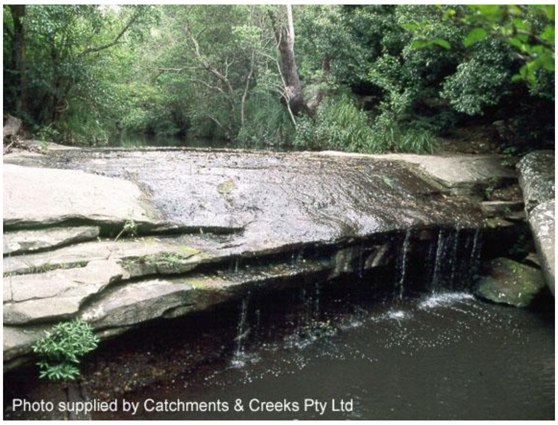
- Rock-based creeks often exist as sections of exposed bed rock located within what is otherwise a clay, sand, or gravel-based creek.
- In the steep upper reaches of some creeks, the exposed rocky bed may extend for a significant length of the waterway.
- Each rock exposure can act like a fish barrier, but viable fish habitats can still exist upstream of these rock outcrops due to fish passage during flood events.

Gowrie Creek, Toowoomba, Qld

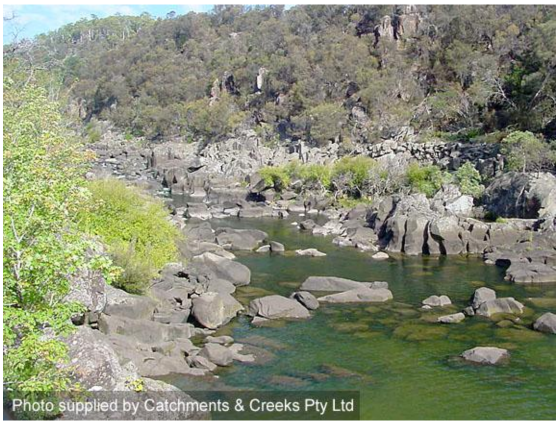
Spicers Creek, near Wellington, NSW

Ithaca Creek, Brisbane, Qld

Upper reaches of South Pine River, Qld

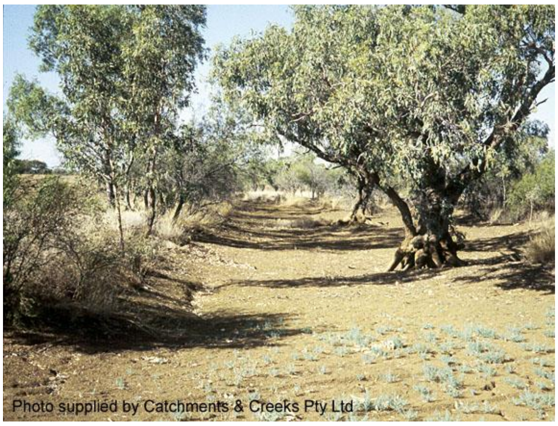


Terrys Creek, Sydney, NSW



Cataract Gorge, Launceston, Tas

Examples of Australian arid and semi-arid waterways



Central Queensland near Alpha, Qld

Arid and semi-arid waterways

- Arid and semi-arid waterways can be difficult to classify.
- Minor arid waterways are more likely to behave like clay-based waterways if they are located away from rocky escarpments.
- Major arid waterways can behave like sand-based waterways given the large volumes of mobile bed sediment.
- Some arid waterways can support significant aquatic life during flood events.

Kings Canyon, Northern Territory

West of Cobar, NSW

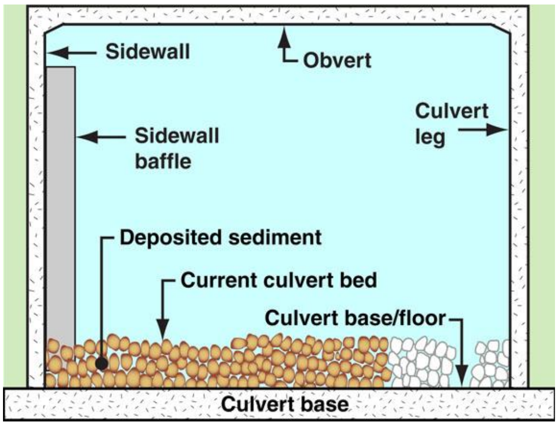
Dolo Creek, Broken Hill, NSW

Black Hill Creek, Silverton, NSW

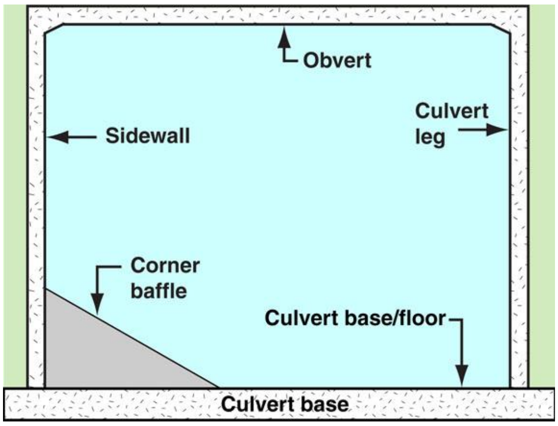
Simpsons Gap, Northern Territory

Todd River, Alice Springs, NT

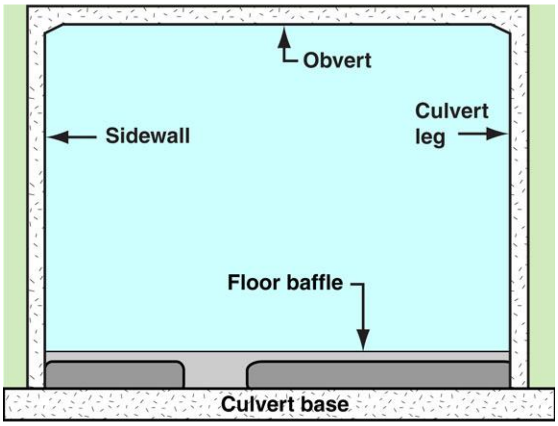
Potential design limitations based on the waterway type



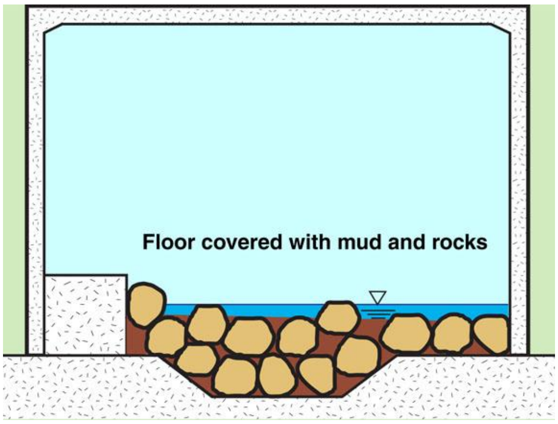
Sidewall baffle



Corner baffle



Floor baffle



Smothered low-flow channel

Introduction

- The design of a fish-friendly culvert depends heavily on the type of waterway that the culvert is crossing, as discussed below.

Sidewall baffles

- Sidewall baffles are used when the culvert is located on a sand-based or gravel-based (alluvial) waterway that is likely to make floor-based baffles inoperative.

Corner baffles

- Corner baffles can be used when the culvert is located on a clay-based or rock-based waterway that does not experience significant sediment movement along the bed.
- Corner baffles should NOT be used when the culvert is located on a sand-based or gravel-based waterway.

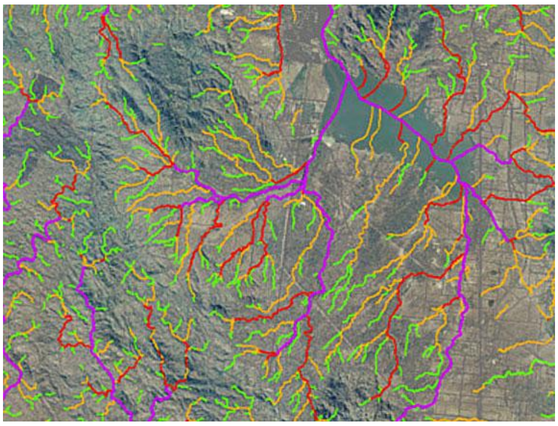
Floor-mounted baffles and added rock roughness

- Floor-mounted baffles can be used when the culvert is located on a clay-based or rock-based waterway that does not experience significant sediment movement along the bed.
- The use of floor-mounted baffles may not be appropriate in urban waterways.
- Floor-mounted baffles should NOT be used when the culvert is located on a sand-based or gravel-based waterway.

Low-flow channels

- Low-flow channels should NOT be used when the culvert is located on a sand-based or gravel-based waterway, or any waterway that experiences significant sediment flow.
- Grouted rock floor for clay-based creeks.
- Natural bed sand for sand-based creeks.
- Loose rocks for gravel-based creeks.
- Grouted rock bed for rock-based creeks.

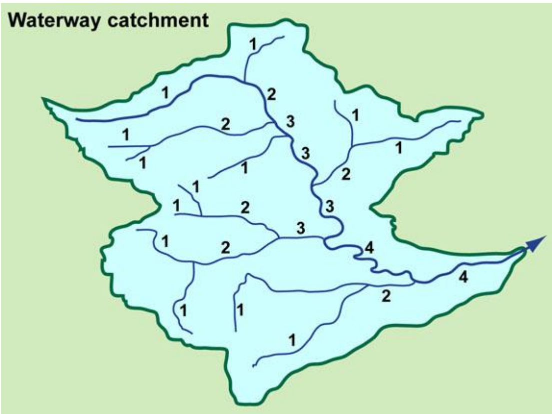
Step 2 - Fish Passage Requirements



Waterway and fish habitat mapping

State mapping

- Each state and territory has its own procedures for assessing the need for fish passage at proposed waterway crossings.
- Consequently the first task should be to contact your local Fisheries Authority.
- Some states provide mapping that ranks the regions of importance, and/or map recognised fish habitats.



Horton's stream order system

Stream order

- Some states base the importance of fish passage on the stream order.
- Horton's stream order ranks the 'reach' of a stream based on the number and ranking of its contributing branches.
- 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.
- Similar for third and fourth-order streams.

Permanent waterway pond (Qld)

Existence of upstream habitats

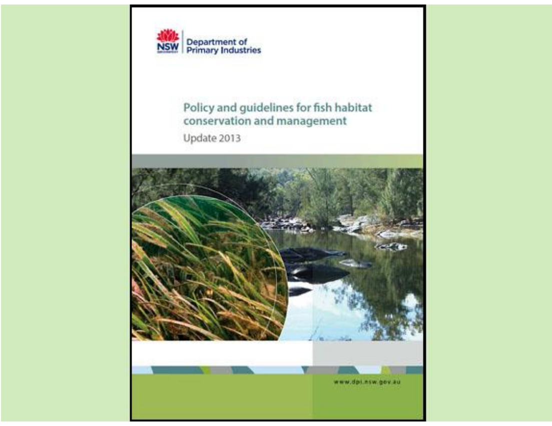
- Some authorities recognise the need for fish passage based solely on the existence of aquatic habitats (e.g. instream pools, lakes, some farm dams) upstream of a proposed culvert.
- There must be suitable aquatic habitats upstream of the culvert, or at least the reasonable expectation that waterway rehabilitation projects will restore, or rehabilitate, natural fish habitats upstream of the proposed culvert.

Classification of waterways and fish habitats

Reviewing catchment plans (SA)

Classification systems

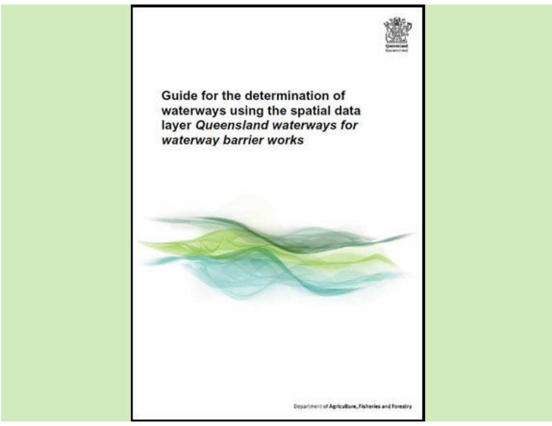
- Some states have mapped their waterways according to the state's adopted fish habitat classification system.
- Some states use a classification system based on a written description of the expected waterway attributes.



NSW Policy and Guidelines, 2013

NSW

- Fisheries NSW Policy and Guidelines for Fish Habitat Conservation and Management (2013 update).
- First published in 1998, updated in 1999.
- NSW Fisheries classify their fish habitats based on a Class 1 to 4 system (refer to next page).



Qld Spatial data users guide, 2013

Queensland

- Queensland had previously identified waterways using a colour-coded system:
  - Green: low risk waterways
  - Amber: medium risk waterways
  - Red: high risk waterways still applicable for self-assessable works
  - Purple: highest risk waterways
  - Grey: tidal areas
- However; it is unclear how this old system fits into the new State Code 18.

Bluff River (NSW)

Waterway classification

- Classifying waterways as either creeks or rivers is not always useful because these terms have different meanings in different regions of the country.
- What may be referred to as a river in southern Australia, may be considered just a creek in northern parts of the country.
- Also, the upper reaches of most rivers are likely to behave more like creeks than rivers, but the local sign-post will still title the waterway as a 'river'.

Step 3 - Type of Fish Passage

Human movement (for comparison purposes)

- People are likely to move through towns and cities for the following reasons:
  - moving out of the family home
  - searching for food or shelter
  - avoiding creditors
  - searching for a mate
  - relocating to a larger town during extended periods of low employment
  - returning home after being displaced by severe weather events.

Fish passage

- Fish are likely to move along waterways for the following reasons:
  - migration as part of life cycle needs
  - searching for food or shelter
  - avoiding predators
  - searching for a mate
  - relocating to larger or deeper pools during extended periods of dry weather
  - returning upstream after being displaced by floodwaters.

Flood water overtopping a culvert (Qld)

Culvert bed roughness (NSW)

Timing of fish passage

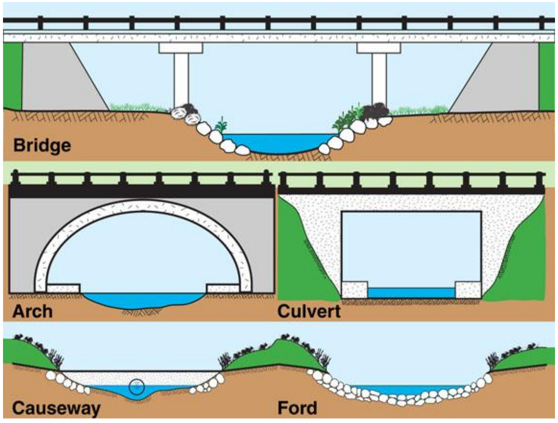
- Fish passage may be required at different times, including:
  - 24 hours, 365 days a year
  - certain months or weeks of a year
  - at the beginning of a flood event
  - during the peak of a flood event when movement over floodplains is possible
  - during the latter stages of a flood event
  - during periods of low velocity.

Movement pathways

- Fish passage may be required along different paths of a waterway, including:
  - the channel bed
  - the channel banks
  - floodplains.
- Bed movement requires bed roughness, or floor baffles within the culvert.
- Bank movement requires sidewall roughness, or baffles, within the culvert.
- Floodplain movement requires special consideration of floodplain culverts.

Step 4: Preferred type of crossing

Step 4 - Preferred Type of Crossing



Bridge, arch, culvert, causeway and ford

Bridge crossing (NSW)

Box culvert (Qld)

Types of crossings

- Prior to designing the culvert, designers should confirm that a culvert is the best type of crossing for this location.
- Types of waterway crossings include:
  - Bridge
  - Arch bridge
  - **Culvert** (the subject of this document)
  - Ford
  - Causeway.

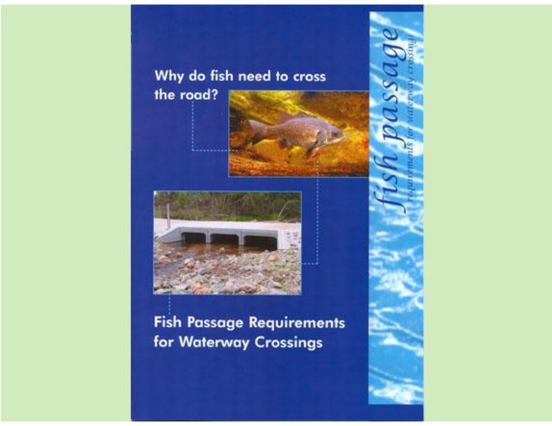
Preferred use of bridge and arch bridge

- The use of bridge and arch crossings is typically preferred in the following cases:
  - major waterways
  - crossing the habitat of a threatened fish species
  - named stream, creek or waterway with semi-permanent to permanent waters in pools, or connected wetland areas
  - waterways containing marine or freshwater aquatic vegetation.

Preferred use of culvert crossings

- The use of culvert crossings is typically preferred in the following cases:
  - waterways with intermittent flow, and waterways that offer potential refuge, breeding zones, or feeding areas for aquatic life
  - minor waterways containing semi-permanent pools that form after rainfall
  - waterways experiencing significant bed erosion (head-cut erosion), which can be arrested by a culvert.

Selection of the preferred type of crossing



NSW Fisheries, 2003

Preferred type of crossings

- The following table was extracted from:
  - Fairfull and Witheridge, 2003, *Why do fish need to cross the road? – Fish Passage Requirements for Waterway Crossings,* NSW Fisheries, Cronulla.
- Application of this table is not mandatory.
- Designers need to refer to their local state or territory policies.

Table 4.1 – Preferred crossing type (Fairfull and Witheridge, 2003)

Classification	Characteristics of waterway type	Minimum [1] recommended crossing type
Major fish habitat **Class 1 (NSW)** **Purple Zone (Qld)**	Major permanently or intermittently flowing waterway (e.g. river or major creek), habitat of a threatened fish species.	Bridge, arch structure or tunnel
Moderate fish habitat **Class 2 (NSW)** **Red Zone (Qld)**	Named permanent or intermittent stream, creek or waterway with clearly defined bed and banks with semi-permanent to permanent waters in pools or in connected wetland areas. Marine or freshwater aquatic vegetation is present. Known fish habitat and/or fish observed inhabiting the area.	Bridge, arch structure, culvert [2] or ford
Minimal fish habitat **Class 3 (NSW)** **Amber Zone (Qld)**	Named or unnamed waterway with intermittent flow and potential refuge, breeding or feeding areas for some aquatic fauna (e.g. fish, yabbies). Semi-permanent pools form within the waterway or adjacent wetlands after a rain event. Otherwise, any minor waterway that interconnects with wetlands or recognised aquatic habitats.	Culvert [3], or ford
Unlikely fish habitat **Class 4 (NSW)** **Green Zone (Qld)**	Named or unnamed waterway with intermittent flow following rain events only, little or no defined drainage channel, little or no flow or free standing water or pools after rain events (e.g. dry gullies or shallow floodplain depressions with no permanent aquatic flora present).	Culvert [4], causeway or ford

[1] In all cases bridges are preferred to arch structures, culverts, fords and causeways (in that order).

[2] High priority given to the High Flow Design procedures presented for the design of these culverts - refer to Design Considerations section of this document, or engineering guidelines.

[3] Minimum culvert design using the Low Flow Design procedures; however, High Flow Design and Medium Flow Design should be given priority where affordable.

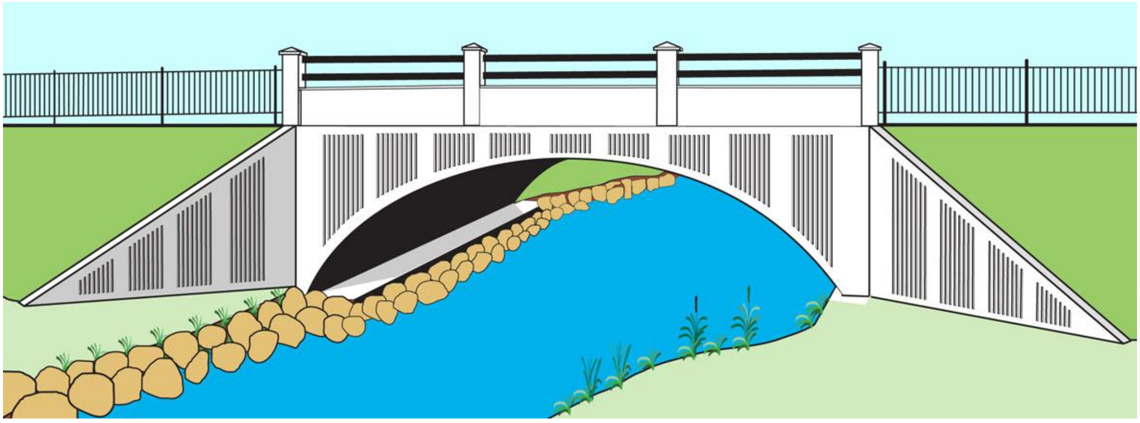
[4] Fish friendly waterway crossing designs possibly unwarranted. Fish passage requirements should be confirmed with the local fisheries department/authority.

Alternative waterway crossings

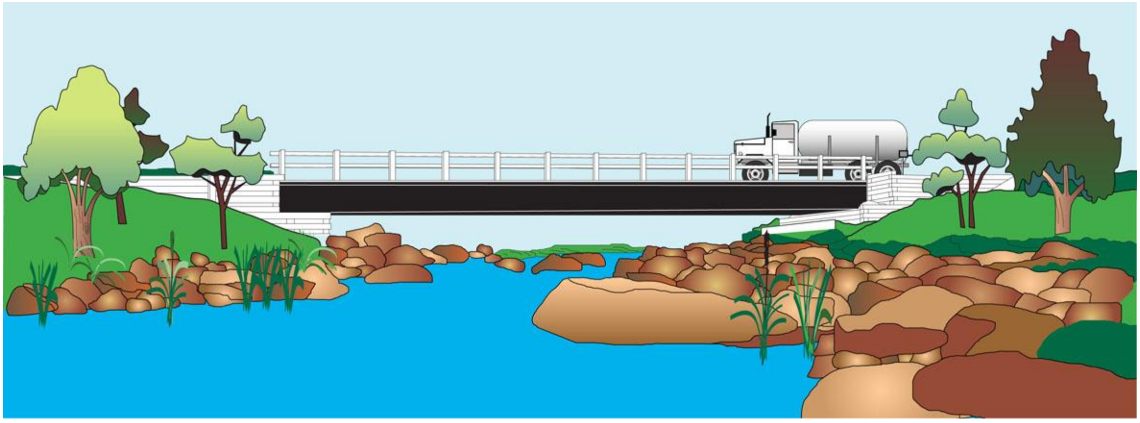
Simple arch crossing (Qld)

Alternative waterway crossings

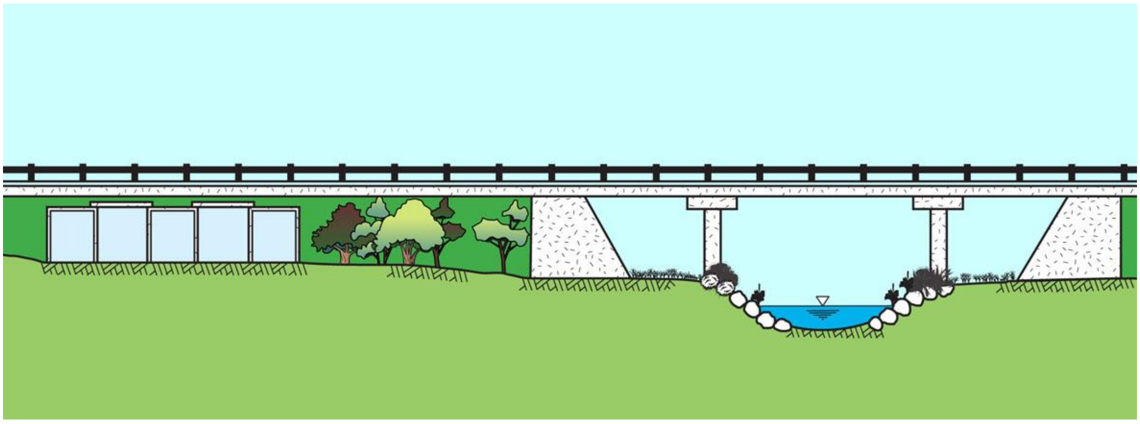
- This page represents a shameless promotion of the use of bridges to cross fish habitats.



Arch bridge



Single span steel girder bridge



Bridge with floodplain culverts

Bridges

Arch bridge (NSW)

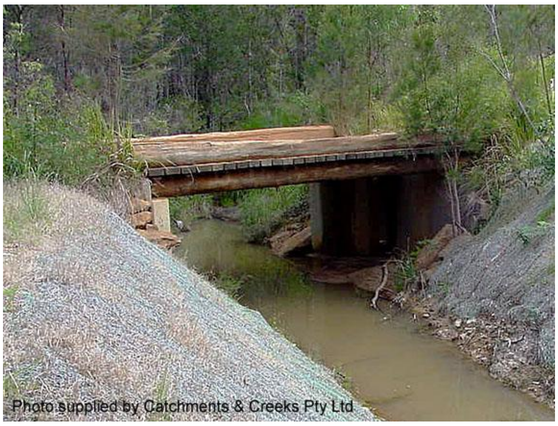
Arch bridge

- Arch bridges can provide ideal fish passage, as well as terrestrial passage.
- Arch bridges usually provide good lighting conditions, favourable for fish passage.
- Arch bridges can only be used when stable ground conditions can support the required foundations.

Single span concrete bridge (NSW)

Single span bridges

- Simple single span bridges can be used on minor waterways, and can be a useful option on private roads, access tracks, and driveways.



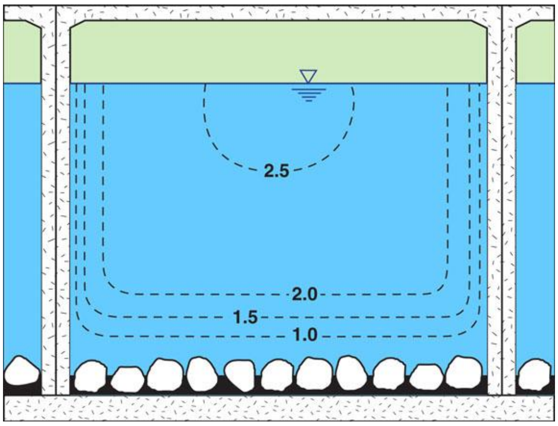
Single span log bridge (NSW)

Single span log bridge (Tas)

Small steel bridge (USA)

Small steel bridge (USA)

Preferred type of culvert



Velocity profile in a rough-bed culvert

Pre-cast box culvert with bridging slab

Corrugated pipe culvert (NSW)

Box culvert with terrestrial pathways (Qld)

Types of culverts

- Pipe culverts are generally cheaper to install than box culverts.
- Box culverts allow better boundary layer conditions to exist within the corners of each conduit.
- Both pipe and box culverts can be designed to be fish friendly.
- Once a culvert cell becomes large enough for maintenance equipment to be driven into the culvert, then box units should be used.

Box culverts

- A box culvert can be formed from:
  - heavily reinforced, pre-cast box units
  - pre-cast bridging slabs used to form an individual cell between two pre-cast box units.
- It is generally considered easier to make a box culvert 'fish friendly' than an equivalent pipe culvert.
- It is generally considered easier to maintain (de-silt) a box culvert than an equivalent pipe culvert.

Pipe culverts

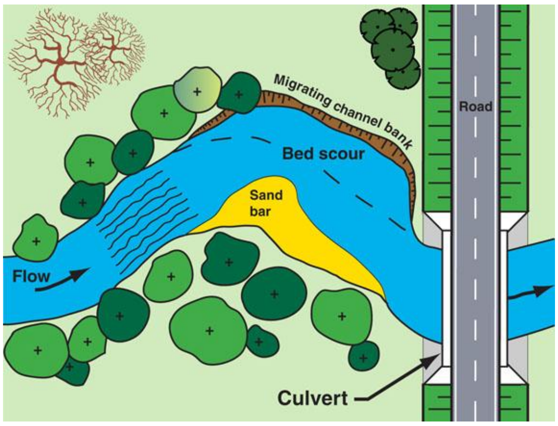
- The majority of pipe culverts are formed from reinforced concrete.
- Corrugated pipe culverts have better sidewall roughness (questionable benefit).
- The corrugated sidewall roughness is only likely to benefit small fish.
- Strong reinforcing is essential around the inlet of corrugated pipe culverts to prevent inward folding of the corrugated iron during major flows.

Accommodation of terrestrial passage

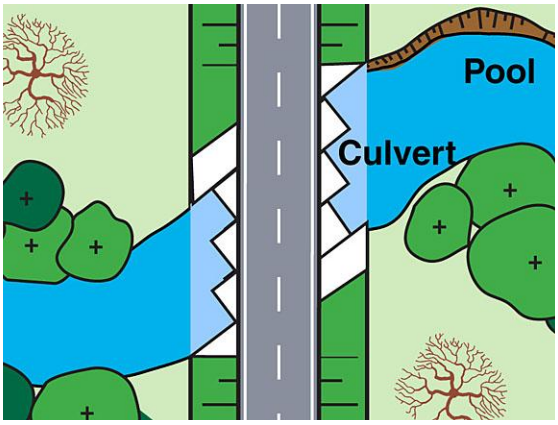
- The selection of the type of culvert must consider the terrestrial passage requirement of the crossing.
- Even Fisheries officers (charged with the protection of fish passage) must consider the potential impact of their fish passage requirements on terrestrial passage as part of their overall environmental duty.
- Terrestrial passage is generally easier to accommodate within box culverts.

Step 5 - Location and Alignment

Meandering waterway (Qld)



Channel erosion upstream of a culvert



Skewed culvert crossing

Introduction

- In most cases, the location of a waterway crossing will be determined by community needs and current land ownership.
- However, in cases where there is flexibility in the location of a crossing, consideration should to be given to:
  - potential long-term erosion, or meandering of the waterway
  - avoiding the use of skewed culverts
  - aligning the culvert with the downstream channel.

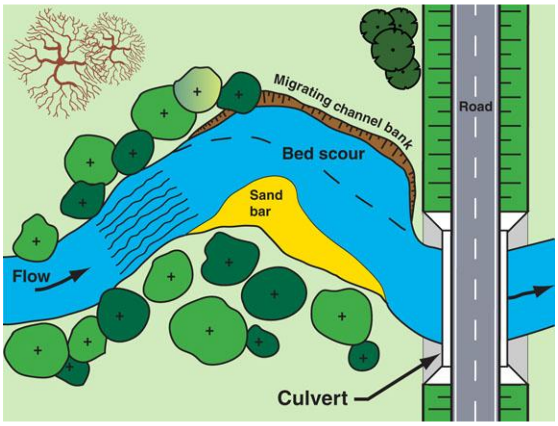
Meandering waterways

- Meandering waterway channels are possibly a greater threat to bridge crossings, than to culvert crossings.
- At culvert crossings, channel meandering can cause:
  - severe inlet and/or outlet turbulence
  - damage to, or undermining of, the adjoining road embankments
  - excessive deposition of sediment within the culvert.

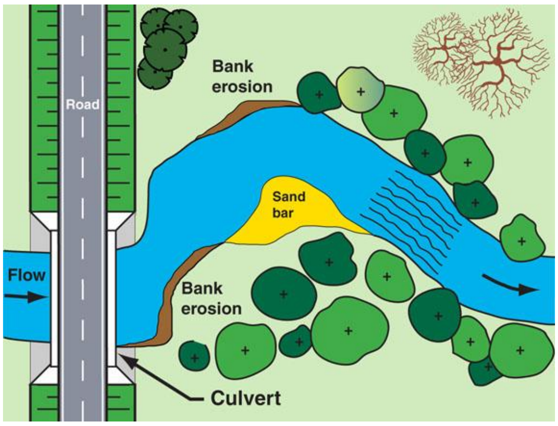
Skewed culverts

- Skewed culverts need to be longer than tangential culverts when passing under a given roadway.
- Increasing the length of a culvert adds to the stress fish experience while trying to pass through the culvert.
- Increasing the length of a culvert also reduces light levels within the culvert.

Culvert location and alignment



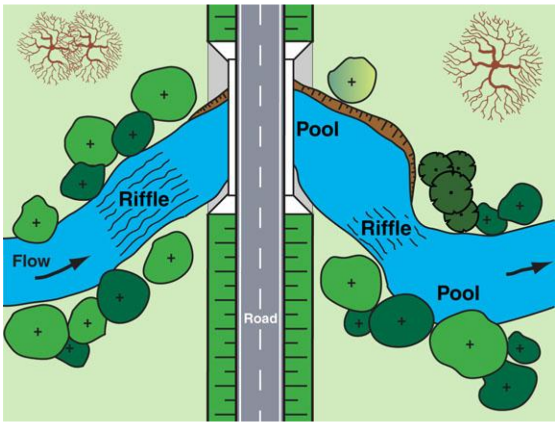
A meandering upstream channel



A meandering downstream channel

Meandering waterways

- Meandering waterway channels are by definition unstable with respect to their location.
- When a road or rail crossing is formed over such an unstable waterway, designers are forced to stabilise (armour) the channel banks in order to prevent the undermining of the culvert.
- If possible, a culvert crossing should be located well-downstream of a sharp or unstable channel bend.
- If the upstream channel is unstable, then any further channel erosion could undermine the road embankment.
- If the downstream channel banks are unstable, then it is less likely that this erosion will migrate up to the road embankment, but if a head-cut exists (a form of bed erosion), then this will migrate up to the culvert.
- In severe cases, a meandering waterway could cut through the roadway embankment during a severe flood.



Culvert located at a 'pool'

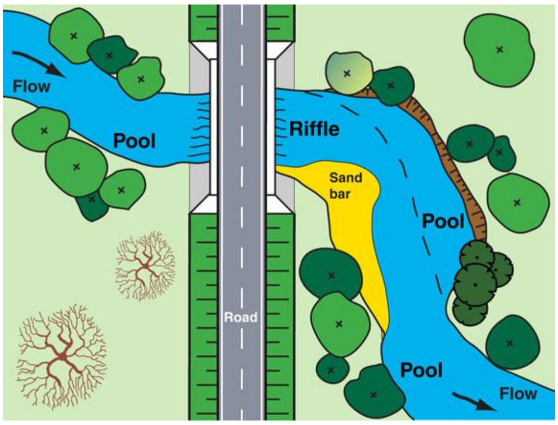
Advantages and disadvantages of locating a culvert at a natural channel <u>pool</u>

Advantages:

- Easier to recess the culvert floor.
- Easier to make the culvert fish friendly.

Disadvantages:

- The channel banks adjacent to the road or rail embankment can be unstable.
- The culvert cells may need to be deeper, and thus more expensive.



Culvert located at a 'riffle'

Advantages and disadvantages of locating a culvert at a natural channel <u>riffle</u>

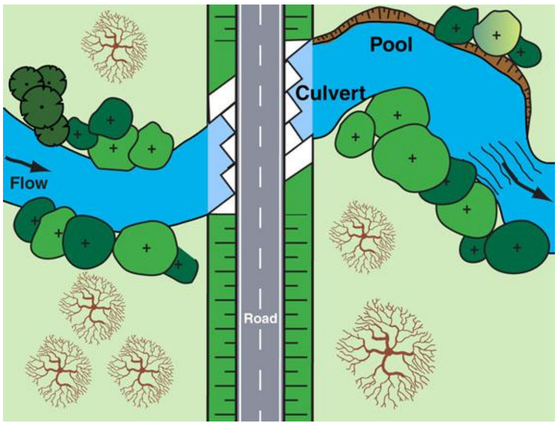
Advantages:

- The channel is more likely to be stable, and therefore less likely to need artificial bank stabilisation.

Disadvantages:

- Culvert construction could damage the riffle.
- Harder to design a fish-friendly culvert.
- The culvert may interfere with the natural migration of bed gravel.

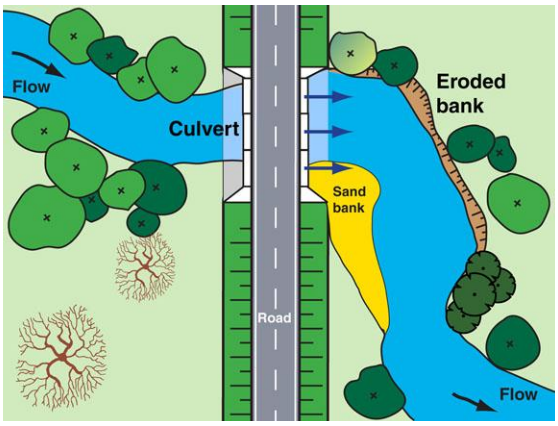
Culvert location and alignment



(Option A) **Skewed culvert**

Skewed culverts

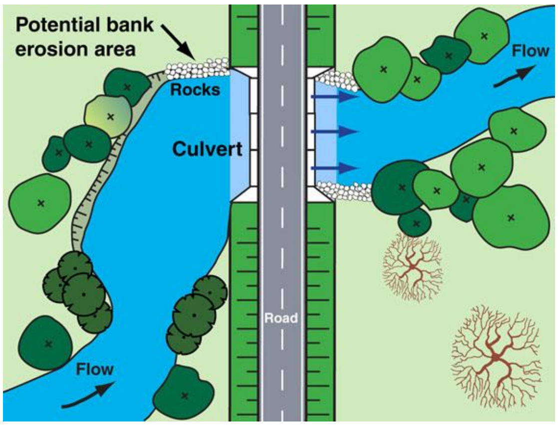
- Ideally, the road should cross the stream at 90-degrees to minimise the length of the culvert.
- However, on high-speed roads it is common for the road alignment to take priority, and for the crossing to be diagonal to the stream channel.
- Ideally, skewed culvert cells should be aligned within 10-degrees of the direction of channel in order to minimise turbulence and bank erosion.



(B) **Culvert aligned with upstream channel**

Culverts aligned with the upstream channel

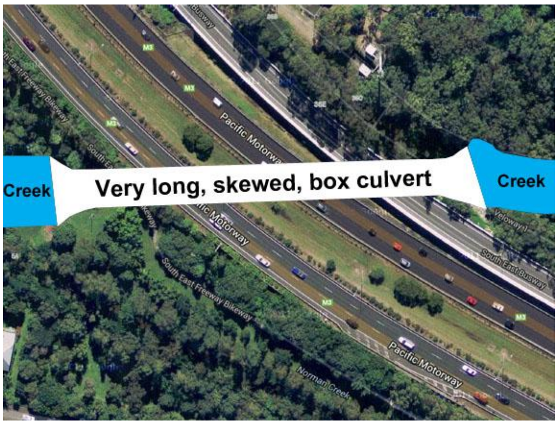
- Design **Option A** (above) avoids the need for channel modifications; however, a skewed culvert has increased length.
- **Options B and C** result in a shorter culvert, which is likely to improve fish passage opportunities.
- Aligning the culvert with the upstream channel (**Option B**) does not really improve the culvert's flow capacity, or fish passage attributes.



(C) **Culvert aligned with downstream**

Culverts aligned with the downstream channel

- Aligning the culvert with the downstream channel (**Option C**) does not necessarily improve the culvert's flow capacity, or its fish passage attributes; however, it can reduce large-scale turbulence, which can benefit fish passage.
- The real benefit of aligning the culvert with the downstream channel is the reduced potential for bank erosion problems (discussed over the page).

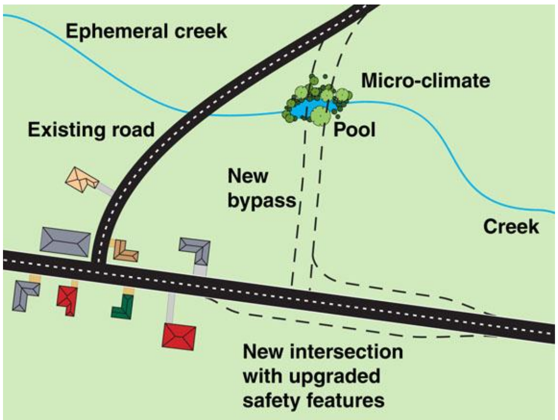


Long culvert under a motorway

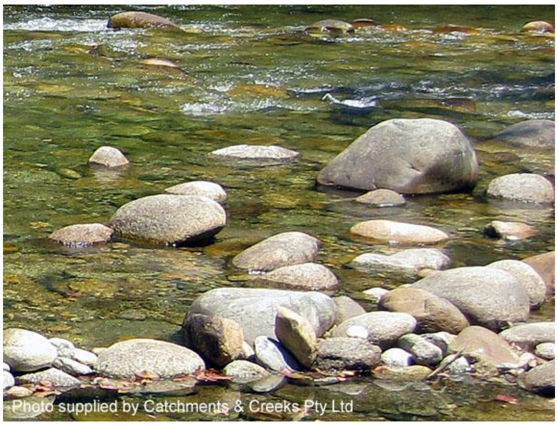
Modifying the waterway channel in order to reduce the culvert length

- On large motorways, skewed culverts can have such a length that fish need to pack a lunch box and torch in order to find their way through.
- The culvert length can be reduced by modifying the approach channels, but such channel modifications should not be undertaken without due consideration.
- Breaking the culvert at the median can provide a resting area, but will increase energy loss through the culvert.

Avoiding critical waterway habitats



Approximate layout of the new bypass



Natural riffle (Vic)

Off-stream wetland (NSW)

Platypus

Case study

- During the inspection of a proposed town bypass, the author walked down a steep valley to the location of a proposed creek crossing only to find a rich and healthy micro-climate created by the steep valley slopes, which was unique along this otherwise dry rural waterway, and which was a fish habitat that was <u>about to be lost</u> due to construction of the bypass.
- This case represented either poor site inspection, or a failure to recognise the importance of this fish habitat.

Where would you expect to find the greatest biodiversity?

- It might surprise some people, but you will often find the greatest biodiversity (i.e. array of aquatic life) within a riffle, and not within the adjacent pool.
- A permanent pool may have a lot of fish life, but fish are not the only aquatic life that are important within a waterway.
- Consequently, locating a waterway crossing at an existing riffle, instead of a pool, may not be the best option.

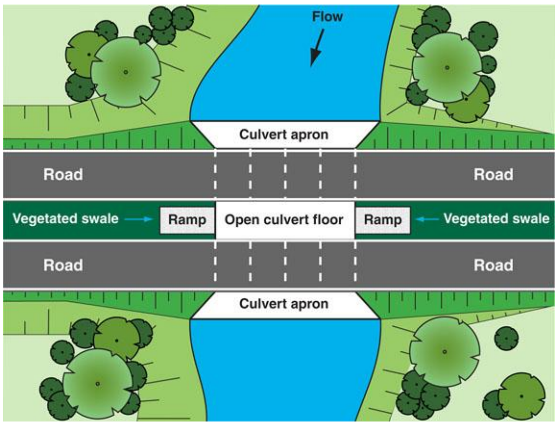
Off-stream water bodies

- Off-stream water bodies typically consist of either pools or wetlands located within the floodplain of an adjacent waterway.
- These water bodies may have been created during the past meandering of the waterway.
- These waters can be more permanent than the adjacent, ephemeral waterway, which means they can provide habitat and aquatic life that can replenish the waterway after a flood event.

Platypus activity

- If your Google search finds an 1865 newspaper report of a platypus sighting in the local creek, or at a proposed creek crossing, then this should <u>not</u> be documented as *'a report of platypus activity'*, unless full disclosure is given.
- However, such information can be a useful indicator of the potential rehabilitation of the waterway.
- The appropriate interpretation of such historical newspaper reports is best made by local Fisheries experts.

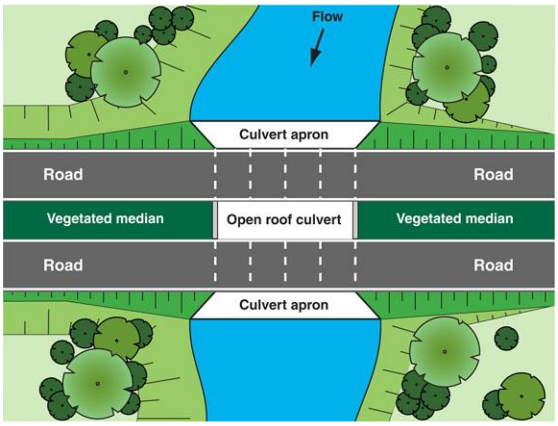
Dual carriageway roads



Trapezoidal channel formed in median

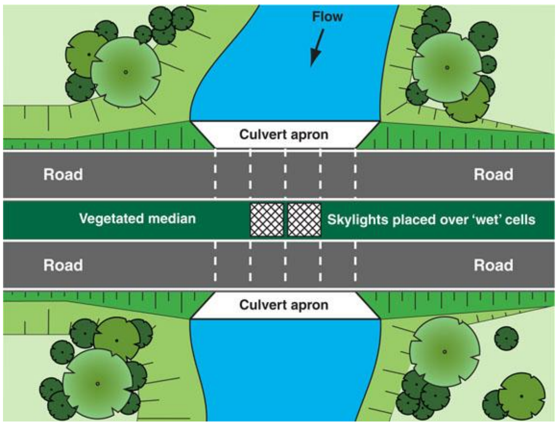
Dual carriageway roads

- In general, the wider the road, the longer the culvert; however, dual carriageways provide us with the opportunity to introduce resting areas for fish.
- These resting areas can also help to improve lighting conditions within the culvert.
- The difficulty for designers is to achieve these outcomes without introducing excessive energy loss within the culvert, which can reduce the culvert's flow capacity.



Open roof section within a long culvert

Open roof section within a long culvert



Skylights placed within the median

Skylights placed within the median (Qld)

Skylights placed within the median (Qld)

Skylights placed in footpath verge (Qld)

Step 6 - Design Flow Rates

Floodwater overtopping a road culvert

Flood control

- The design of a waterway culvert is a complex process requiring the consideration of several, sometimes competing, issues.
- Each of these issues can be associated with a different design flow rate, for example:
  - 1 in 100 year ARI for flood impacts
  - 1 in 50 year ARI for traffic useability
  - 1 in 10 year ARI for fish passage
  - 1 in 2 year ARI for bikeway underpass.

River flooding (Qld)

Design flow rates

- For fish passage considerations, authorities may choose to nominate a minimum design standard based on:
  - a particular storm frequency (such as the 1 in 10 year event) at the crossing, or
  - a particular flood event based on a whole of catchment approach (i.e. when fish migration is triggered by a river flood), or
  - a particular flow area for the culvert.

Low flow conditions (Qld)

Fish passage design

- Fish passage requirements may incorporate several design conditions depending on the target species.
- Fish passage conditions may need to be checked for:
  - zero-flow for day-to-day fish passage in ephemeral waterways
  - 1 in 5 yrs or 10 yrs for fish migration that is likely to occur throughout a flood
  - 1 in 50 years for fish migration likely to occur only during the peak of a flood.

Fish migration triggered by flood events

Fish migration (USA)

Again, I emphasise that I am not a biologist, and I do not claim to have expertise in fish migration.

Introduction

- What can trigger fish migration varies with the fish species and location.
- Mass migration can be triggered by:
  - a given time of the year
  - a sustained increase in stream flows
  - a flood event at the mouth of the river.

Fish passage (SA)

Fish migration triggered by a given time of the year

- When fish migration is triggered by a given time of year, then fish-friendly conditions will likely be required for a wide range of flows, from low-flow conditions, to high-flow conditions.
- The minimum desirable design standard would be the Medium Flow Design.
- A Medium Flow Design is described over the page.

Fish migration (Qld)

Migration triggered by stream flows

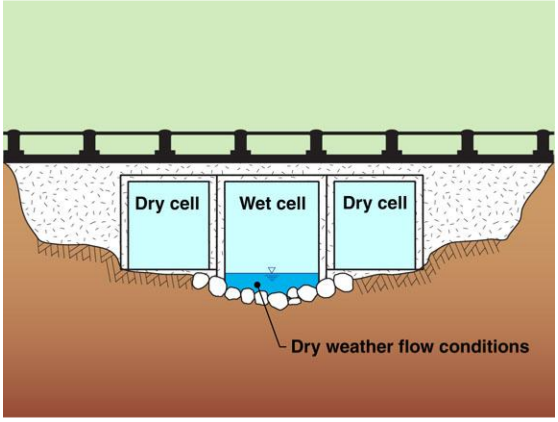
- When fish migration is triggered by an increase in stream flow, then fish migration may start out during a minor flood, but these flow conditions could steadily rise (relative to the flood frequency) as fish moved upstream.
- The waterway may be in a 1 year flood condition when migration starts, but the waterway may be in a 10 year flood condition by the time fish reach the upper catchment.

Sediment plume from a river flood

Fish migration triggered by river flooding

- Fish migration of this type could involve migration from saline waters into the fresh waters of the upper catchment.
- During these flood events, the lower catchment (likely dominated by bridge crossings) may be experiencing a 1 in 50 year event, while the upper catchment tributaries may only have minor flooding.
- The minimum desirable design standard would be the High Flow Design in the lower catchment, and the Medium Flow Design in the upper catchment.

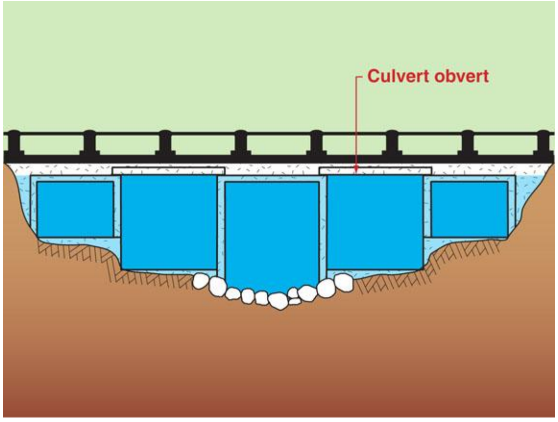
Flow conditions at a given crossing location



Example Low Flow Design culvert

Low Flow Design

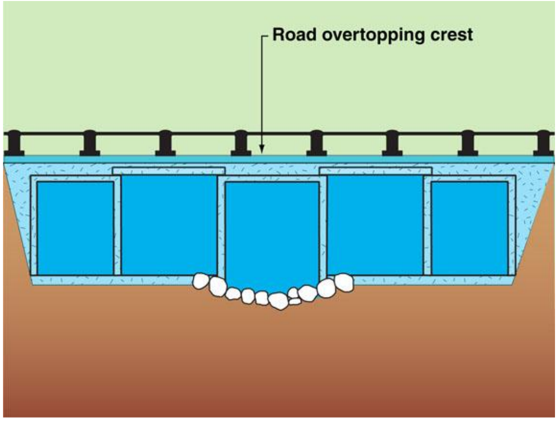
- In circumstances where a desirable minimum flow area cannot be achieved, designers should at least aim to satisfy a specified low-flow condition.
- Typically Low Flow Design conditions are:
  - minimum flow depth of 200 to 500 mm depending on species
  - maximum average flow velocity within fish passage cells of 0.3 m/s.
- This design standard targets the day-to-day movement of fish, not fish migration.



Example Medium Flow Design culvert

Medium Flow Design

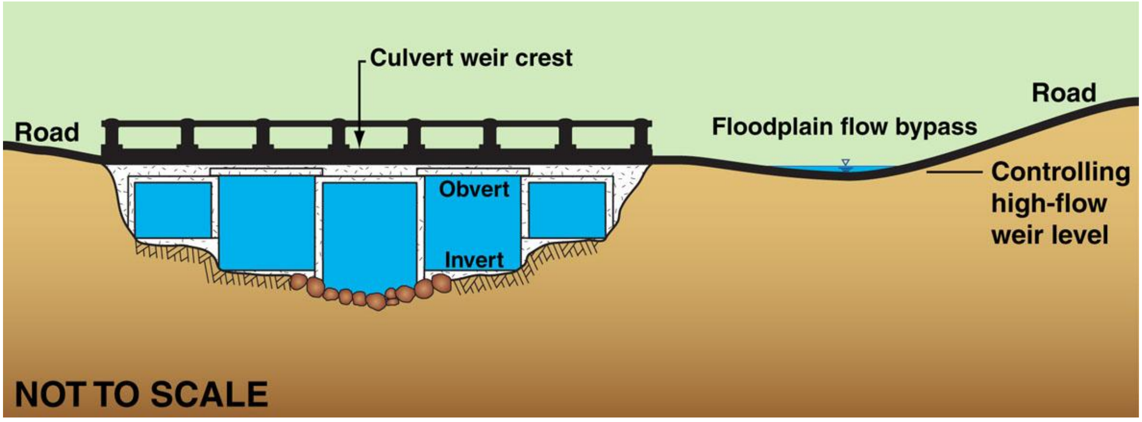
- The Medium Flow Design is based on providing suitable fish passage when:
  - flows are below the culvert roof, and
  - flows are overtopping the crossing,
  - but not when flows are level with the culvert deck.
- A Medium Flow Design requires a minimum culvert flow area equal to the stream's natural flow area below the elevation of the culvert's obvert (roof).



Example High Flow Design culvert

High Flow Design

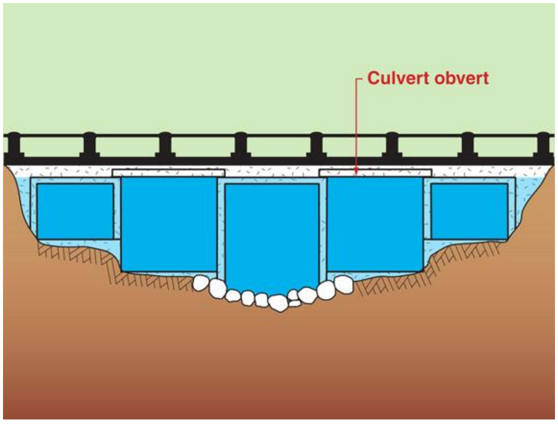
- A High Flow Design requires a minimum culvert flow area equal to the stream's natural flow area below the crossing's overtopping weir elevation.
- The depth of a culvert's deck (i.e. obvert to road crest) is typically around 1 metre; however, design options may be available to reduce this depth.
- If the crest of the culvert is higher than one of the approach roads, then the approach road crest should be taken as the crossing's overtopping elevation (below).



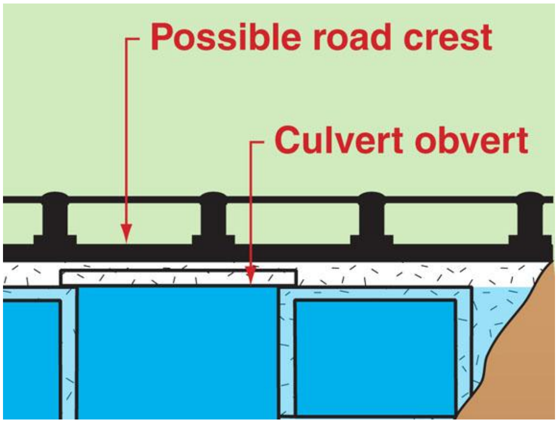
Road culvert with adjacent floodplain lower than the culvert crest elevation

Step 7 - Required Flow Area

Multi-purpose culvert with wet & dry cells



Example <u>Medium</u> Flow Design culvert



Culvert obvert and road crest elevation

Different design standards

- There are varying points of view with regards to the minimum culvert flow area.
- Some agencies focus only on the flow conditions within the nominated 'wet' cells, with less regard given to the flow in non-baffled cells (conduits) of the culvert.
- Some agencies focus on specifying a minimum flow area for the whole culvert.
- However, from a flood control perspective, all of the culvert cells will be functional during a flood, so it does not matter if the cells are classified as 'wet' or 'dry'.

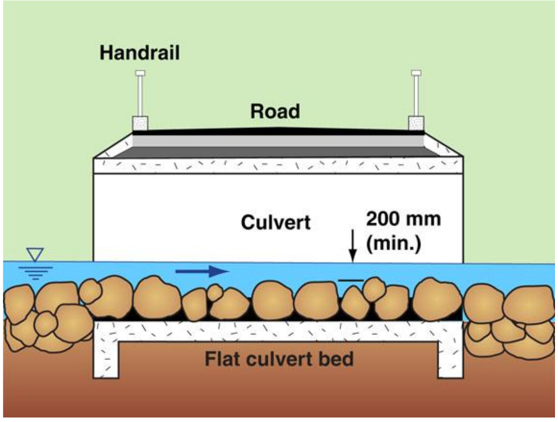
Recommended minimum dimensions

- It is generally considered desirable for the minimum flow area of the culvert to be equal to the stream's natural flow area below an elevation equivalent to either:
  - the road crest (High Flow Design), or
  - culvert obvert (Medium Flow Design).
- The minimum size of all cross drainage culverts should be 375 mm for the pipe diameter, as well as for the minimum height of a box culvert.

Finding the stream's natural flow area

- Measuring the stream's natural flow area up to a specific elevation on the culvert (e.g. the obvert or road crest) requires the designer to:
  - find a natural 'choke' in the stream's topography (e.g. riffle) where fish have already demonstrated that they can negotiate, and then
  - adjust the nominated culvert elevation to the location of this natural choke by adding or subtracting the change in bed elevation between the two locations.

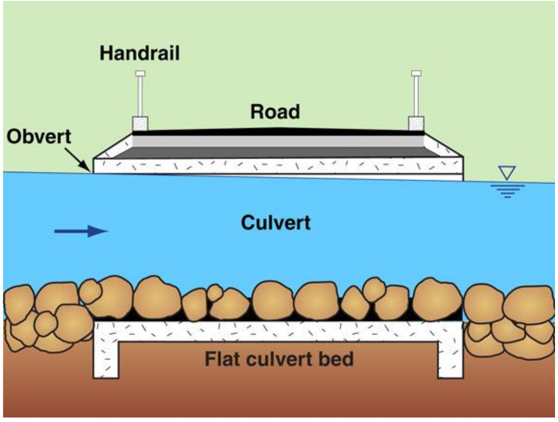
Determine the required flow area



Low flow design conditions

Low Flow Design

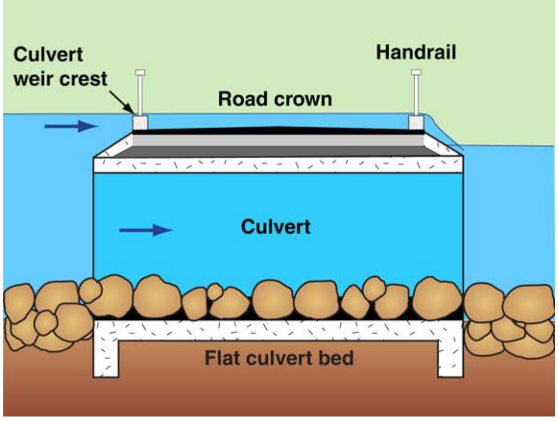
- A Low Flow Design is based on a maximum average flow velocity within the assigned 'wet' cells of 0.3 m/s and a minimum flow depth of 200 to 500 mm depending on target species.
- This design condition is aimed at providing viable fish passage conditions for day-to-day movement within wet cells.
- In addition, the cells adjacent to the stream's banks (possibly 'dry' cells) should have any necessary sidewall roughness.



Medium flow design conditions

Medium Flow Design

- A Medium Flow Design requires a minimum culvert flow area equal to the stream's natural flow area below the elevation of the culvert's obvert (roof).
- This design condition is aimed at providing viable fish passage conditions for flows up to the culvert flowing full.
- Bed roughness conditions should be satisfied within both wet and dry cells, and sidewall roughness is required on the sidewalls adjacent to the stream banks.



High flow design conditions

High Flow Design

- A High Flow Design requires a minimum culvert flow area equal to the stream's natural flow area below the crossing's overtopping weir elevation.
- This design condition is aimed at providing viable fish passage conditions for all flows up to full overtopping flow.
- If the crest of the culvert is higher than one of the adjacent approach roads, then this road level should be taken as the crossing's crest elevation.

Supercritical flow conditions (Qld)

High-velocity low flows

- If the culvert has a sloping bed, then an analysis should be undertaken of the low-flow conditions within the designated 'wet' cells.
- Flows should never be allowed to achieve supercritical conditions, which can be very problematic for fish passage if the culvert has a smooth concrete base.
- Flow conditions can be greatly improved by introducing (i) bed roughness, (ii) recessing the culvert floor, or (iii) providing the culvert with a zero-slope bed.

The impact of deck thickness on 'fish passage' and 'human safety'

Box culvert with deep deck (Qld)

Potential problems caused by deep deck profiles

- The potential problems caused by a deep culvert deck include:
  - reduced hydraulic capacity
  - increased hydraulic entrance losses (in real terms)
  - potential changes in flow velocity when the culvert is flowing full
  - increased probability of the culvert operating in a full, or near-full condition, during storm events.

Culvert with exposed services (Qld)

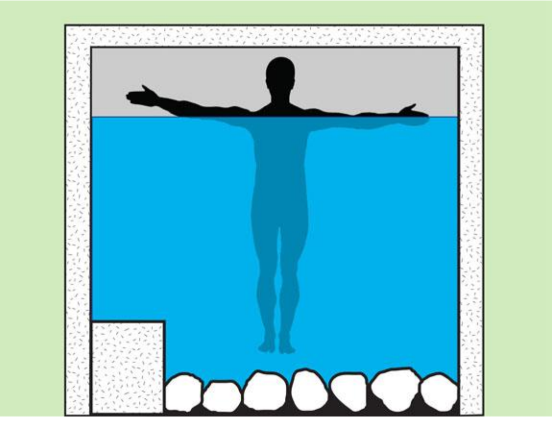
Possible reasons why a culvert may be forced to have a deep deck

- The most common reason for a deep deck is the need for the culvert cells to pass under existing services (pipes and cables) that run along the road reserve.
- The image shown left is a rare example of a culvert with non-related pipe work passing through the culvert.

Rural, multi-cell box culvert (NSW)

Typical culvert deck thickness/depth

- The average deck thickness is around 1 m, which consist of:
  - roof thickness of the pre-cast cells
  - thickness of a bridging slab (if used)
  - the covering concrete slab
  - road kerb, footpath and/or the foundation beam for a handrail or guardrail.
- Some designers have gone to extremes to minimise the thickness of the top deck (as shown left).



Safer flow condition relative to flowing full

Public safety issues

- The taller the culvert cell, the greater the probability of the culvert flowing partially-full during storm events.
- Having a reasonable air gap between the flood level and the culvert's obvert gives any person swept through the culvert the greatest chance of survival.
- For trapped humans, the most dangerous flow condition is when the culvert is flowing full.

Minimum cover requirements

Roadbase cover over a box culvert (Qld)

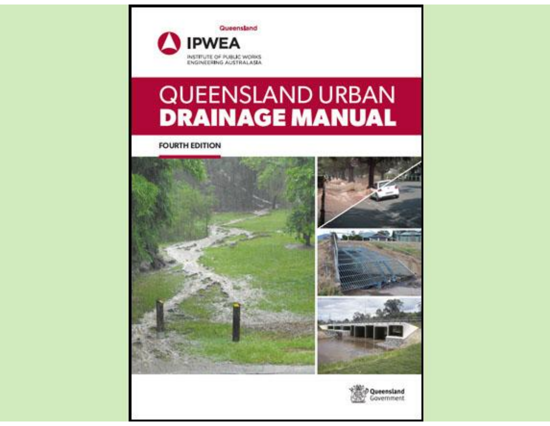
Minimum cover over culverts

- Culverts require a minimum cover to protect the pre-cast cells from traffic loading.
- If service pipes are located within the space above the culvert (e.g. water main, sewer, or stormwater), then the required cover for these pipes must also be applied.

Concrete Pipe Association of Australasia

Concrete Pipe Association

- Designers should refer to Standards Australia publications for the minimum cover requirements.
- Similar guidelines exist for steel and PVC pipe work.
- The Concrete Pipe Association of Australasia's website provides links to the relevant Australian and New Zealand standards.



Queensland Urban Drainage Manual

Queensland Urban Drainage Manual (QUDM)

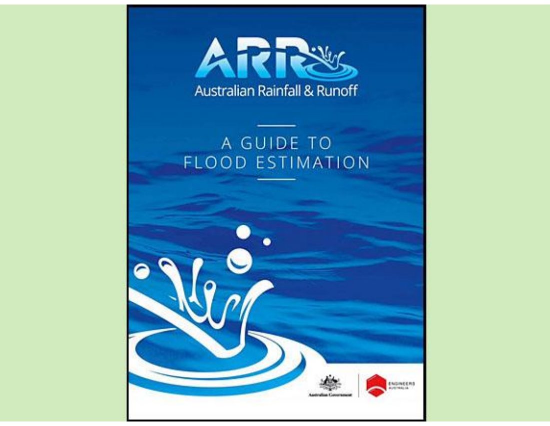
- Institute of Public Works Engineering Australia, Queensland Division and the Department of Energy and Water Supply. Brisbane, Australia, 4th edition, 2017.
- In the 2017 edition of QUDM:
  - minimum cover requirements are provided in sections 7.10 & 10.4.9
  - blockage issues in 10.4.10
  - culvert sizing in 10.4.5.

Small pipe culvert on a gravel road (Qld)

Typical requirements (check before use)

- Depending on the concrete/loading class, the generally accepted minimum allowable fill cover to protect the cells from traffic loading is:
  - 300 mm over Concrete Pipes
  - 100 mm over Reinforced Concrete and Slab Link Box Culverts (RCBC and SLBC respectively) and Reinforced Concrete Slab Deck Culvert (RCSDC)
  - 600 mm over Corrugated Metal Pipes.

Blockage allowance (refer to Step 11 for blockage controls)



Australian Rainfall and Runoff (2016)

Introduction

- The discussion of blockage factors in *Australian Rainfall & Runoff* relates to 'flood estimation' hydrology.
- The *Australian Rainfall & Runoff* publication does not provide guidance on blockage factors applicable to the design of fish-friendly culverts.
- The minimum flow areas presented here for Low Flow, Medium Flow and High Flow designs are based on zero debris blockage.

Tidal 'mud' (Qld)

Tidal sediment blockage

- The depth of tidal sediment deposition within a culvert can be as high as the local high tide elevation.
- This sediment can sometimes be flushed from the culvert by stream flows, if such flows occur within days of the sediment deposition.
- However, over time, these sediments can become very cohesive and near-impossible to displace, other than through jet washing or mechanical removal.

Waterway sediment (Qld)

Waterway sediment blockage

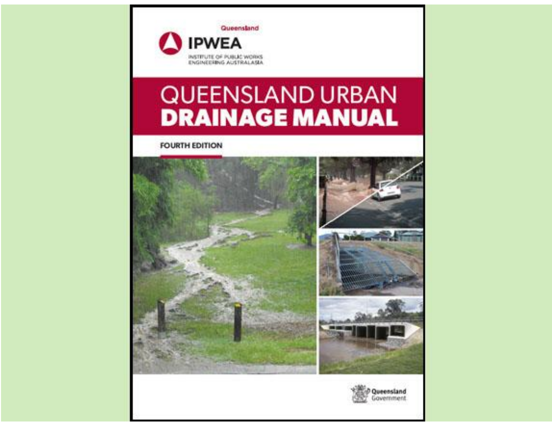
- Sediment transported into a culvert by stream flows, rather than tidal flows, can:
  - build-up slowly over time
  - result from the migration of an upstream sediment 'slug'
  - be deposited during a single flood event.
- Sediment blockages occur as a 'bottom–up' blockage, rather than a 'top–down' blockage.

Culvert fully blocked by flood debris (Qld)

Flood debris

- The degree of flood debris blockage depends on:
  - the clear opening width/height of the culvert cells
  - the availability of loose floating debris within the upstream catchment
  - the degree of recent winds, or the storm wind, that can release woody debris.
- Debris deflector walls can be introduced to reduce the potential impact of woody debris (see Appendix G in Part 3).

Blockage allowance (Queensland)



Queensland Urban Drainage Manual

Source: Brisbane City Council (2009)

Queensland Urban Drainage Manual (QUDM)

- Institute of Public Works Engineering Australia, Queensland Division and the Department of Energy and Water Supply. Brisbane, Australia, 4th edition, 2017.
- In the 2017 edition of QUDM:
  - Section 10.4.10 'Blockage considerations and debris deflector walls'
- *'Waterway culverts can experience debris problems in a number of circumstances, especially where:*
  - *the upstream waterway is heavily vegetated and is currently undergoing channel expansion due to changing catchment hydrology*
  - *the waterway has a large catchment area*
  - *the culvert has insufficient clear waterway area to allow the free passage of debris*
  - *the culvert is downstream of potential slip areas that could result in significant debris flow*
  - *the culvert has a history of debris problems.'*

Table 7.1 – Suggested blockage factors for culverts [1] (same as Table 12.1 in Step 12)

Culvert conditions	Blockage factor	
	Design value	Severe storm [2]
Inlet height < 3 m, or width < 5 m: Inlet Chamber (barrel)	20% [3]	100%
Inlet height > 3 m and width > 5 m: Inlet Chamber (barrel)	10% [3]	25% [3]
Culvert inlets with effective debris control features for culverts with inlet height < 3 m and width < 5 m	As above	As above
Screened culvert inlets	50%	100%

Notes:

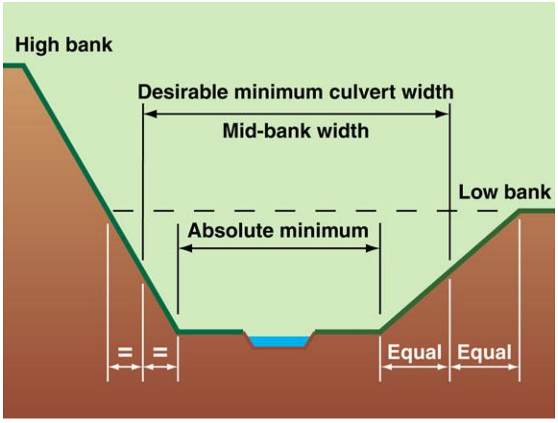
[1] Developed from Engineers Australia (2012), presented in QUDM, 2017.

[2] Refer to discussion below on severe storm investigations.

[3] Adopt 25% bottom-up sediment blockage unless such blockage is unlikely to occur.

[4] The degree of blockage typically depends on availability of suitable bridging matter, such as large branches and fallen trees, that can 'bridge' across the structure opening.

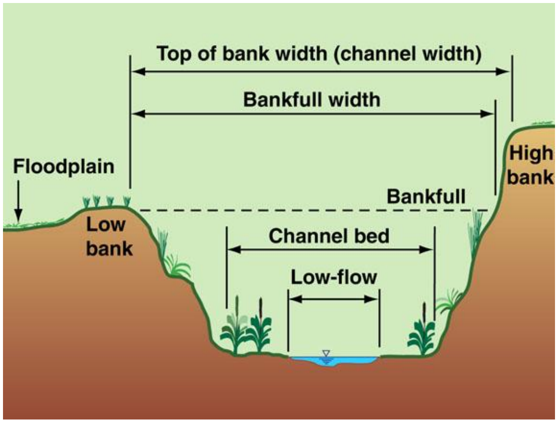
Step 8 - Desirable Culvert Width



Desirable minimum culvert bed width

Design aims (not mandatory)

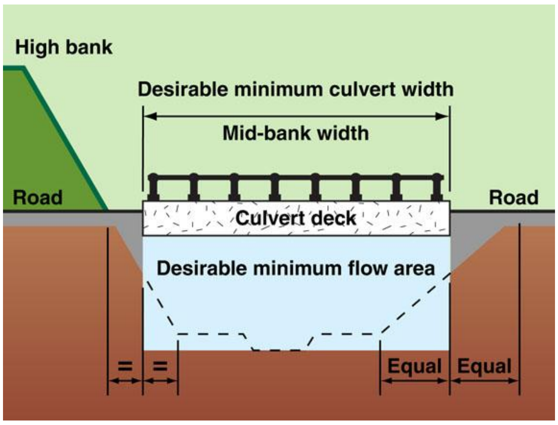
- The width of the culvert, across all 'wet' cells, should be as close as possible to the width of the low-flow channel (whether or not the low-flow channel is ephemeral, or permanent).
- The total width of the culvert across all cells ('wet' and 'dry') should be as close as possible to:
  - the channel's bed width (minimum)
  - where practical, the mid-bank width.



Channel width terminology

Bankfull width

- Various 'widths' can be defined within a channel, including:
  - low-flow channel width
  - bed width
  - mid-bank width (see above diagram)
  - bankfull width
  - top of bank width (channel width)
  - riparian width.
- The bankfull width is usually defined by the lowest bank elevation.

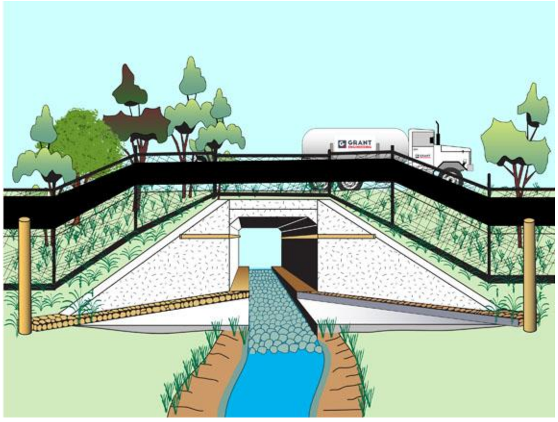


Desirable minimum flow area

<u>Desirable</u> minimum flow area

- Discussion about 'High Flow', 'Medium Flow' and 'Low Flow' design standards is presented in Step 6.
- The information presented in this diagram (left) refers only to the general idea of:
  - a desirable minimum culvert width, and
  - a desirable culvert invert.
- **Note:** A recessed culvert sits below the creek bed, but has natural bed material resting on the floor of the culvert, thus reducing its effective flow area.

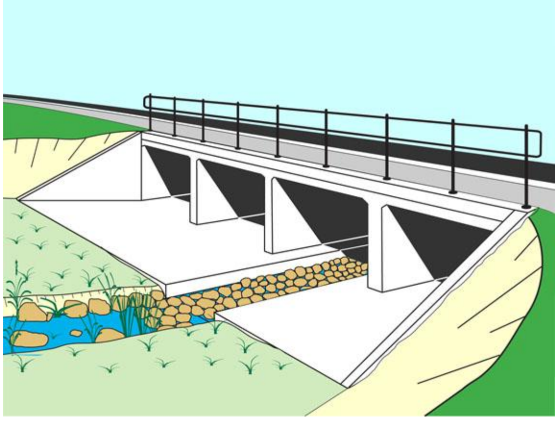
Step 9 - Use of Low-flow Channels



Single cell culvert with low-flow channel

Introduction

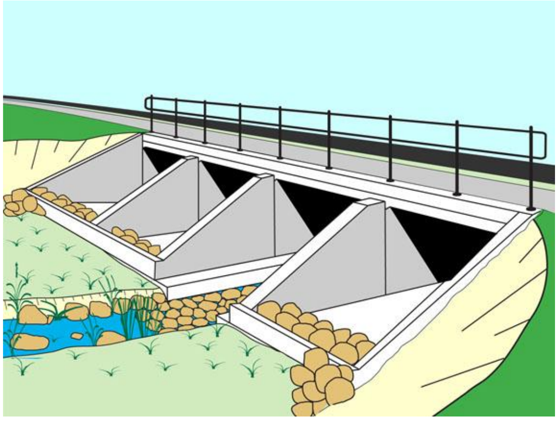
- Before we define the culvert's bed elevation and gradient (in Step 10), we need to determine if the culvert requires a low-flow channel.
- Some design guidelines identify the existence of a low-flow channel as essential in fish-friendly culverts; however, their use depends on the site conditions, especially the type of bed material (substrate) that exists within the waterway (clay, sand, gravel or cobbles).



Multi-cell culvert with a low-flow channel

Types of low-flow channels

- A low-flow channel can exist as either:
  - a narrow channel formed into the bed of a wet cell
  - the full bed width of a wet cell, or several wet cells.
- The latter case is usually not referred to as a low-flow channel, but instead is termed a recessed wet cell.



Culvert with a recessed wet cell

Intended purpose of low-flow channels

- Reasons for including a low-flow channel can include:
  - to blend smoothly with an existing low-flow channel
  - to mimic the hydraulic properties of an existing low-flow channel
  - to encourage the existing low-flow channel (upstream and downstream of the culvert) to maintain a specific position within the waterway channel.

Site conditions that support the inclusion of a low-flow channel

Natural low-flow channel (NSW)

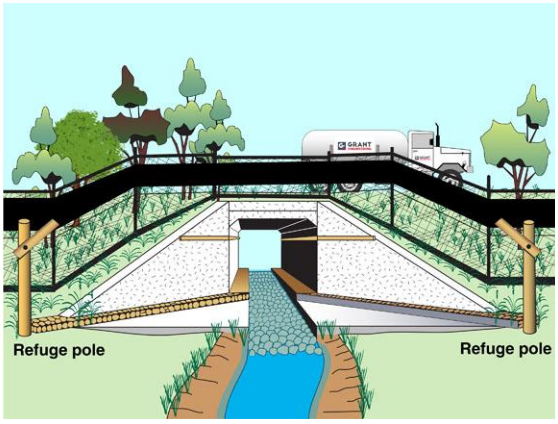
Maintaining the properties of an existing low-flow channel

- For waterways that have an existing low-flow channel, and where fish are known to move along this channel, then the fish passage attributes associated with the low-flow channel should be reproduced through the culvert.
- However, if the culvert is to be designed to operate as (i) a riffle system, or (ii) as a pool system, then a low-flow channel may not be appropriate.

Stable sand movement along channel

Maintaining the natural movement of bed sediments during periods of low flow

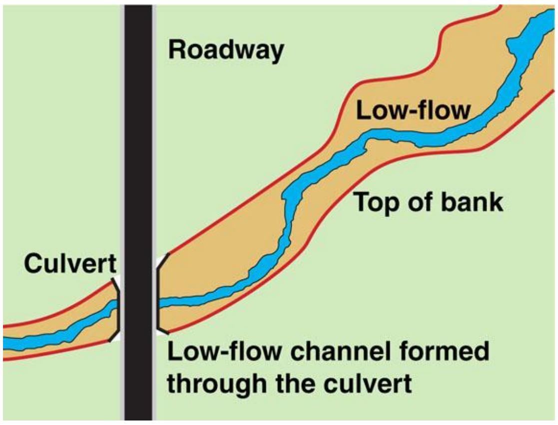
- Modified waterways that have re-formed a low-flow channel, may have established a stable flow of bed sediments along this low-flow channel
- Reconstructing this low-flow channel through the culvert could mean that sediment flows will also be maintained through the culvert (a good outcome).



Combined terrestrial and aquatic passage

Both fish passage and terrestrial passage must be integrated into the same culvert cell

- Integrating terrestrial and aquatic passage into the same culvert cell inevitably results in the formation of a low-flow channel.



Plan view of a culvert crossing

To limit the lateral migration of the existing low-flow channel

- Sometimes the existence of a low-flow channel in a culvert can help prevent the upstream and/or downstream low-flow channels from migrating too close to either channel bank, thus reducing the risk of bank erosion near the culvert (a good outcome).

Site conditions that do not support the inclusion of a low-flow channel

Rocks deposited in a low-flow channel

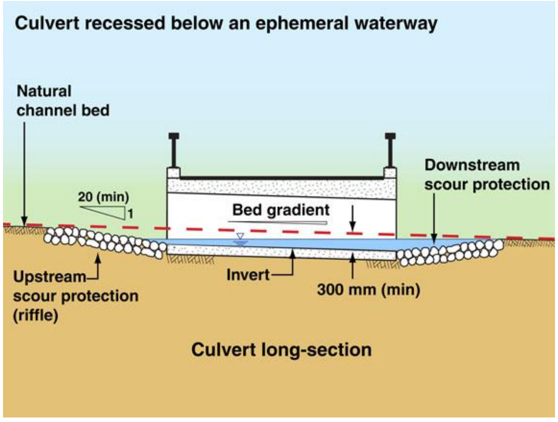
Waterways with high sediment flow

- If the waterway has a high bed load (sediment flow), then this sediment can quickly smother a low-flow channel.
- The moving sediment may form its own low-flow channel, but this will be beyond the control of the culvert designer.
- A high sediment flow can be expected in:
  - sand-based waterways
  - gravel-based waterways
  - urban waterways with significant urban sediment runoff.

Culvert placed over a gravel-based creek

Sand-based or gravel-based waterways

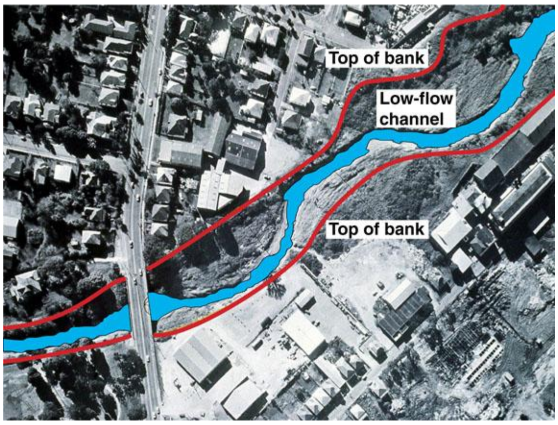
- Low-flow channels should NOT be used when the culvert is located on a sand-based or gravel-based waterway, or any waterway that experience significant sediment flow.



Recessed culvert

Cases where fish passage is best achieved by recessing the wet cells to form a pool

- A low-flow channel is unnecessary in a culvert with a recessed floor.
- In such cases, the full width of the recessed wet cells will become the effective low-flow channel.

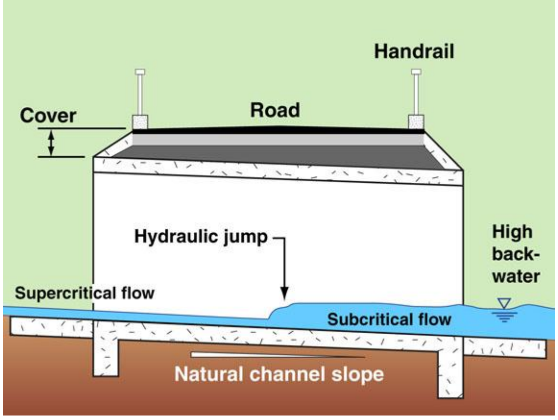


Wide low-flow channel (Qld)

Cases where the existing low-flow channel is wider than a nominated wet cell

- In some large waterways, the existing low-flow channel can be wider than the width of individual culvert cells, making a formal low-flow channel unnecessary.

Step 10 - Bed Gradient and Elevation



Supercritical flow within a culvert

Supercritical flow within a culvert (Qld)

Hydraulic jump & downstream subcritical

Introduction

- In the past, culverts were designed to have the same gradient as the waterway.
- Such designs meant that the floor of the culvert (the invert) aligned with the upstream and downstream channel beds at the time of construction.
- If the culvert floor was left 'smooth', then there was the risk of high-velocity (supercritical) flows occurring within the culvert, which can be very problematic for fish passage (a bad outcome).

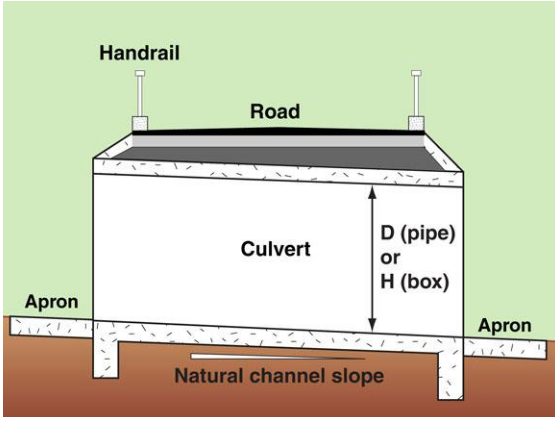
Supercritical flow

- Of course, supercritical flows can occur naturally within waterways; however, in most waterways it is common for the bed roughness (i.e. size of bed gravels) to increase as the bed gradient increases.
- Supercritical flows can be:
  - shallow
  - have a high velocity
  - and have minimal boundary layer thickness.

Hydraulic jump and subcritical flow

- The hydraulic jump (HJ) that forms as flows transition back to subcritical, can be highly turbulent, and difficult for fish to pass through.
- The turbulence that is initiated at a hydraulic jump, will usually continue for some distance downstream of the jump.
- Both flat-bed culverts, and sloping-bed culverts, have their advantages and disadvantages with respect to fish passage—both conditions can work, and both can fail!

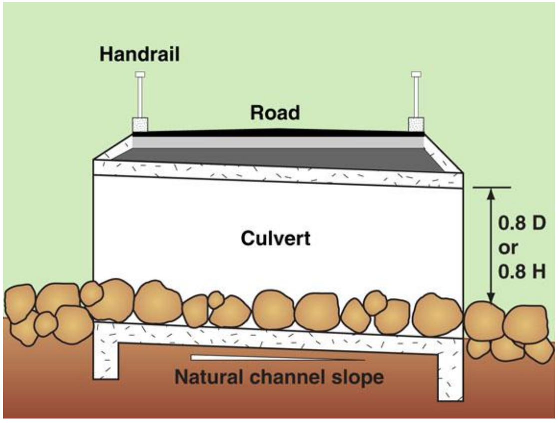
Sloping-bed culverts (stream slope design)



Not fish friendly

Traditional design procedure

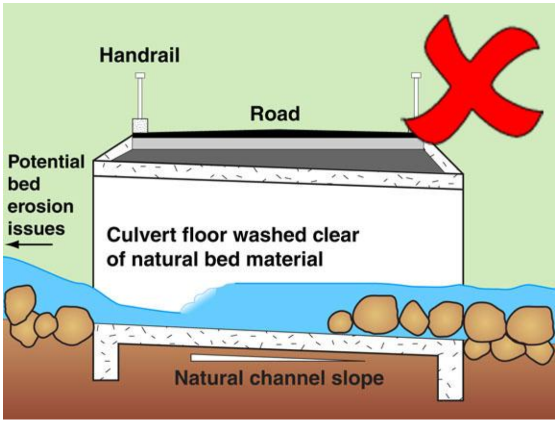
- Sloping-bed culverts can be designed as fish-friendly culverts; however, designers should be aware of the potential problems that can result from such designs, including:
  - supercritical flow and hydraulic jump issues as discussed on the previous page
  - difficulties in retraining bed roughness (e.g. rocks) on the floor of the culvert.



Recessed, stream slope culvert

Fish-friendly stream slope design

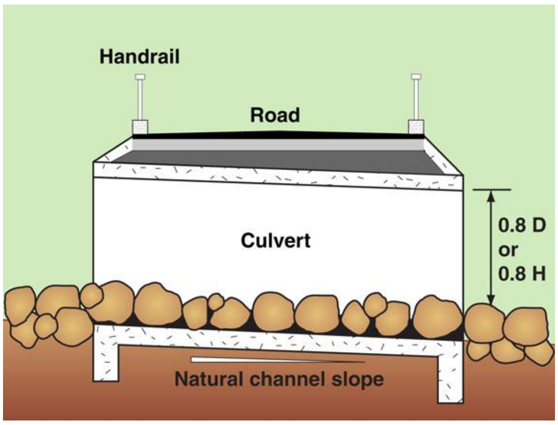
- This diagram (left) shows a culvert recessed into the bed of a gravel-based waterway.
- In such an arrangement, the culvert is designed to act like a riffle.
- In a sand-based waterway, the culvert would be similarly recessed into the sandy bed such that sand can continue to pass through the culvert.
- In a clay-based waterway, rocks are normally grouted to the culvert bed.



Material washed from culvert bed

Worst case outcomes

- Allowing natural bed material to settle, loosely, on the culvert floor facilitates the natural migration of sand or gravel through the culvert.
- Issue: However, there is a high risk that the culvert can be washed clear of all bed material during flood events.
- Issue: Such an outcome can cause a bed discontinuity to form at the culvert's inlet, which can initiate head-cut erosion.
- Issue: Such culverts are difficult to de-silt after flood events.

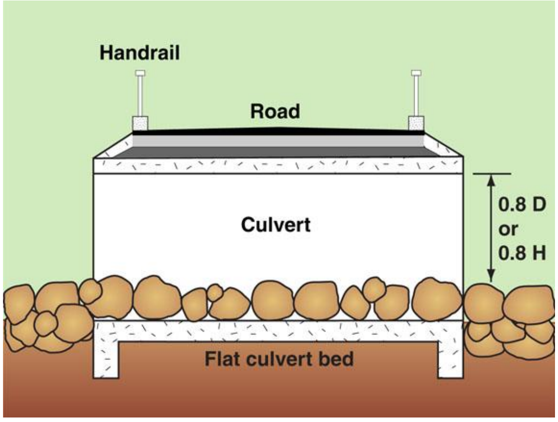


Rocks fixed to culvert bed

Grouted bed roughness

- In clay-based waterways it is common for rocks to be grouted to the bed of the culvert.
- Grouted rocks can also be used in sand-based and gravel-based waterways; however, this can interfere with the natural migration of sand or gravel along the bed.
- De-silting can be managed with water jets (flushing), but not mechanical (digging) removal of the sediment.

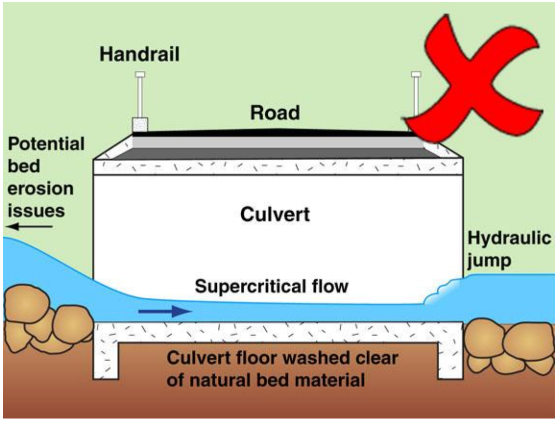
Flat-bed culverts (culverts functioning as a pool)



Recessed, flat bed culvert

Flat bed design option

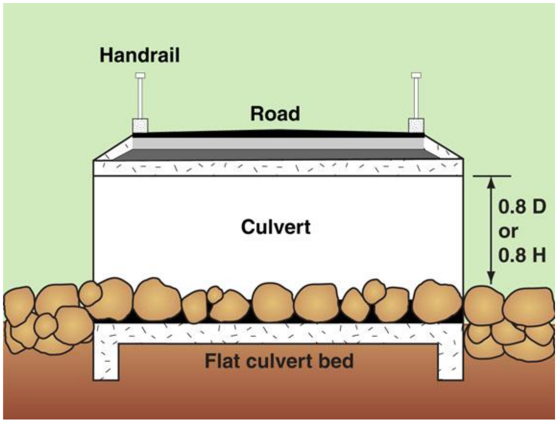
- A flat bed culvert can be used independent of whether the culvert is acting as a pool or a riffle.
- If the culvert is placed at the location of a natural channel pool, then this does not mean the floor of the wet cells should be left as smooth concrete.
- The culvert should be recessed into the channel bed, and natural bed sediment should be allowed to settle on the floor of the culvert.



Material washed from culvert bed

Stream bed discontinuities

- During major floods, flow velocities can be very high, even in natural pools, but especially within culverts acting as ‘pools’.
- Issue: Even though the risks are lower for recessed culverts, bed roughness can still be washed from the culvert bed.
- Issue: Such an outcome can cause a bed discontinuity to form at the culvert’s inlet, which can initiate head-cut erosion.
- Issue: Culvert de-silting can become a maintenance issue.



Rocks fixed to culvert bed

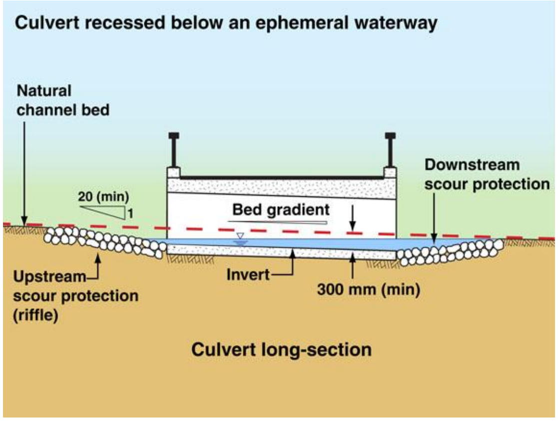
Natural movement of stream bed material

- The benefits of grouting rocks to the culvert floor (left) depends on what types of culvert maintenance is expected.
- Issue: Flat bed culvert have an increased risk of forming a bed discontinuity at the upstream end of the culvert.
- Issue: At the site shown below, a riffle had been constructed upstream of the culvert in order to maintain ‘natural’ water levels upstream of the new culvert; however, the riffle eventually washed away causing the upstream pool to drain (oops!).

Constructed upstream riffle (2001)

Inlet riffle washed away (2022)

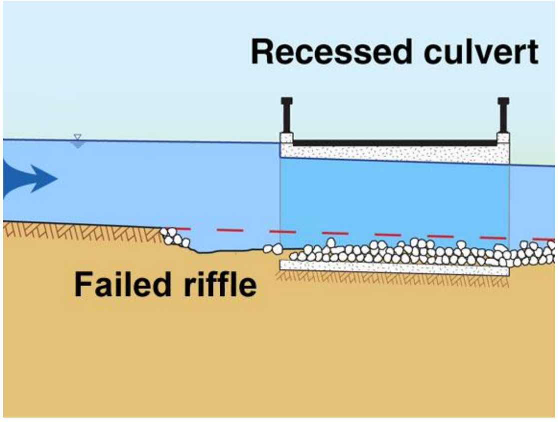
<u>Upstream</u> erosion risks associated with recessed culverts



Recessed culvert

Introduction

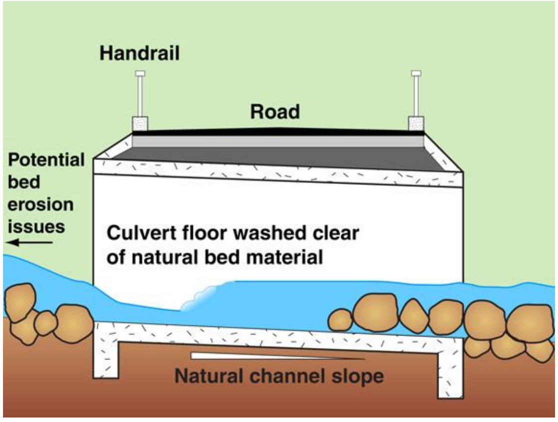
- Recessing the bed of a culvert can provide many benefits to fish passage; however, these potential benefits do not come without some long-term risks to the waterway's stability.
- Designers must always consider the potential long-term erosion risks, which ultimately could remove any of the short-term fish passage benefits.



Failure of the inlet riffle

Failure of a constructed culvert inlet riffle

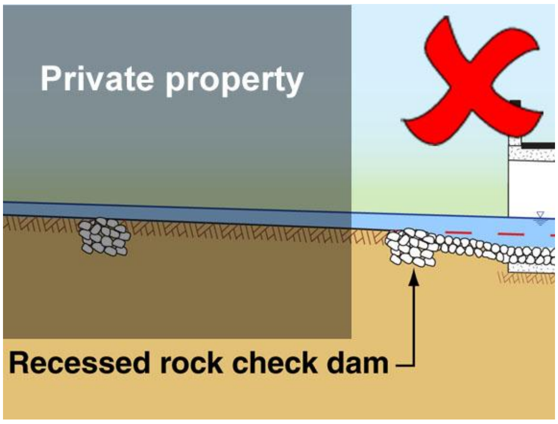
- A critical component of the design is the long-term stability of any upstream bed stabilisation measures.
- Such bed stabilisation measures usually take the form of a constructed rock chute or riffle (also known as a rock ramp).
- If such a structure were to fail, then it could initiate a form of head-cut (bed) erosion that could migrate up the waterway (a bad outcome).



Material washed from culvert bed

Loose bed roughness rocks washed from inside the culvert

- Another potential failure mode is the removal of bed roughness from inside the culvert.
- The removal of this roughness can increase flow velocities both within the culvert, and at the culvert's inlet.
- This increase in flow velocity can cause the failure of upstream bed stabilisation measures (another bad outcome).



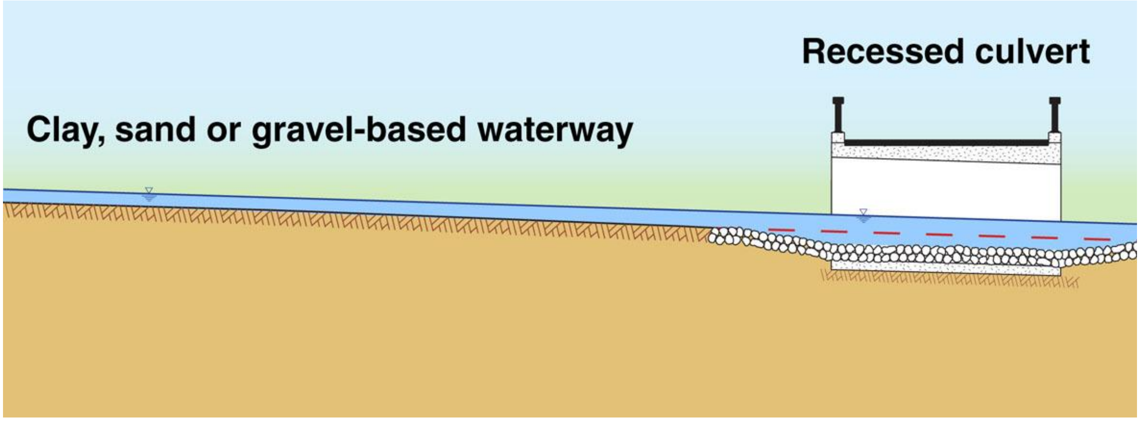
Works located outside the road reserve

Limiting works to within the road reserve

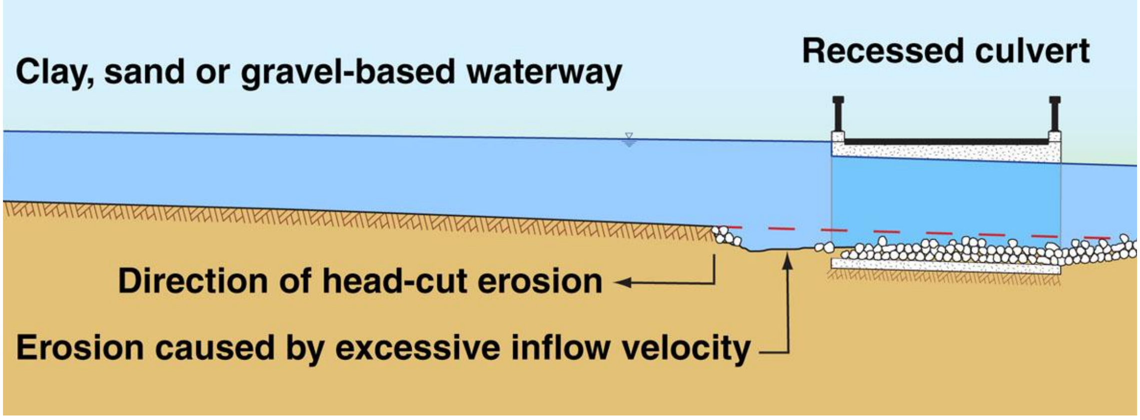
- Another design problem can be caused by the limited width of the road reserve at the waterway crossings.
- Ideally, it may be necessary to install additional bed stabilisation structures well-upstream of the culvert, but access to these upstream areas of the waterway may be prevented by the owner of that land.

Over the page is an example of how bed erosion issues can extend upstream of the culvert.

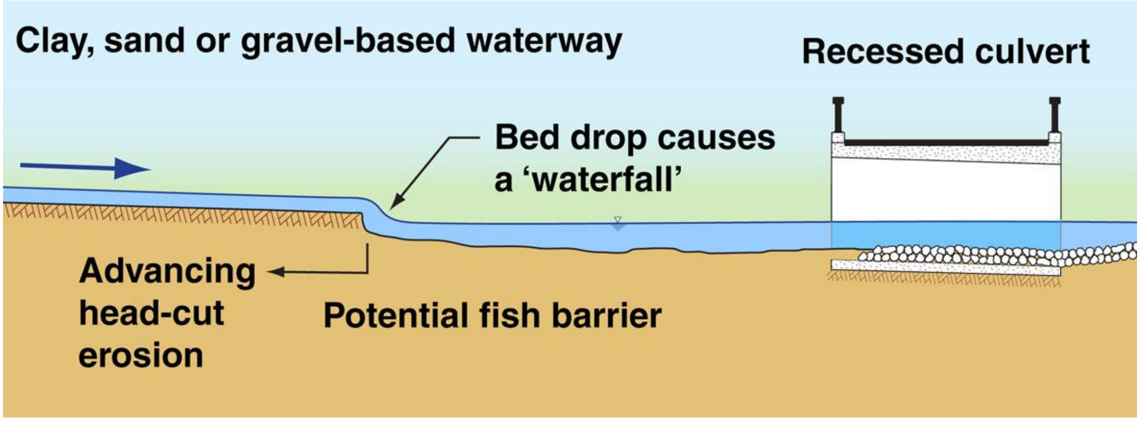
<u>Upstream</u> erosion risks associated with recessed culverts



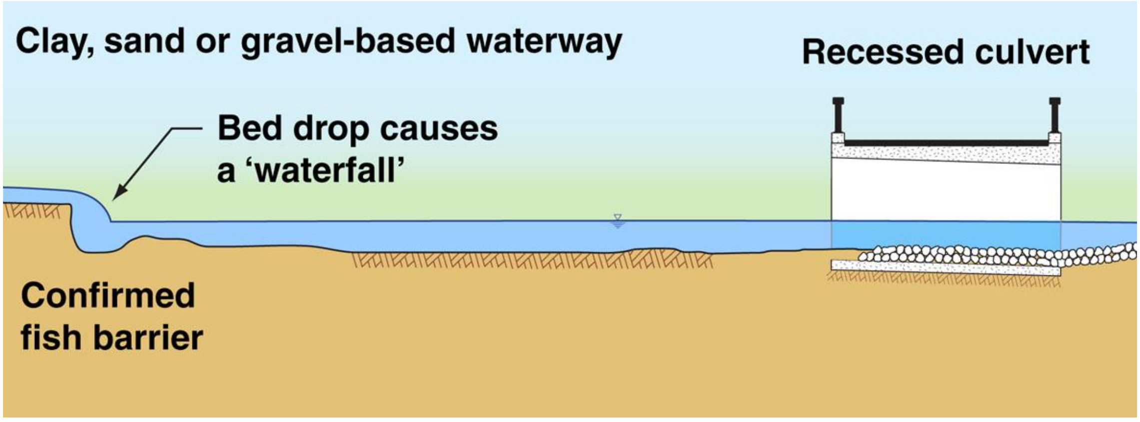
Before: Upstream channel stabilised with a constructed riffle



After: Riffle washed away, which initiates upstream head-cut erosion

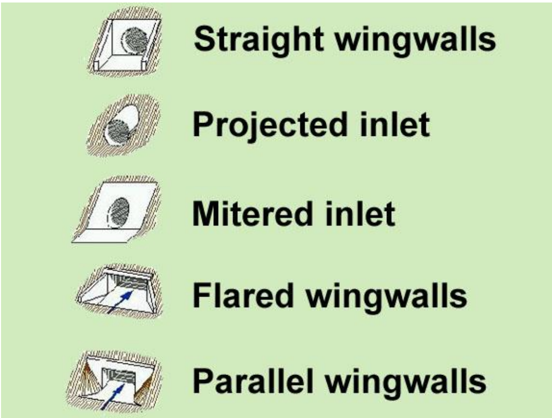


Bed erosion migrates upstream



Bed erosion eventually forms a head-cut, which acts as a barrier to fish passage

Step 11 - Culvert Inlet



Culvert inlet structures

Inlet safety screen on a detention basin

Severe debris blockage of a culvert (Qld)

Inlet geometry

- Energy loss at the culvert inlet is usually less than the potential energy loss at the culvert outlet.
- However, there is a greater potential to reduce the energy loss at the culvert inlet compared to at the culvert outlet.
- In addition to the normal hydraulic issues, there are also potential effects of:
  - inlet safety screens (Appendix H)
  - debris blockage (Appendix G)
  - sediment deposition (Appendix G).

Inlet safety screens

- The use of inlet safety screens is a complex issue that must not be adopted without expert advice.
- In general, the placement of an inlet safety screen on a waterway culvert should be avoided as discussed in Appendix H (in Part 3).
- However, these concerns are reduced if the culvert crosses a waterway or channel that does not have a flood debris problem.

Debris blockage and sediment deposition

- There are two main sources of debris blockage:
  - floating flood debris (usually organic)
  - sediment (from clay to boulders).
- Debris blockage can cause three main issues:
  - increased energy loss
  - form a fish barrier
  - increased risk of overtopping flows, which can increase the risk to life.

Inlet geometry and the expected entry loss coefficient

Flush or straight headwall (Qld)

Flush headwall

- A flush headwall without wingwalls has the potential for significant flow contraction and entry loss.
- In some cases the banks of the upstream watercourse may act like wingwalls, thus reducing the flow contraction; especially if heavily vegetated; however, this is not usually considered during the design.
- **Entry loss coefficient typically = 0.5**

Angled wingwalls (Qld)

Angled (flared) wingwalls

- Angled wingwalls can help to direct flows into a culvert, but significant flow separation/turbulence can still occur.
- Straight wingwalls (i.e. projected wingwall set parallel to the culvert barrels):
  - act like a projected inlet if located on a wide channel
  - act like parallel wingwalls if located on a narrow channel.
- **Entry loss coefficient typically = 0.4**

Projected pipe inlet (SA)

Projected inlet

- Projecting a culvert inlet can result in significant energy loss at the inlet; **however**, designers need to be careful in what they nominate as a 'projected inlet'.
- The skewed culvert shown (below) would <u>not</u> experience the adverse effects of a projected box culvert inlet because the:
  - outer cells sit flush with the wingwalls
  - internal legs would not experience significant flow separation.
- **Entry loss coefficient typically = 0.7**

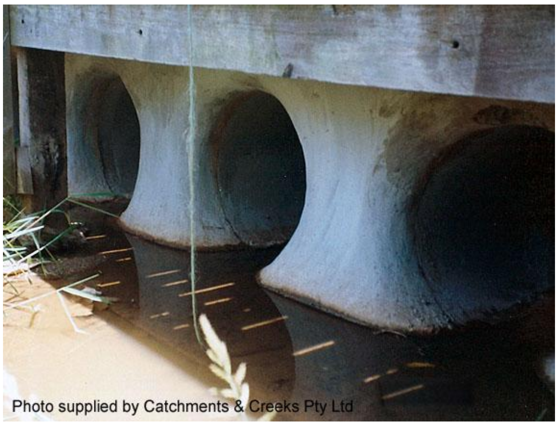
Projected inlets (Qld)

Skewed culvert inlet

- In most cases, the entry loss coefficient of skewed culverts is equal to that adopted for a flush headwall.
- The chosen entry loss coefficient depends on the potential for flow separation (within the conduit) at the inlet.
- The width of the vena contracta for a skewed culvert is similar to that of a square-edged culvert (see Step 18).
- **Entry loss coefficient typically = 0.5**

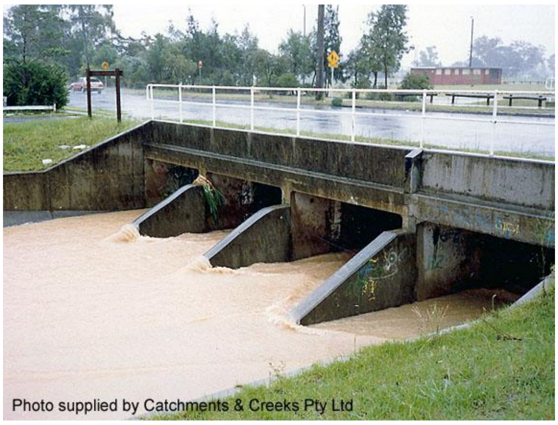
Minimising entry loss

Rounded face of a box culvert leg (NSW)



Rounded inlet (Qld)

Curved inlet wingwalls (Qld)



Debris deflection walls (NSW)

Introduction

- The best way to minimise energy losses at the culvert inlet is to streamline the flow conditions, with the aim of minimising flow separation at:
  - the wingwalls
  - the dividing walls (box culvert legs)
  - the obvert (roof of the culvert).
- A greater benefit is achieved by rounding the culvert entrance, than by building expensive curved wingwalls (for more discussion, refer to Step 18).

Rounded inlet

- The recommended radius of this curved surface is = D/12.
- On box culverts, both the culvert legs and the top deck (roof) should be rounded.
- Good quality entry conditions can reduce the entrance loss from 0.5 down to 0.2.
- A minimum 0.2 coefficient will exist because of the energy required to build the boundary layer within the barrel.
- **Entry loss coefficient typically = 0.2–0.5**

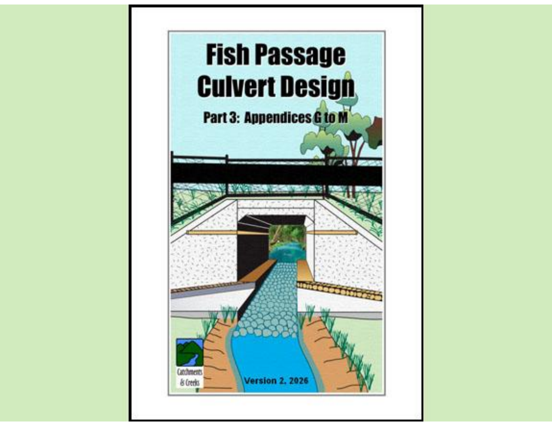
Curved inlet walls (minimum energy structures)

- In general, the cost of large curved wingwalls cannot be justified.
- In effect, these wingwalls deal with large-scale hydraulic issues, which do not contribute significantly to the energy loss.
- Rounding the entrance to each cell (barrel) deals with small-scale hydraulic issues, which have a greater impact on controlling flow separation.

Minimising debris blockages

- If inlet blockage caused by flood debris is an issue, then some of the control measures can include:
  - debris deflection walls
  - debris capture poles (which can also reduce the risk of large debris striking bridge piers)
  - upstream trash racks.
- The problems of debris blockages, and the potential control measures are presented in Appendix G in Part 3.

Debris blockages



Fish Passage Culvert Design, Part 3

Introduction

- Further information on debris blockage issues is provided in Step 12 of this document.
- An expanded discussion is provided in Appendix G in Part 3 of this publication.

Woody flood debris (Qld)

Floating flood debris

- Culvert blockages that result from floating debris is often referred to as 'top–down' blockage.
- The title suggests that the blockage starts at the top of the culvert, then slowly increases in size, thus extending 'down' the culvert inlet.
- However, floating debris can start collecting around the legs of a culvert early in a flood, and the water pressure can prevent the debris from moving.

Blockage by industrial waste bins (Qld)

Floating urban debris

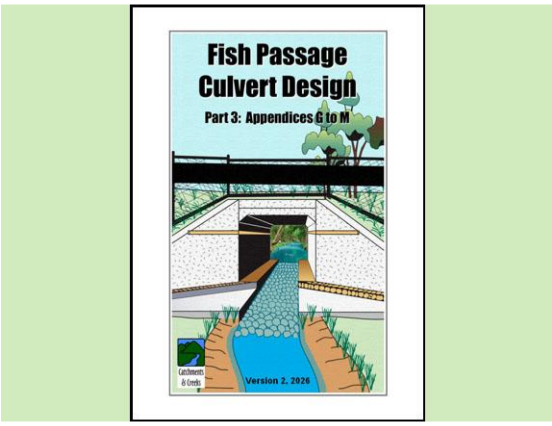
- The severity of the debris blockage depends on a number of factors, including:
  - dimensions of each cell
  - the amount of debris in the catchment
  - the arrival of large debris that can 'bridge' across the culvert opening, which can 'screen' more debris.
- Large urban objects, such as cars, industrial waste bins, rainwater tanks, and garbage bins, can significantly reduce the operational size of the culvert opening.

Sediment blockage (Qld)

Sediment and rocks

- Culvert blockages that result from sediment deposition can be referred to as 'bottom–up' blockage.
- Sediment deposition can occur:
  - daily
  - during a flood
  - during tidal cycles.
- Sediment deposited during a flood can continue to migrate through the culvert, but regular sediment deposits can become cohesive and resist any movement.

Inlet safety screens



Fish Passage Culvert Design, Part 3

Introduction

- Further information on safety screens is provided in Step 21 of this document.
- An expanded discussion is provides in Appendix H in Part 3 of this publication.

Inlet safety screen on a culvert (Qld)

Purpose

- Inlet screens typically have three potential purposes:
  - prevent a person or animal from being swept into the stormwater pipe or culvert
  - to assist a person or animal who has been swept towards the culvert, to exit the waterway
  - to collect and retain flood debris.

Inlet safety screen at the outlet of a lake

Usage

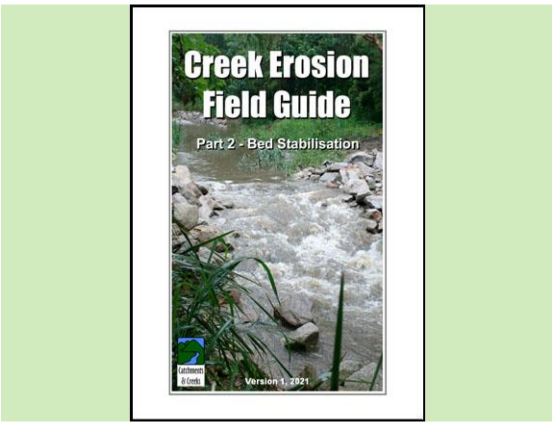
- In most cases, the use of inlet safety screens on waterway culverts should be avoided in preference to avoiding the design of a culvert that presents a safety risk.
- Inlet safety screens are used when:
  - the culvert presents an unacceptable safety risk
  - the safety risks cannot be removed by other, more acceptable, measures.

A fully blocked inlet screen (Qld)

Issues

- Potential issues include:
  - people can still drown if trapped on the screen, or they strike sharp debris already captured by the screen
  - increased risk of debris blockages
  - safety risks associated with increased risk of overtopping flows (e.g. pedestrian and road traffic safety)
  - increased risk of local flooding
  - increased maintenance costs.

Recessed culverts – Managing the upstream erosion risk



Creek Erosion Field Guide, Part 2

The potential cause of upstream erosion

- Erosion control measures are usually focused on the culvert outlet, but inlet erosion, if it occurs, can be more damaging than outlet erosion.
- If a form of head-cut erosion is triggered at the inlet, then this could migrate up the waterway causing:
  - bed and bank erosion, or
  - gully erosion if the culvert is located in an ephemeral waterway or gully.

Early stage of upstream gully erosion

Increased flow velocities at the culvert inlet

- Introducing a culvert into a waterway can increase the flow velocities within the immediate upstream channel by:
  - concentrating flows into a culvert's inlet
  - reducing the natural amount of overland flow (i.e. forcing flood water to pass through the culvert rather than over the roadway).
- Erosion control measures can be found in Part 2 on the *Creek Erosion Field Guide*.

Severe inlet erosion on cane field railway

Concentration of flows at the culvert

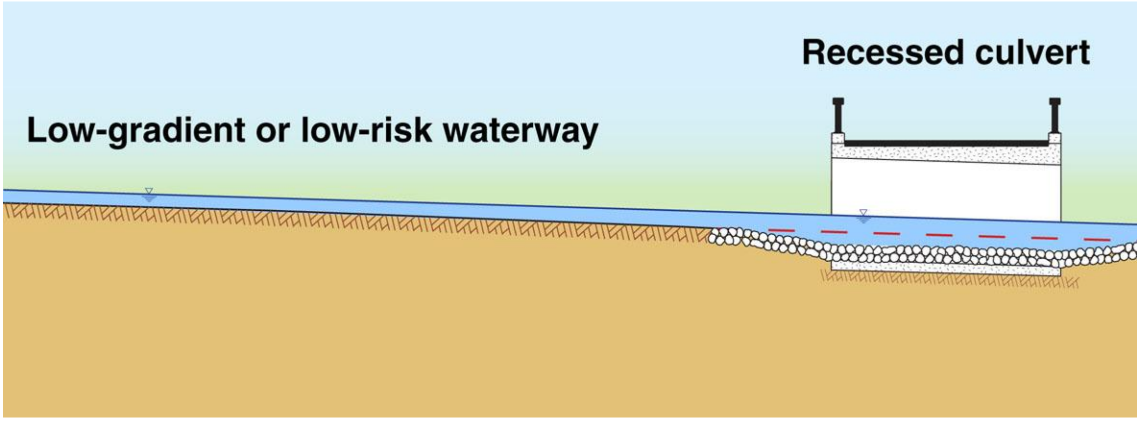
- Introducing a culvert into a waterway can concentrate flows upstream of the culvert by:
  - partially blocking the floodplain by introducing a raised road or rail embankment
  - focusing all flows towards the culvert's entrance.
- Erosion control measures can be found in Part 2 on the *Creek Erosion Field Guide*.

Gully erosion upstream of a drop inlet

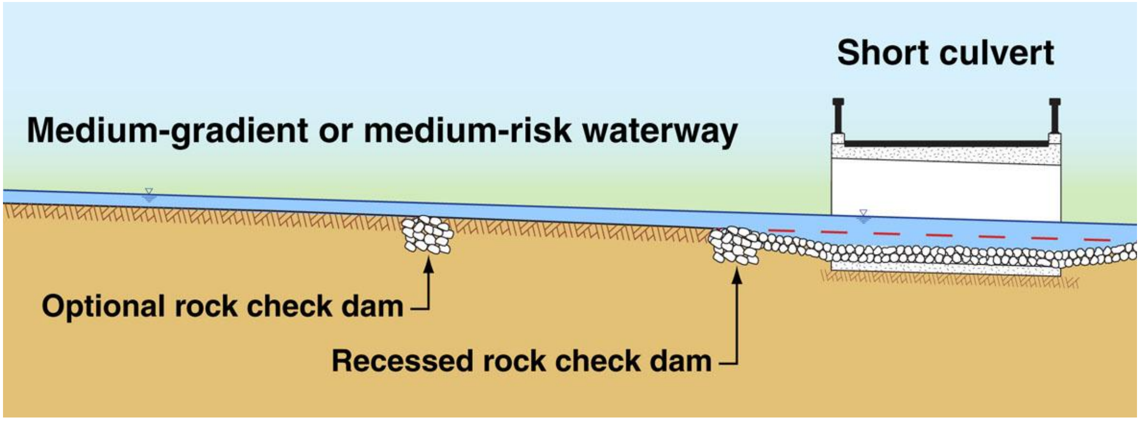
Structural failure of an inlet structure

- The types of inlet failures that can initiate upstream channel erosion include:
  - loss of rocks from a rock-lined inlet apron
  - failure of a rock riffle constructed upstream of the culvert
  - failure of the culvert's drop-inlet structure.
- Erosion control measures can be found in Part 2 on the *Creek Erosion Field Guide*.

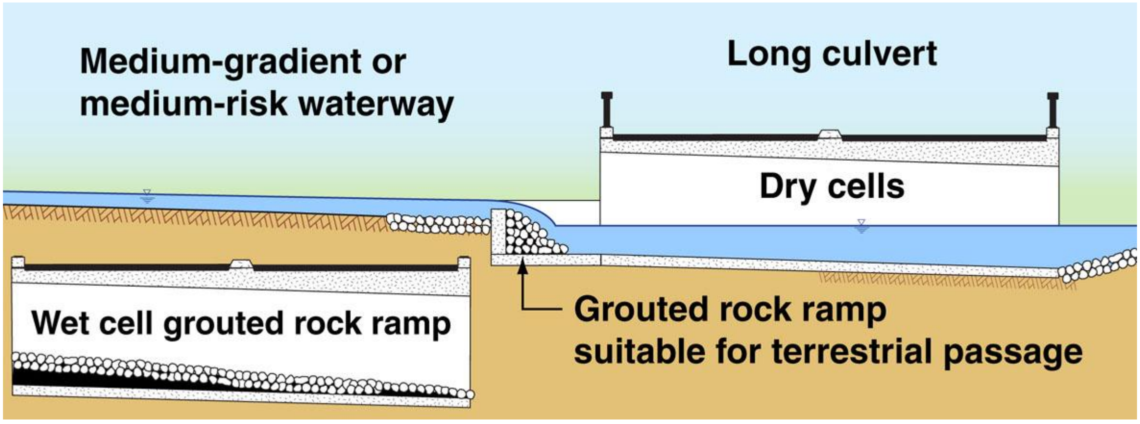
Recessed culverts – Managing the upstream erosion risk



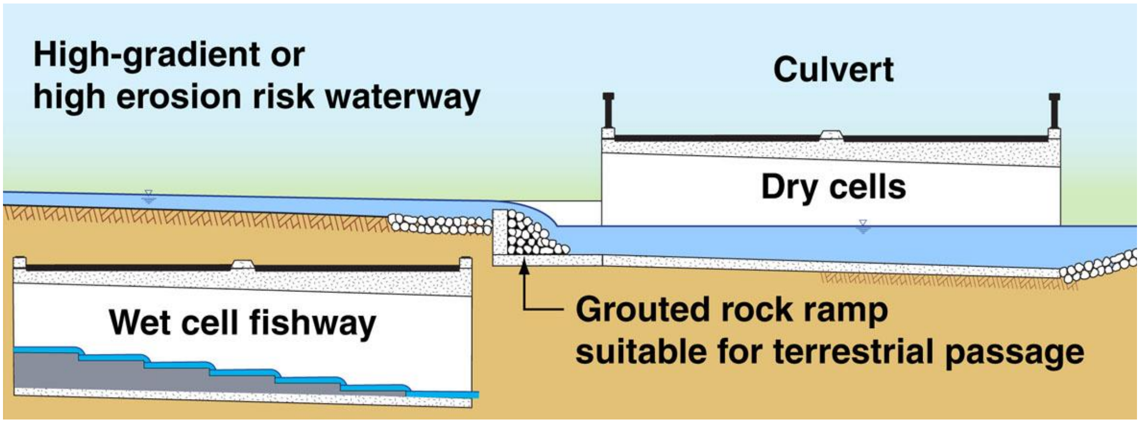
Low gradient waterway



Short length culvert (two lane road) on a medium-gradient waterway

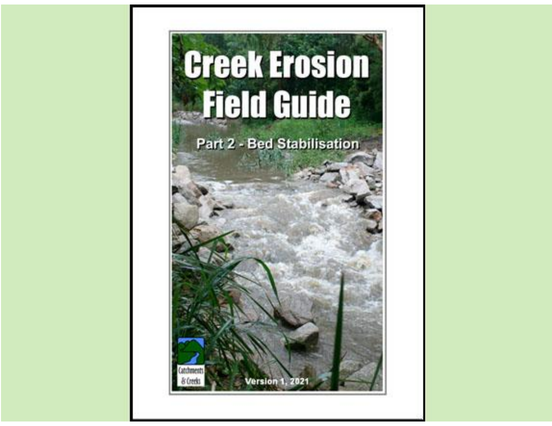


Long culvert (four lane road) on a medium-gradient waterway



Long culvert (four lane road) on a steep-gradient waterway

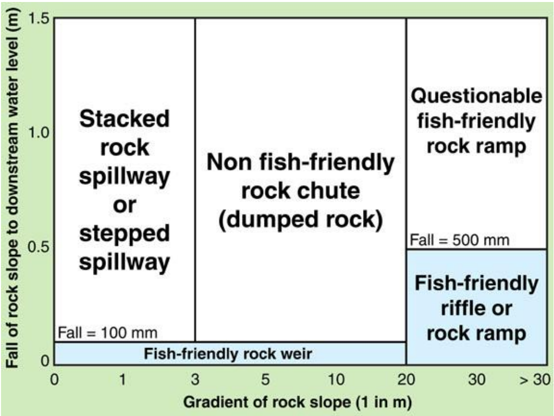
Recessed culverts – Stabilised inlet structures



Creek Erosion Field Guide, Part 2

Introduction

- Fish-friendly stabilised culvert inlets may consist of:
  - rock chutes (also known as rock ramps)
  - a series of pools and riffles, with the fall of each riffle not exceeding 500 mm
  - a series of ridge rock weirs.
- A flat inlet apron is usually included as part of the inlet structure.



General classification of rock chutes

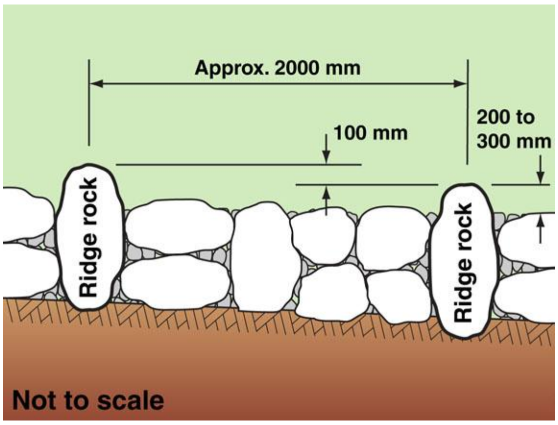
Rock chute (ramp) inlets

- Rock chutes/ramps placed in waterways are normally required to be fish friendly, while rock chutes placed in gullies are usually not 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 fall not exceeding 500 mm
  - a gradient no steeper than 1 in 20

Constructed pool–riffle system (Qld)

Constructed pool–riffle inlets

- 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.



Ridge rock – Typical dimensions

Ridge rock bed stabilisation

- 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.

Recessed culverts – Problematic treatment of drop inlet culverts

Non-fish-friendly structure

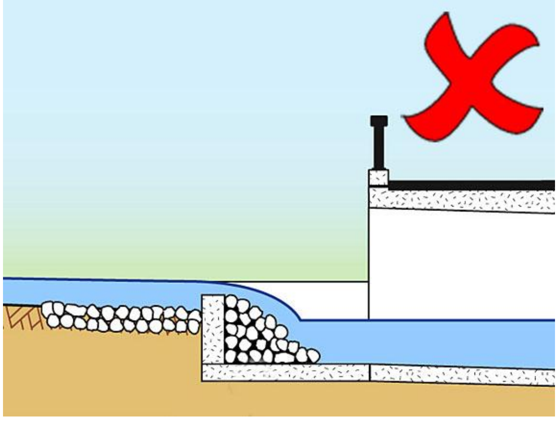
Drop inlet (not fish friendly)

- Drop inlets are not recommended in fish passage waterways.
- Inlet structures such as shown left, allow fish passage only when the inlet is fully drowned.
- The raised weir (shown left) is used to:
  - reduce flow velocities immediately upstream of the weir in order to reduce the risk of bed scour
  - reduce approach velocities to improve safety.

Drop inlet with no raised weir

Drop inlets placed only on 'dry' cells

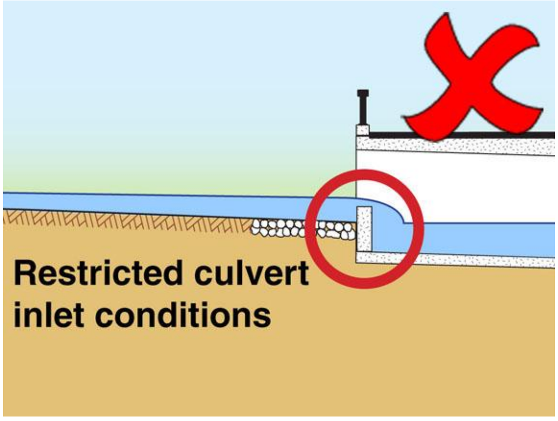
- If a drop inlet is formed from wire baskets (gabions), then the eventual structural failure of the wire baskets should be expected, which can cause upstream erosion issues.
- If the drop inlet is installed without a raised weir, then the hydraulic draw-down of the water surface can increase flow velocities well-upstream of the drop inlet, which can result in the erosion and safety issues listed above.



Drop inlet formed on nominated dry cell

Drop inlets placed on nominated dry cells

- It is common for weirs of various designs to be located at the inlets of the nominated dry cells in order to direct low flows into the nominated wet cells.
- The fact that these weirs are located on dry cells does not mean that they don't need to be fish friendly.
- Fish will try to swim through both wet and dry cells during flood events, so the design of any inlet structure must consider the potential impact on fish passage, including turtle movement.



Drop inlet located at the culvert inlet

Inappropriate location of drop inlet weir

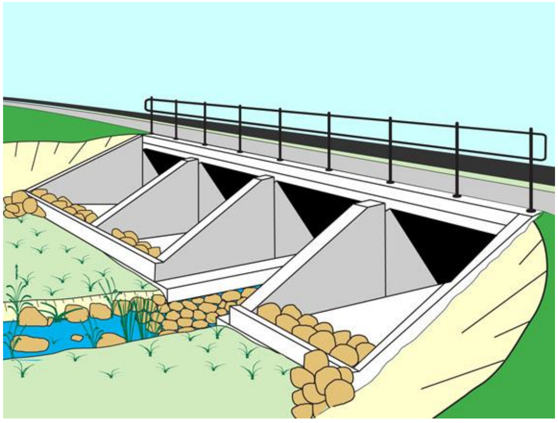
- If flow control weirs and/or drop inlet structures are placed on the inlet of a culvert, then these structures must be located far enough upstream of the culvert's headwall to:
  - prevent any reduction in the inlet flow area
  - prevent any interference in the culvert's inlet hydraulics or flow capacity
  - minimise flow turbulence that could adversely affect fish passage.

Other issues

Wide flat aprons are not fish friendly

Apron design

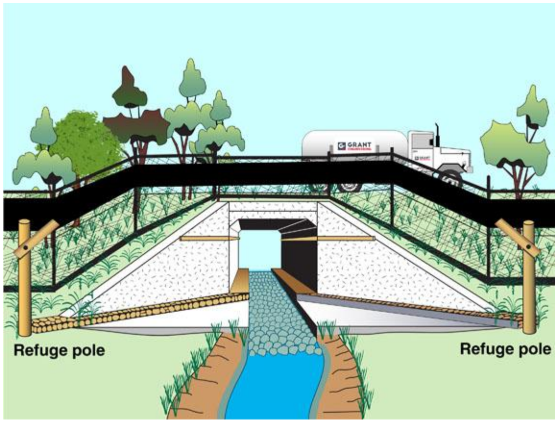
- Flat aprons rarely provide suitable fish passage conditions, unless the culvert apron is fully drowned during normal low flows (e.g. a recessed culvert).
- The problems caused by wide, flat inlet and outlet aprons include:
  - promotes uniform, shallow flow conditions during low flows (unless the culvert is recessed)
  - low bed roughness promotes shallow boundary layer conditions.



Low-flow channel

Use of low-flow channels

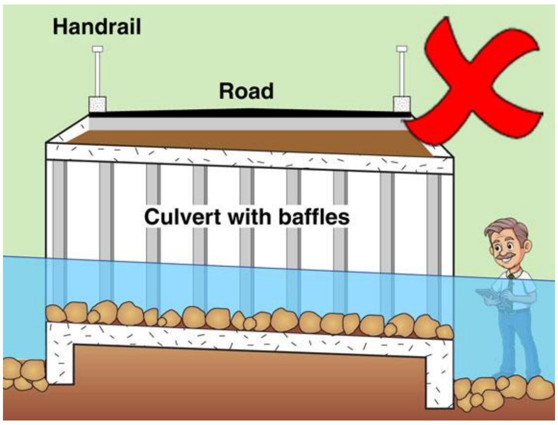
- If the culvert cannot be recessed in a manner that turns the culvert into a 'pool', then consideration should be given to the formation of a low-flow channel.
- Low-flow channels can:
  - direct low flows into a designated wet cell
  - aid fish passage during periods of low flow
  - aid in the natural migration of bed sediments.



Single-cell culvert with terrestrial pathways

Terrestrial passage

- The design of the culvert inlet needs to consider both aquatic and terrestrial passage.
- If terrestrial passage is required through the culvert, then a raised terrestrial path needs to be constructed across the inlet apron, and through the cells located adjacent to the waterway banks.
- Terrestrial passage issues are discussed further in **Step 17** and **Appendix J**.

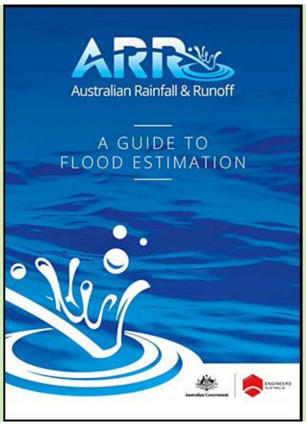


Unsafe maintenance inspection conditions

Access and safety for inspections and maintenance

- Culverts usually need to be inspected annually, and after flood events.
- Maintenance personnel will need to view inside each cell to check for damage and flood debris.
- Maintenance personnel will also need to check the condition of fish passage baffles and low-flow channels.
- A stable inlet apron is usually required in order to provide safe access.

Step 12 - Debris Blockage and Control



Australian Rainfall and Runoff, 2016

Reference document

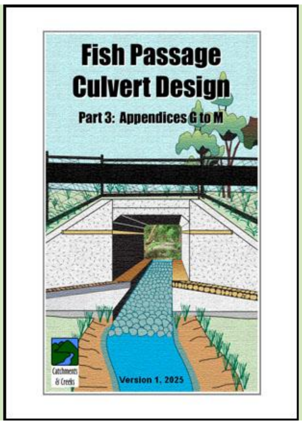
- The discussion of blockage factors that is found in *Australian Rainfall & Runoff* relates to 'flood estimation' hydrology.
- The *Australian Rainfall & Runoff* publication does not provide guidance on blockage factors applicable to the design of fish-friendly culverts.
- The minimum flow areas presented here for Low Flow, Medium Flow and High Flow designs are based on zero debris blockage.

AR&R Project 11, Stage 2, 2012

Additional reference document

Project 11: Blockage of Hydraulic Structures, Australian Rainfall and Runoff (AR&R), Report Number P11/S2/007, March 2012, Engineers Australia, Barton, ACT

W. Weeks, G. Witheridge, E. Rigby, A. Barthelmess and G. O'Loughlin



Fish Passage Culvert Design, Part 3

Detailed discussion

- An expanded discussion on debris blockage is provided in Appendix G of Part 3 of this document.

Types of culvert blockage

Culvert blocked by flood debris (Qld)

Woody bridging debris (Qld)

100% blockage of a road culvert (Qld)

Partial sediment blockage of a culvert

Introduction

- Sediment and debris blockages are important because they can:
  - reduce water flow through a culvert
  - reduce fish passage
  - reduce movement of terrestrial fauna.
- Flood debris can consist of:
  - long grasses and leaves
  - woody debris
  - urban litter
  - large floating objects.

Bridging debris (not the blockage of bridges)

- Even though most flood debris is small enough to pass through a culvert, this material can become trapped at the culvert inlet because:
  - the material wraps around the legs of a multi-cell culvert
  - the material wraps around, or is captured by a network of large woody debris that 'bridges' the culvert opening.
- Bridging debris primarily consists of logs and branches.

Top-down blockages

- Top-down blockages are primarily generated by floating debris, which mainly collects around the top of the culvert cells.
- This can mean that floodwater and fauna can continue to pass under the debris blockage.
- If the flood level rises above the culvert deck, the debris raft can become trapped under traffic barriers, or captured by a fencing/railing system, which can further exacerbate local flooding.

Bottom-up blockages

- Bottom-up blockages are generated by:
  - the natural migration of bed sediments that have been interrupted by the culvert hydraulics
  - introduced rural or urban sediment runoff.
- If the culvert is correctly sized, then the natural migration of bed sediment should pass freely through the culvert; however, blockages can occur if the culvert is designed to function as a 'pool'.

Issues of consideration

Design engineer

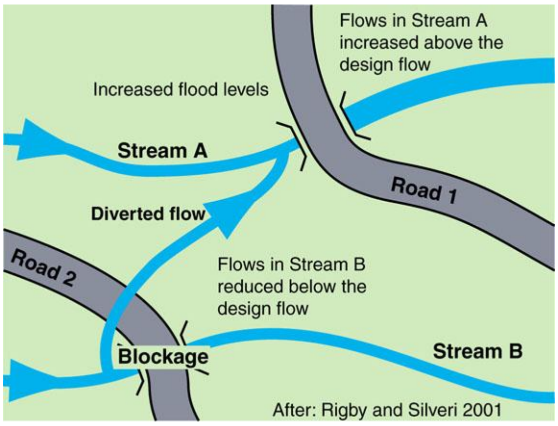
Introduction

- The critical issues of consideration depend on whether you are looking at the culvert from a fish passage perspective, or as part of a flood mapping exercise.
- The focus of *Australian Rainfall & Runoff* is flood estimation.
- The focus of this document is on fish passage.

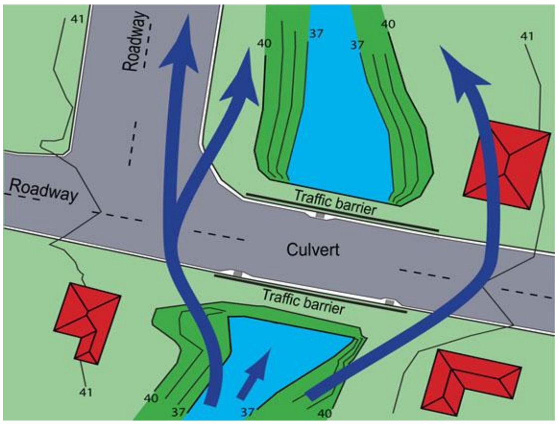
Debris blockage (Qld)

Fish passage issues

- From a fish passage perspective, the critical issues are likely to be:
  - potential blockage of essential fish migration during those limited times when fish migration is likely to occur
  - potential blockage of day-to-day fish movement if flood debris is not removed in a timely manner after each flood event
  - the design of debris control structures that can benefit fish passage.



Flow bypass caused by blockages

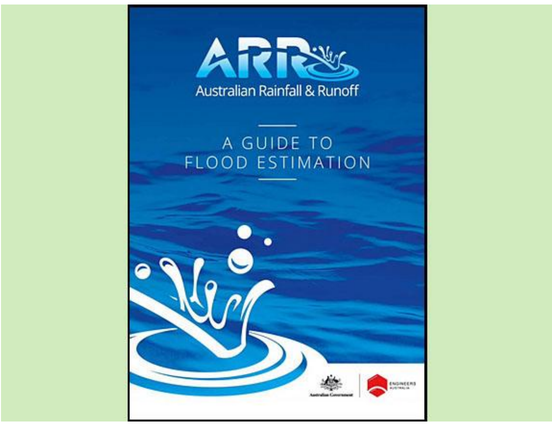


Flow bypassing caused by blockages

Flood estimation issues

- From a flood estimation perspective, the critical issues are likely to be:
  - the quantity and type of debris that would reach the structure in the design event
  - the type, location, porosity and timing of a blockage at the structure
  - the likely extent and coincidence of such blockages across the catchment
  - the impacts of the blockage on the hydraulic behaviour of the structure
  - potential impacts on adjacent watercourses if blockage causes flow diversion
  - the impacts of the blockage on the catchment, community assets, and public safety
  - the impact of the blockage on fish passage and terrestrial passage
  - the cost of post-flood maintenance.
- The occurrence of all of these issues is not a certainty, which means flood modelling needs to consider the probability of such events.

Assumed blockage conditions



Australian Rainfall & Runoff, 2019

Reference document:

Australian Rainfall and Runoff (AR&R), Engineers Australia, ACT. 2019.

The primary reference document for flood estimation investigations should be:

- **Chapter 6** (*Blockage of Hydraulic Structures*) of Book 6 (Flood Hydraulics)

Example of a low level of debris blockage

Smaller, more frequent floods (AEP > 5%)

- Recommended design conditions are:
  - If the catchment has been assessed as having a high risk of debris production, then adopt medium level of debris blockage.
  - Medium risk of debris production, then adopt low level of debris blockage.
  - Low risk of debris production, then adopt low level of debris blockage, say 10%.

Medium level of debris blockage

Medium floods (AEP 5% to 0.5%)

- If the catchment has been assessed as having a high risk of debris production, then adopt high level of debris blockage.
- Medium risk of debris production, then adopt medium level of debris blockage, say 20%.
- Low risk of debris production, then adopt low level of debris blockage.

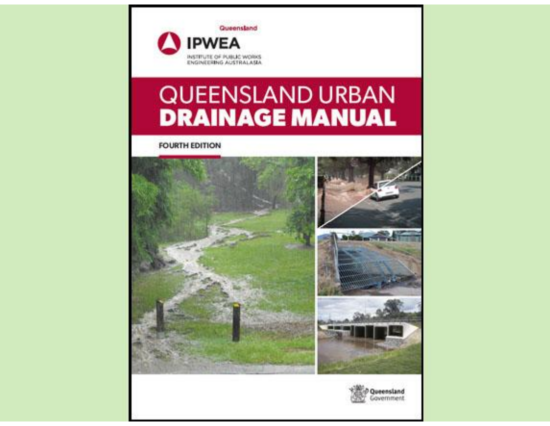
High level of debris blockage

Major floods (AEP < 0.5%)

- If the catchment has been assessed as having a high risk of debris production, then adopt high level of debris blockage.
- Medium risk of debris production, then adopt high level of debris blockage.
- Low risk of debris production, then adopt medium level of debris blockage.

- The adoption of 100% blockage is only used to set upstream flood levels, not downstream flood levels.

Blockage allowance (Queensland)



Queensland Urban Drainage Manual

Source: Brisbane City Council (2009)

Queensland Urban Drainage Manual (QUDM)

- Institute of Public Works Engineering Australia, Queensland Division and the Department of Energy and Water Supply. Brisbane, Australia, 4th edition, 2017.
- In the 2017 edition of QUDM:
  - Section 10.4.10 'Blockage considerations and debris deflector walls'
- *'Waterway culverts can experience debris problems in a number of circumstances, especially where:*
  - *the upstream waterway is heavily vegetated and is currently undergoing channel expansion due to changing catchment hydrology*
  - *the waterway has a large catchment area*
  - *the culvert has insufficient clear waterway area to allow the free passage of debris*
  - *the culvert is downstream of potential slip areas that could result in significant debris flow*
  - *the culvert has a history of debris problems.'*

Table 12.1 – Suggested blockage factors for culverts [1] (same as Table 7.1 in Step 7)

Culvert conditions	Blockage factor	
	Design value	Severe storm [2]
Inlet height < 3 m, or width < 5 m: Inlet Chamber (barrel)	20% [3]	100%
Inlet height > 3 m and width > 5 m*:* Inlet Chamber (barrel)	10% [3]	25% [3]
Culvert inlets with effective debris control features for culverts with inlet height < 3 m and width < 5 m	As above	As above
Screened culvert inlets	50%	100%

Notes:

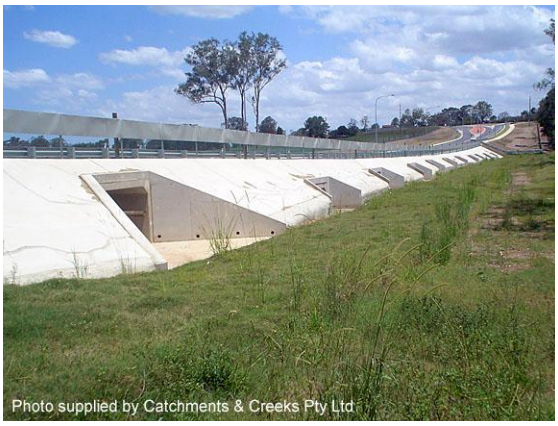
[1] Developed from Engineers Australia (2012), presented in QUDM, 2017.

[2] Refer to discussion below on severe storm investigations.

[3] Adopt 25% bottom-up sediment blockage unless such blockage is unlikely to occur.

[4] The degree of blockage typically depends on availability of suitable bridging matter, such as large branches and fallen trees, that can 'bridge' across the structure opening.

Reducing the effects of debris blockages



Floodplain culvert with well-spaced cells

All culverts

- Steps that can be taken to reduce the risk of debris blockage include:
  - maximise the clear height of the culvert cells, even if this results in the culvert having a hydraulic capacity the exceeds the design standard
  - maximise the clear width of the culvert cells
  - separating individual culvert cells to reduce the risk of debris wrapping around the connecting culvert leg.

Debris deflection walls, 1995 (Qld)

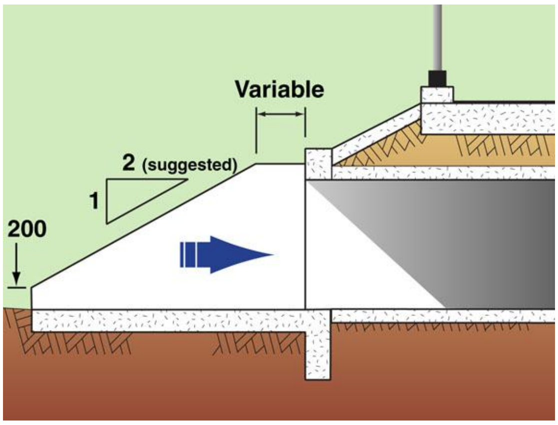
Debris deflection walls

- One means of maintaining the hydraulic capacity of culverts in high debris streams is to construct debris deflector walls.
- The purpose of these walls is to allow the debris raft:
  - to be held away from the culvert entrance
  - to rise with the flood, and ultimately to rest high on these walls, thus allowing fish passage to continue.

Post-flood condition, 1995 (Qld)

Fish passage benefits

- If the debris raft can be lifted above the channel bed, then fish passage can occur under the debris raft.
- If the debris raft remains held above the channel bed after the flood, then this critical period of fish passage can continue while the culvert waits for post-flood maintenance.

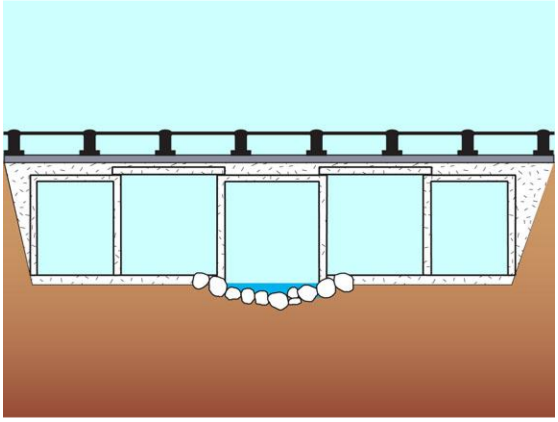


Typical debris deflection wall dimensions

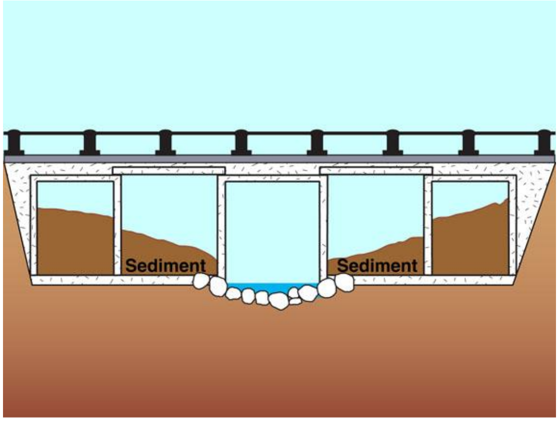
Design details

- Debris deflector walls typically have a leading edge slope of (1V:2H).
- If conditions allow, a ledge can be formed at the top of the walls to hold the debris raft once the flood peak has passed.

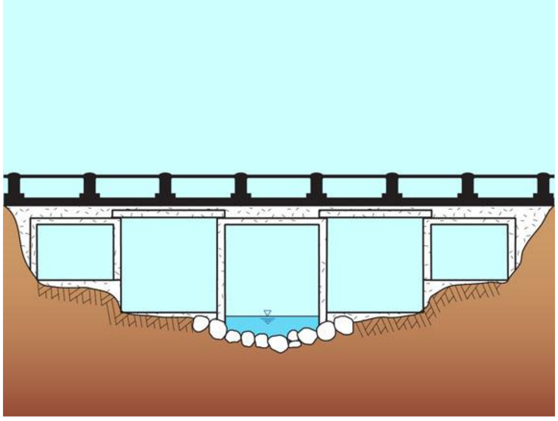
Sediment control options at culverts



Wide-bed culvert (as built!)



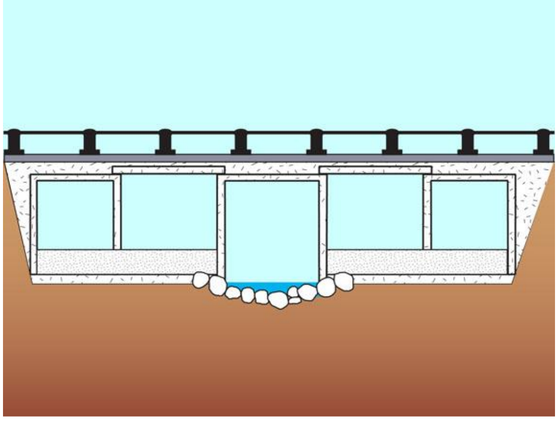
Wide-bed culvert (with sedimentation)



Complex multi-cell culvert

Variable floor level multi-cell culverts

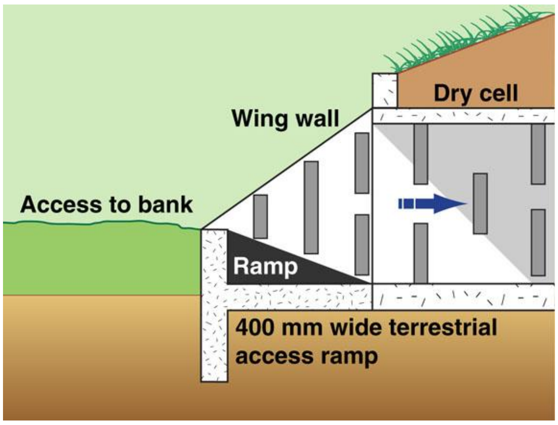
- Creeks respond to a wide multi-cell culverts in the same way they respond to channel widening—they allow the outer cells to fill with sediment.
- One solution to this problem is to construct the culvert with variable invert levels such that the profile of the base slab simulates the natural cross-section of the channel.
- However, this option may not provide the culvert with sufficient flow area for flood control, or fish passage.



Sediment training walls

Wide-bed culverts with sediment training walls

- An alternative solution is to construct a sediment training wall in front of the nominated dry cells.
- These low walls must completely isolate the dry cells from any dry-weather flows.
- Debris deflection walls can be integrated into the design of these sediment training walls.

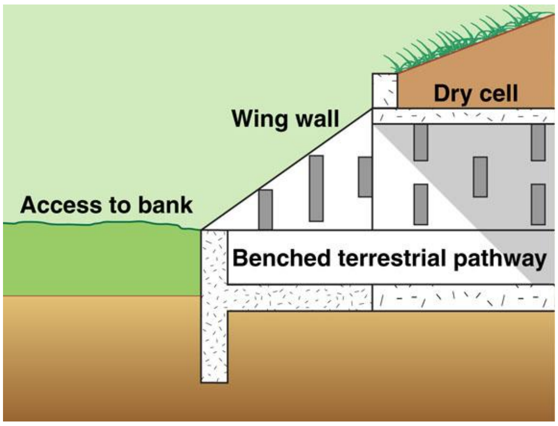


Terrestrial passage features

Allowance for terrestrial passage

- Sediment training walls and debris deflector walls can be combined to solve a number of common culvert maintenance problems.
- Sediment training walls allow sediment to be deposited upstream of the culvert where it can be removed.
- Various designs can be used to allow terrestrial passage over these low walls.

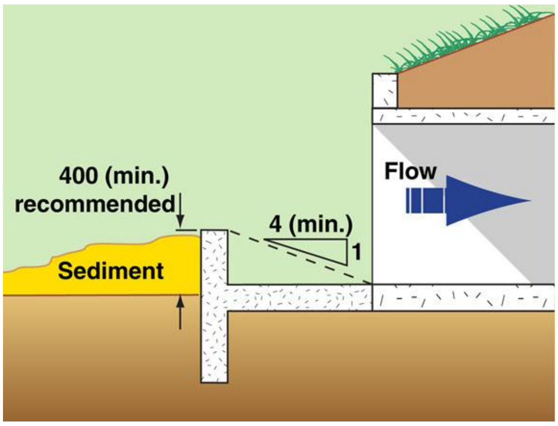
Sediment control options at culverts



Terrestrial passage features

Terrestrial passage features

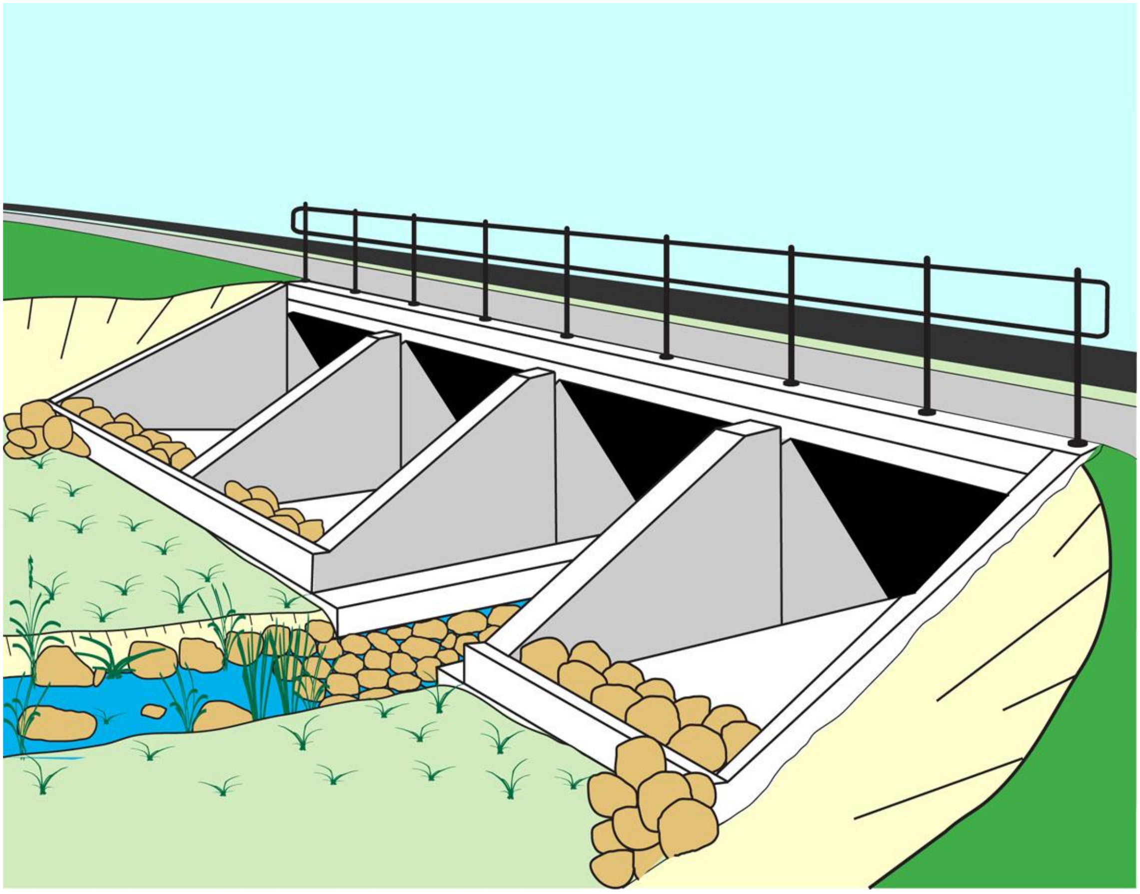
- Terrestrial passage, specifically the movement of turtles, can be aided with the inclusion of:
  - concrete ramp (previous page)
  - a raised terrestrial pathway bench (left)
  - grouted rock ramps (below).
- It is essential for the terrestrial pathway to join with the creek bank.



Hydraulic design

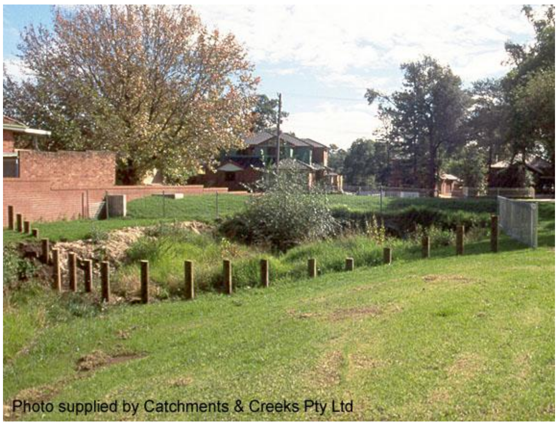
Design of sediment training walls

- Sediment training walls need to be placed well-away from the culvert's entrance in order to allow for the free passage of flood waters into the culvert.
- The walls need to be at least 300 to 500 mm high (the author recommends a minimum height of 400 mm).



Multi-cell culvert with debris deflection walls and sediment training walls

Debris traps placed upstream of culverts



Safety poles (NSW)

Introduction

- Various debris capture systems can be installed upstream of high-risk culverts.
- A 'high-risk' culvert is a culvert where any form of debris blockage would adversely affect flooding that has the potential to enter buildings.

Pile field (NSW)

Pile fields

- Pile fields can be used for a variety of purposes in waterways, including:
  - debris collection
  - debris impact poles
  - human safety (to reduce the risk of a person being swept into a culvert)
  - flow diversion system (to guide flows around a channel bend)
  - a buried erosion control system (to limit the extent of bed erosion)
  - outlet energy dissipation (image left).

Trash rack (ACT)

Trash racks

- Trash racks of various designs have been used in urban waterways as part of an overall stormwater quality system.
- Trash racks can be used to keep debris away from culverts.
- These trash racks are used in non-fish habitat regions of urban waterways (typically constructed stormwater drains).

Debris impact pole (SA)

Debris impact poles

- Debris impact poles can be used to:
  - prevent debris rafts collecting around bridge piers
  - reduce the risk of high-energy impacts on bridge piers (a structural engineering issue).

Step 13 - Design of Nominated Wet Cells

Single cell culvert (Qld)

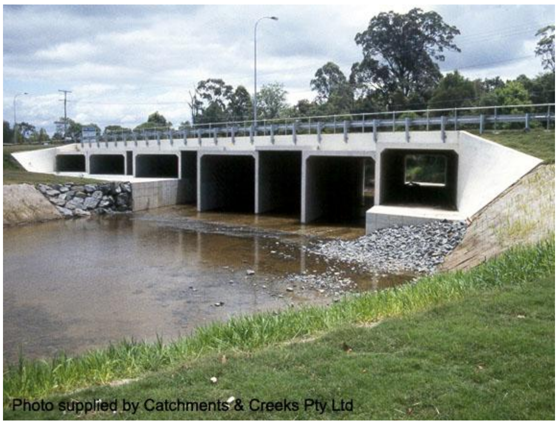
Introduction

- The cells or conduits of a culvert can be classified as either:
  - wet cells
  - dry cells.
- Wet cells are those cells that are normally (but not always) wet during:
  - extended periods of dry weather
  - periods of low flow within ephemeral waterways.

Culvert with multiple wet cells (NSW)

The function of wet cells

- The function of wet cells typically includes:
  - fish passage during periods of low flow
  - sediment (base load) transport during low flows
  - the passage of floodwater during flood events.



Multi-cell culvert (Qld)

Combined width of the wet cells

- The combined width of all the wet cells is typically based on the natural bed width of the waterway.
- If the channel has been widened as part of flood mitigation works, then:
  - the combined width of the wet cells can be based on the modified bed width, or
  - the combined width of the wet cells may be based on the 'natural' bed width in order to minimise the risk of sedimentation within the culvert.

Bed conditions within wet cells

Natural deposition of bed material (NSW)

Natural deposition of bed sand (NSW)

Placement of loose rock (NSW)

Gravel bed within a culvert (NSW)

Introduction

- Special bed treatment conditions typically only apply to the designated 'wet' cells; however, roughened bed conditions may also be necessary in 'dry' cells to aid fish passage during minor flood events.
- Desirable wet cell bed conditions depend on:
  - natural stream channel bed conditions
  - expected sediment flow along the bed
  - the type of bed material (clay, sand, gravel, cobbles).

Allowance for the natural deposition of bed sediments

- The natural deposition of bed material is generally preferred in rivers and sand-based waterways.
- In clay-based waterways that experience significant bed load sediment movement, grouted bed rocks are preferred because they allow culvert de-silting activities to occur.

Placement of loose rock

- Loose rock is typically used in gravel-based waterways.
- Gravel-based waterways are more suited to the free flow of rocks across the bed of the culvert.
- Imported loose rocks are normally placed on the culvert floor at the time of construction, unless suitable rocks are allowed to be obtained from the creek bed when the site is cleared for placement of the culvert foundations.

Sizing rock for loose rock placement

- If the rock is placed loose on the culvert floor, and is expected to resist movement, then the minimum size rock is given by:
  - to minimise the risk of movement, the minimum size of loose angular rock placed on the bed of culverts should be:

$$d_{50} = 0.04\,V^2 \qquad (13.1)$$

  - alternatively, the minimum size for loose rounded rock placed on the bed of culverts should be:

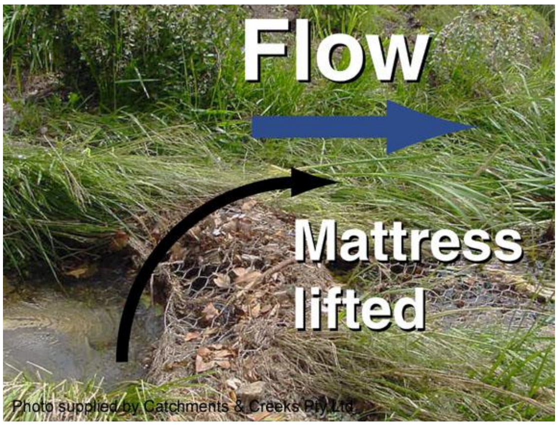
$$d_{50} = 0.05\,V^2 \qquad (13.2)$$

The use of rock mattresses for bed roughness is not recommended

Rock mattress placed on culvert bed

Introduction

- The use of rock mattresses as a form of bed roughness is **not** recommended due to possible breakage or displacement of the baskets.
- Past problems have already been observed by the author.



Lifting of rock mattress (Qld)

Rock mattresses lifted by hydraulic forces

- These mattresses have been known to lift from the culvert floor and block the culvert cell during flood events (personal communication conveyed to the author during AR&R blockage study).
- The author has observed two occasions where rock mattresses (placed outside of culverts) have begun to lift and curl due to high velocity flows passing over the mattresses.

Wire mesh ripped open

Rock mattress wire damaged by flood debris

- Flood events can carry an array of woody debris.
- If this woody material catches on the wire baskets it can rip the baskets open leading to the loss of rocks.

Damaged wire mesh

Rock mattress wire damaged by flood-induced sand-blasting

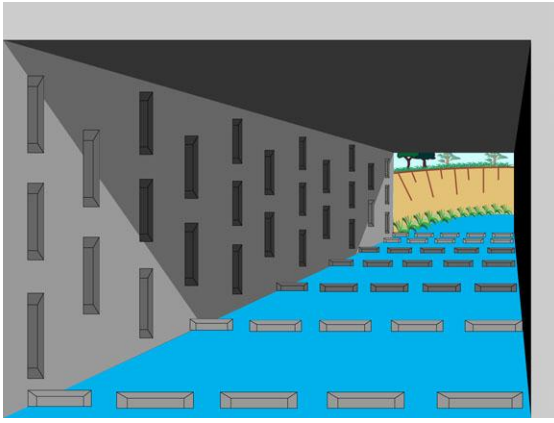
- Flood events can carry significant quantities of sand and gravel.
- These materials can effectively 'sand-blast' the plastic coating and galvanised protection from the wire baskets, ultimately resulting in the early failure of the baskets.

Baffle options for floor baffles

Sediment deposition (USA)

The retention of natural bed sediments

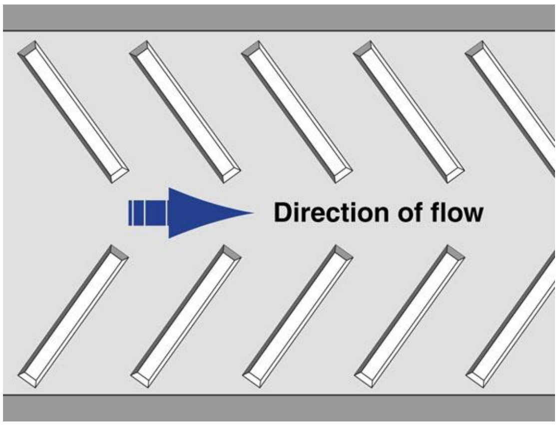
- Floor baffles can be used in low sediment waterways to provide resting zones for fish that prefer to move along the channel bed.
- However, it is essential for the choice of floor baffle to be compatible with the needs of the fish, the behaviour of the waterway, and the needs of the asset manager.
- Most waterways experience some degree of sediment flow, especially during flood events.



Floor baffles (perspective view)

Floor baffles used to aid fish passage along the culvert floor

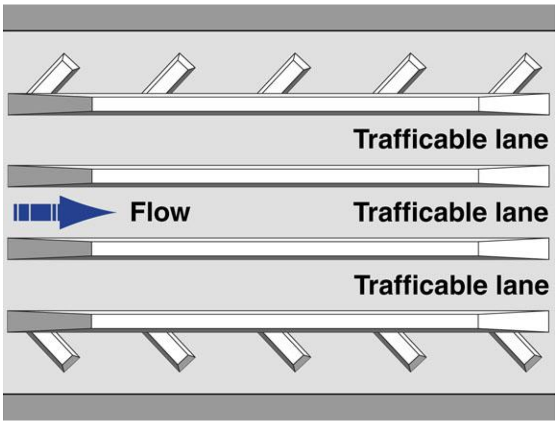
- Floor baffles are typically 100 to 200 mm high.
- Typical spacing of floor baffles is 6 (six) times the baffle height.
- Consideration can be given to the use of commercial pre-cast 'parking stops' (refer to Step 15).



Floor baffle arrangement (plan view)

Floor baffles used to aid the retention of bed sediments on the culvert floor

- Floor baffles are typically 100 to 200 mm high.
- Placing the baffles on an angle to the direction of flow can aid in the jet washing (maintenance) of the culvert after a flood event (if such post-flood maintenance is required).
- Typical spacing of floor baffles is 6 (six) times the baffle height.

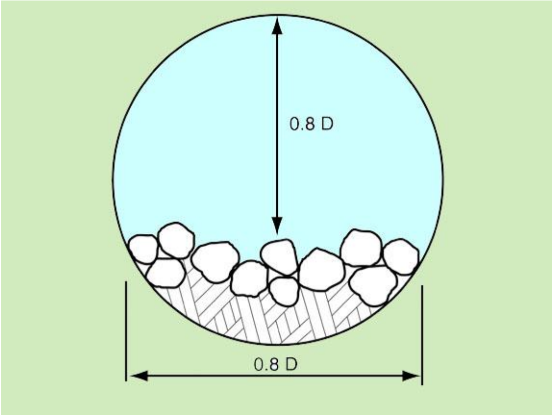


Floor baffle arrangement (plan view)

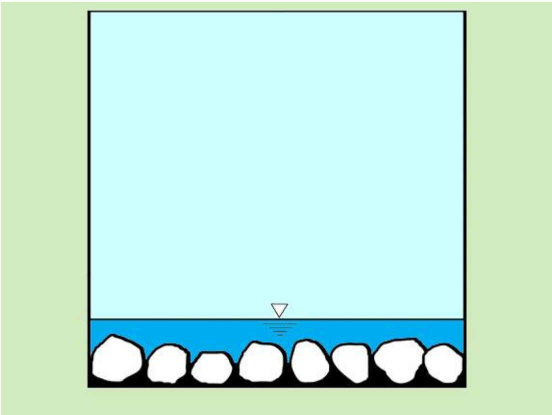
Floor baffles that can assist post-flood de-silting operations

- If the culvert is large enough to allow mechanical equipment to enter the culvert for the purpose of clearing away excess sediment and flood debris, then:
  - the floor baffles should be arranged in a manner that would allow a skid-steer loader to manoeuvre over or through the baffles
  - the arrangement of floor baffles will be site specific depending on the type of equipment used for maintenance.

Hydraulic properties of rock-lined culvert beds

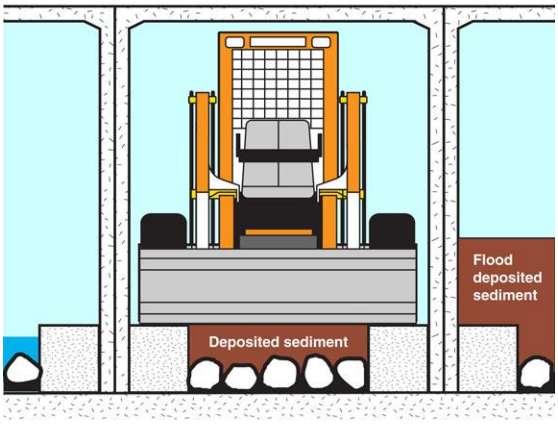


Natural bed material in a pipe culvert



Rocks grouted to bed of box culvert

Major de-silting program (Qld)



Post-flood debris and sediment removal

Pipe culverts

- Wet cells in pipe culverts are typically recessed 20% of their diameter into the channel bed.
- Recessing the culvert cells will reduce the effective flow area (A), wetted perimeter (P), hydraulic radius (R) and alter the pipe roughness (n).
- Hydraulic parameters for pipe culverts flowing full and recessed 20% into the channel bed are provided in tables 13.1 to 13.4 for various rock size distributions (d_{50}/d_{90}).

Box culverts

- Wet cell box culverts can also be recessed 20% of the cell height, or at least 300 mm.
- Hydraulic parameters for box culverts flowing full and recessed 20% into the channel bed are provided in tables 13.5 and 13.6 for various rock size distributions (d_{50}/d_{90}).
- If grouted rocks are used, then the installation costs may be reduced by grouting the rock onto the base slab prior to placement of the pre-cast units.

Post-flood de-silting of culverts

- Some culverts regularly require the post-flood removal of excess sediment.
- The removal of sediment from culverts can cause the disturbance, or total removal of, the introduced bed roughness.
- If sediment deposition is expected to become a maintenance problem (independent of the type of waterway), then consideration should be given to the firm grouting of the roughness units.

Potential benefits of terrestrial pathway benching

- To allow both aquatic and terrestrial passage within a single cell box culvert, benching may be required, otherwise the low-flow channel can be recessed into the base slab.
- In special circumstances, the wet cell can be designed to allow easy access for de-silting equipment without affecting the constructed wet cell bed roughness.
- This would be a rare outcome!

Hydraulic properties of pipe culverts containing artificial bed roughness

The placement of rocks and gravels on the bed of pipe culverts will alter the overall hydraulic roughness of the conduit. Tables 13.1 to 13.4 provide the hydraulic parameters for various pipe culvert conditions. These tables are based on an assumed smooth wall Manning's roughness (n) of 0.013.

Hydraulic properties of box culverts containing artificial bed roughness

Tables 13.5 and 13.6 provide the Manning's roughness for the rock-lined bed of an artificially roughened box culvert. This bed roughness will need to be incorporated with the soffit and sidewall roughness to determine a composite Manning's roughness for a box culvert flowing full.

The placement of **loose** rock is most appropriate in gravel-based waterways that experience a regular movement of similar sized rocks down the channel. Loose rock can also be used in clay-based waterways (if sediment flow down the channel is negligible) however, grouted rock may be required to avoid loss of the rocks during flood events.

If grouted rocks are used, then the cost of their installation may be reduced by grouting the rocks onto the base slab prior to installation of the pre-cast units. Grouted rocks are likely to have a slightly lower Manning's roughness to that of loosely placed rocks.

If loosely placed rocks are used, then consideration should be given to the placement of a raised sill at the downstream end of the culvert to help retain the rocks during high flows.

Benching is normally only used in single cell box culverts when it is necessary to provide both wet (aquatic) passage and dry (terrestrial) passage. If it is desirable for natural bed material to form across the bed of the culvert, then the height of the benching must be sufficient to allow a dry path to exist during normal base flow conditions.

If the culvert and the raised benching is appropriately sized, then 'bobcats' (skid-steer loaders) can travel along the raised benching to facilitate the removal of excessive sediment deposits, and the general maintenance of the culvert.

Table 13.1 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and d_{50}/d_{90} = 0.2

Mean bed rock size d_{50} =				50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	A (m^2)	P (m)	R (m)	Pipe full Manning's roughness (n)				
450	0.136	1.356	0.101	0.06				
525	0.192	1.610	0.119	0.05	0.09			
600	0.251	1.839	0.136	0.05	0.08			
750	0.391	2.297	0.170	0.05	0.07			
825	0.473	2.526	0.187	0.04	0.07			
900	0.564	2.758	0.204	0.04	0.07			
1050	0.765	3.213	0.238	0.04	0.06	0.10		
1200	1.001	3.674	0.272	0.04	0.06	0.09		
1350	1.268	4.136	0.307	0.04	0.05	0.09		
1500	1.564	4.594	0.341	0.034	0.05	0.08	0.11	
1650	1.892	5.052	0.375	0.032	0.05	0.08	0.10	
1800	2.251	5.510	0.408	0.031	0.05	0.07	0.10	
2100	3.143	6.511	0.483	0.029	0.04	0.07	0.09	0.11

Notes:

D = Nominal internal pipe diameter (mm)

A = Potential flow area within the pipe excluding the area taken up by the grouted rocks (m^2)

P = Potential wetted perimeter of a pipe with grouted bed rock (m)

R = Potential hydraulic radius of a pipe with grouted bed rock (m)

Table 13.2 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and d_{50}/d_{90} = 0.3

			Mean bed rock size d_{50} =	50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	A (m^2)	P (m)	R (m)	Pipe full Manning's roughness (n)				
450	0.136	1.356	0.101	0.038				
525	0.192	1.610	0.119	0.035	0.05			
600	0.251	1.839	0.136	0.033	0.05			
750	0.391	2.297	0.170	0.031	0.04			
825	0.473	2.526	0.187	0.029	0.04			
900	0.564	2.758	0.204	0.029	0.04			
1050	0.765	3.213	0.238	0.027	0.04	0.06		
1200	1.001	3.674	0.272	0.026	0.04	0.06		
1350	1.268	4.136	0.307	0.025	0.035	0.05		
1500	1.564	4.594	0.341	0.024	0.033	0.05	0.06	
1650	1.892	5.052	0.375	0.024	0.032	0.05	0.06	
1800	2.251	5.510	0.408	0.023	0.031	0.05	0.06	
2100	3.143	6.511	0.483	0.022	0.029	0.04	0.05	0.06

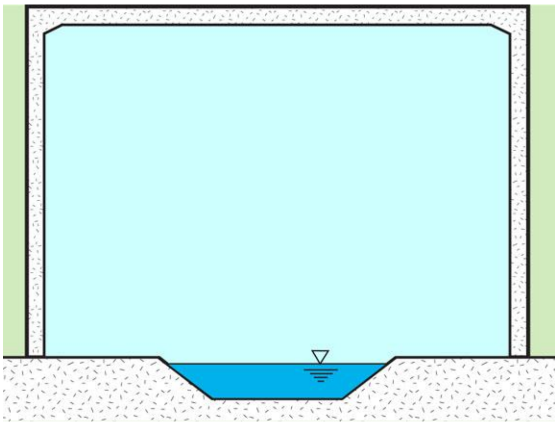
Table 13.3 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and d_{50}/d_{90} = 0.5

			Mean bed rock size d_{50} =	50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	A (m^2)	P (m)	R (m)	Pipe full Manning's roughness (n)				
450	0.136	1.356	0.101	0.024				
525	0.192	1.610	0.119	0.023	0.032			
600	0.251	1.839	0.136	0.022	0.030			
750	0.391	2.297	0.170	0.021	0.028			
825	0.473	2.526	0.187	0.021	0.027			
900	0.564	2.758	0.204	0.020	0.026			
1050	0.765	3.213	0.238	0.020	0.025	0.034		
1200	1.001	3.674	0.272	0.019	0.024	0.032		
1350	1.268	4.136	0.307	0.019	0.023	0.031		
1500	1.564	4.594	0.341	0.019	0.023	0.030	0.037	
1650	1.892	5.052	0.375	0.018	0.022	0.029	0.035	
1800	2.251	5.510	0.408	0.018	0.022	0.028	0.034	
2100	3.143	6.511	0.483	0.018	0.021	0.027	0.032	0.037

Table 13.4 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and d_{50}/d_{90} = 0.8

			Mean bed rock size d_{50} =	50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	A (m^2)	P (m)	R (m)	Pipe full Manning's roughness (n)				
450	0.136	1.356	0.101	0.019				
525	0.192	1.610	0.119	0.018	0.022			
600	0.251	1.839	0.136	0.018	0.021			
750	0.391	2.297	0.170	0.017	0.020			
825	0.473	2.526	0.187	0.017	0.020			
900	0.564	2.758	0.204	0.017	0.020			
1050	0.765	3.213	0.238	0.017	0.019	0.024		
1200	1.001	3.674	0.272	0.017	0.019	0.023		
1350	1.268	4.136	0.307	0.016	0.019	0.022		
1500	1.564	4.594	0.341	0.016	0.018	0.022	0.025	
1650	1.892	5.052	0.375	0.016	0.018	0.021	0.024	
1800	2.251	5.510	0.408	0.016	0.018	0.021	0.024	
2100	3.143	6.511	0.483	0.016	0.018	0.020	0.023	0.025

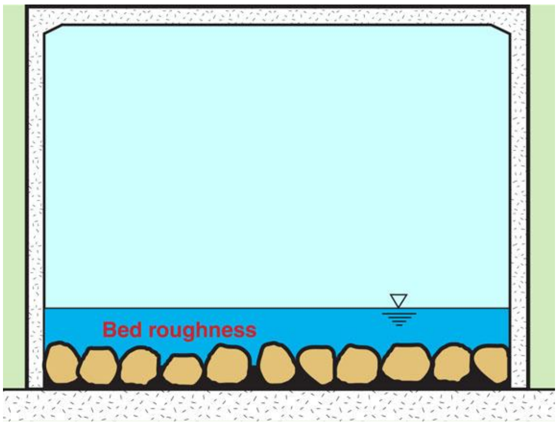
Rock placement in box culverts



Smooth-bed wet cell with low-flow channel

Smooth-bed wet cell with low-flow channel

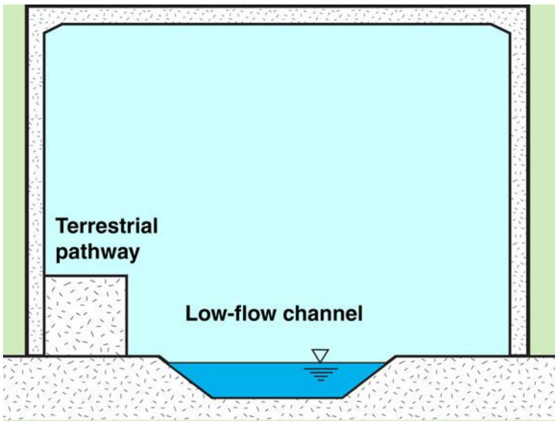
- A 'clean' floor is less likely to block with debris or sediment.
- A smooth floor creates a very thin boundary layer, which provides little benefit to fish passage.
- Bed roughness can (and should) be added to the low-flow channel.



Wet cell with rock roughness

Wet cell with rock roughness

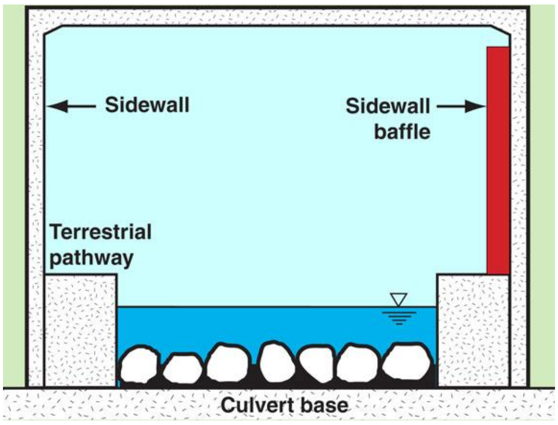
- Bed roughness can be highly beneficial to fish passage.
- Bed roughness allows the development of a thick boundary layer adjacent to the rocks.
- **Caution:** Wet cells with bed roughness can be difficult to maintain after flood events.



Wet cell with terrestrial pathway

Wet cell with terrestrial pathway

- Benching allows both fish and terrestrial passage within a single cell culvert.
- The wet cell may include a low-flow channel, or introduced bed roughness as necessary for the site conditions.
- **Caution:** A single bench does not allow terrestrial passage along both sides of the watercourse.



Wet cell with twin terrestrial pathways

Wet cell with twin terrestrial pathways

- In single cell culverts, sidewall baffles may only be required on one side of the culvert.
- Twin terrestrial passage benching allows terrestrial passage along both sides of the watercourse.

Table 13.5 – Manning's roughness for rock-lined surfaces in shallow water

d_{50}/d_{90}	d_{50}/d_{90} = 0.2					d_{50}/d_{90} = 0.3				
d_{50} (mm)	50	100	200	300	400	50	100	200	300	400
R (mm)	Channel bed Manning's roughness (n)					Channel bed Manning's roughness (n)				
200	0.12	0.21	0.38	0.53	0.67	0.07	0.12	0.21	0.29	0.37
300	0.10	0.17	0.30	0.40	0.51	0.06	0.10	0.16	0.22	0.28
400	0.08	0.14	0.24	0.33	0.42	0.05	0.08	0.14	0.19	0.23
500	0.07	0.12	0.21	0.29	0.37	0.05	0.07	0.12	0.16	0.20
600	0.07	0.11	0.19	0.26	0.32	0.04	0.07	0.11	0.15	0.18
700	0.06	0.10	0.17	0.23	0.29	0.04	0.06	0.10	0.13	0.17
800	0.06	0.09	0.16	0.21	0.27	0.04	0.06	0.09	0.12	0.15
900	0.06	0.09	0.15	0.20	0.25	0.04	0.06	0.09	0.11	0.14
1000	0.05	0.08	0.14	0.19	0.23	0.04	0.05	0.08	0.11	0.13
1200	0.05	0.08	0.12	0.17	0.21	0.03	0.05	0.07	0.10	0.12
1400	0.05	0.07	0.11	0.15	0.19	0.03	0.05	0.07	0.09	0.11
1600	0.04	0.07	0.10	0.14	0.18	0.03	0.04	0.06	0.08	0.10
1800	0.04	0.06	0.10	0.13	0.16	0.03	0.04	0.06	0.08	0.10
2000	0.04	0.06	0.09	0.12	0.15	0.03	0.04	0.06	0.08	0.09

Table 13.6 – Manning's roughness for rock-lined surfaces in shallow water

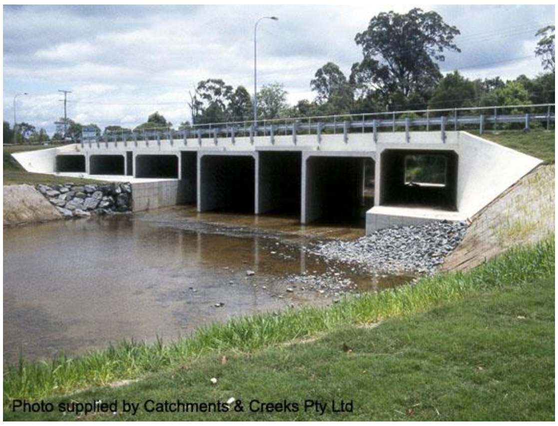
d_{50}/d_{90}	d_{50}/d_{90} = 0.5					d_{50}/d_{90} = 0.8				
d_{50} (mm)	50	100	200	300	400	50	100	200	300	400
R (mm)	Channel bed Manning's roughness (n)					Channel bed Manning's roughness (n)				
200	0.04	0.06	0.10	0.14	0.17	0.03	0.04	0.06	0.08	0.09
300	0.04	0.05	0.08	0.11	0.14	0.03	0.03	0.05	0.06	0.08
400	0.03	0.05	0.07	0.09	0.12	0.03	0.03	0.04	0.05	0.07
500	0.03	0.04	0.06	0.08	0.10	0.03	0.03	0.04	0.05	0.06
600	0.03	0.04	0.06	0.08	0.09	0.03	0.03	0.04	0.05	0.05
700	0.03	0.04	0.05	0.07	0.09	0.03	0.03	0.04	0.04	0.05
800	0.03	0.04	0.05	0.07	0.08	0.03	0.03	0.04	0.04	0.05
900	0.03	0.04	0.05	0.06	0.08	0.03	0.03	0.04	0.04	0.05
1000	0.03	0.03	0.05	0.06	0.07	0.03	0.03	0.03	0.04	0.05
1200	0.03	0.03	0.04	0.06	0.07	0.03	0.03	0.03	0.04	0.04
1400	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
1600	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
1800	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
2000	0.03	0.03	0.04	0.05	0.05	0.03	0.03	0.03	0.04	0.04

Step 14 - Design of Nominated Dry Cells

Dry cells set just above base flow level

The elevation of 'dry' cells

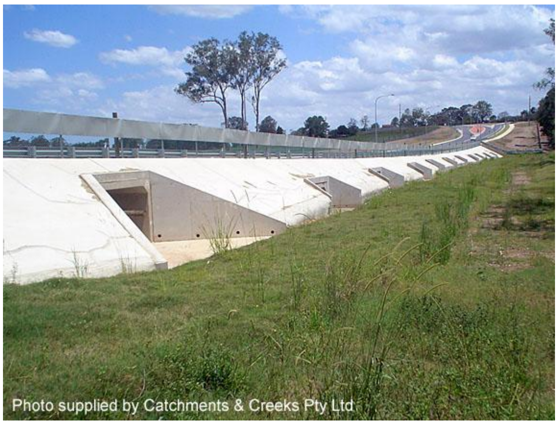
- The nominated dry cells can sit at various elevations, including:
  - elevated just above the base flow level, or dry-weather water level
  - set at mid-bank elevation
  - placed at floodplain level with an elevated (flood free road) built over top.
- Low-level dry cells provide the benefit of carrying more flow during flood events.



Multi-cell culvert with future bikeway (right)

Floor elevation near half bank height

- In the example shown here (left), a pedestrian tunnel (cell of far-right) was built into the culvert as part of a future pedestrian and bikeway tunnel.
- Flood events do not care if the cells are designated wet, dry, or pedestrian, all the cells can carry floodwater.



Dry cells elevated to floodplain level

Elevated roadways

- Floodplain culverts are obvious terrestrial underpass culverts, but what is not so obvious is the importance of floodplain culverts to fish passage.
- During flood events, fish, especially larger fish, often swim within the floodplains rather than along the channel.
- Floodplain culverts may require sidewall roughness for fish passage.
- Bed roughness (baffles) in floodplain culverts may be subjected to excessive sediment blockage.

Floodplain culverts (dry cells)

Floodplain culvert (bridge on far right)

Introduction

- Floodplain culverts can appear adjacent to a waterway culvert, or a bridge crossing.
- Floodplain culverts are almost always associated with elevated (embankment roads and railways.

Floodplain culvert adjacent a bridge (Qld)

Wide spacing between culvert cells

- The wider the spacing between individual culvert cells, the lower the risk of flood debris wrapping around a central 'leg'.
- Therefore, the wider the spacing between individual culvert cells, the lower the risk of debris blockage.
- The site shown here (left) displays a wide spacing of every other cell.

Floodplain culvert (NSW)

Incorporation of a low-flow channel

- The incorporation of a low-flow channel can help to keep the floor of the 'dry' cell dry.
- Many native animals prefer to only pass through a floodplain culvert if the floor is dry.

Floodplain culvert (Qld)

Terrestrial passage features

- Floodplain culverts are obvious terrestrial underpass culverts.
- However, during flood events, fish often swim across floodplains rather than along high-velocity waterways.
- Floodplain culverts may also require sidewall roughness in order to provide ideal fish passage conditions (seek local Fisheries advice).

Positioning of baffles in dry cells

[1] Cell adjacent to the waterway bank

- If fish passage is likely during flood events, then sidewall baffles should be located adjacent to both channel banks.
- These baffles would likely extend to the roof (obvert) of the culvert cell.

[2] Nominated 'dry' cells (but not above)

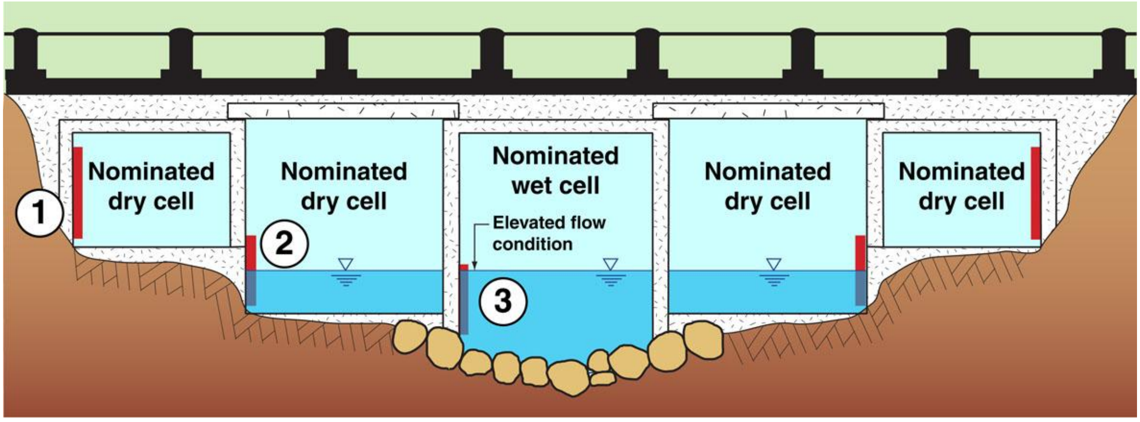
- If fish passage is likely during elevated flows (non-flood events), then sidewall baffles may need to be located within internal 'dry' cells if there is an elevation difference compared to the 'wet' cells (as shown in the example below).

[3] Nominated 'wet' cells

- If fish passage is likely on a day-to-day basis, then sidewall baffles should be located on one side of the 'wet' cell.

Exceptions for low velocity cases

- An exception exists to all of the above; if the average flow velocity through the culvert is less than 0.3 m/s during any of these flow conditions, then sidewall baffles are unlikely to be required for that flow condition.

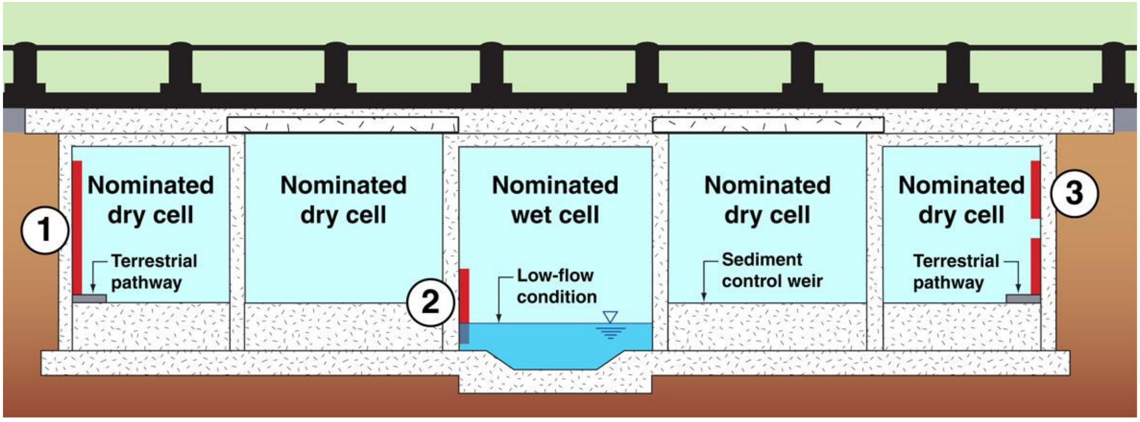


Multi-cell culvert

Culvert with sediment control weirs (Qld)

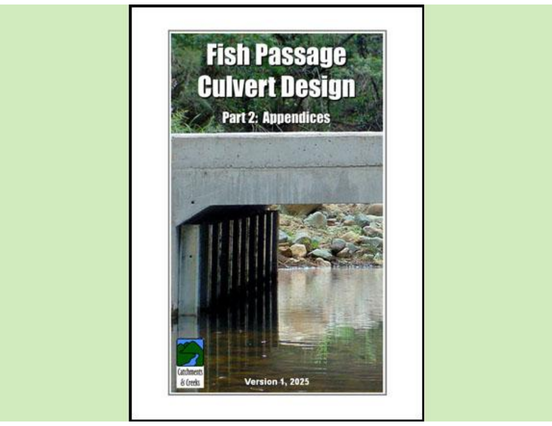
Multi-cell culvert with sediment control weirs

1. If fish passage is likely during flood events, then sidewall baffles should be located adjacent to both channel banks.
2. If fish passage is likely on a day-to-day basis, then sidewall baffles should be located on one side of the 'wet' cell.
3. Alternatively, short-length sidewall baffles or sidewall roughness units (spoiler baffles) can be used.

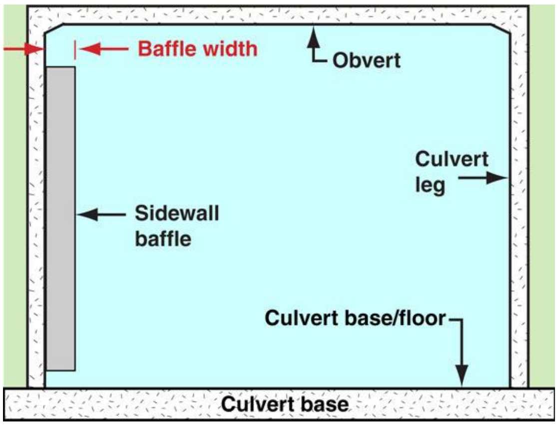


Multi-cell culvert with sediment control weirs

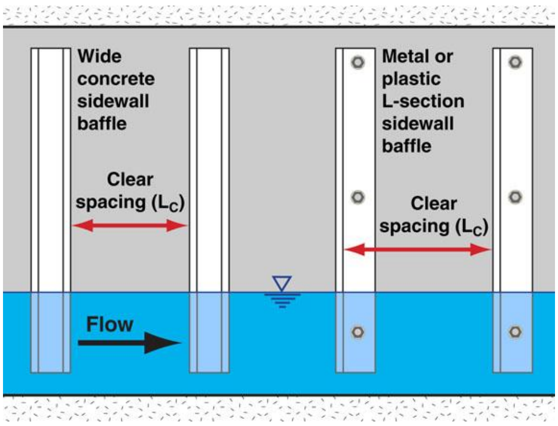
Step 15 - Design of Sidewall Baffles



Fish Passage Culvert Design Part 2



Baffle depth



Baffle clear spacing

Introduction

- Designers should not think of baffles and bed roughness as a means of controlling flow velocities.
- Sidewall baffles are used as a means of simulating natural bank roughness, and the benefits this roughness provides to boundary layer development, and consequently, fish passage.
- An expanded discussion of baffles is provided in appendices E & F in Part 2 of this document.

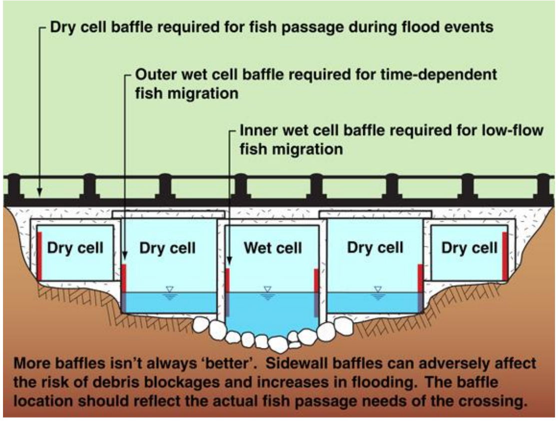
Baffle width

- The width of a sidewall baffle (i.e. its protrusion from the sidewall) should be at least equivalent to the maximum 'body thickness' of the target species.
- Typical depth (k) is 100 to 200 mm.

Baffle clear spacing (L_C)

- The spacing of sidewall baffles should be:
  - Six (6) times the baffle width for baffle widths less than 100 mm
  - Five (5) times the baffle width for baffle widths less than 200 mm
  - Five (5) times the baffle width for baffle widths greater than, or equal to 200 mm, and flow velocity less than 2 m/s.
  - Four (4) times the baffle width for baffle widths greater than, or equal to 200.
  - Four (4) times the baffle width on the culvert wingwalls.

Design issues relating to the needs of the fish



Cross-section of multi-cell culvert

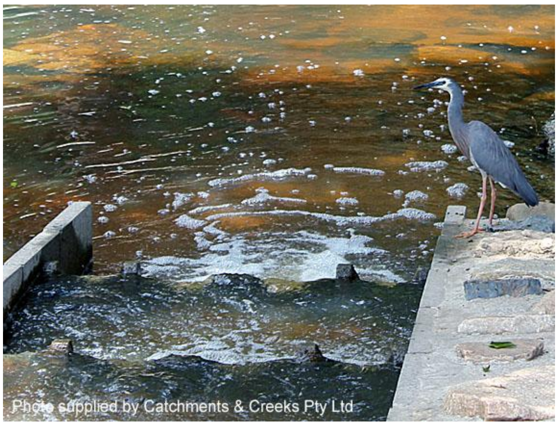
Baffle location in multi-cell culverts

- In multi-cell culverts, it is likely that baffles will only be required along the sidewalls located immediately adjacent to the waterway banks.
- Variations in this requirement may occur if fish passage is expected at water levels that do not adequately 'wet' the outer cells of the culvert.
- For example, if fish migrate at a set time of year, independent of the flow rate, then baffles may be required in the 'wet' cells.

Baffles placed on a culvert wingwall (Qld)

Baffles placed on wingwalls

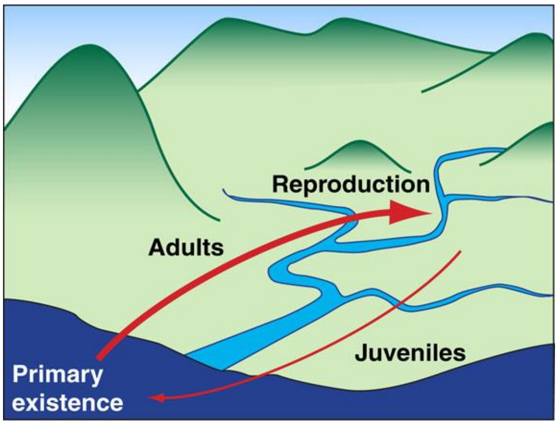
- Special consideration must be given to the placement of baffles on wingwalls, both upstream and downstream of the culvert.
- The author cautions the placement of baffles only on those wingwalls that form a region of flow contraction, whether upstream or downstream of the culvert.
- The suggested baffle spacing is four (4) times the baffle width on the wingwalls.



Lunching at a culvert fishway (Qld)

Fishways should not become a lunchroom for other wildlife

- Consideration must be given to the risk of fish loss by predatory waterbirds that may take advantage of fish movement along a confined fishway.
- This does not mean that a fishway should not be constructed; but simply that all reasonable and practicable measures should be taken the minimise the unnatural loss of fish stocks (if possible).



Anadromous fish movement

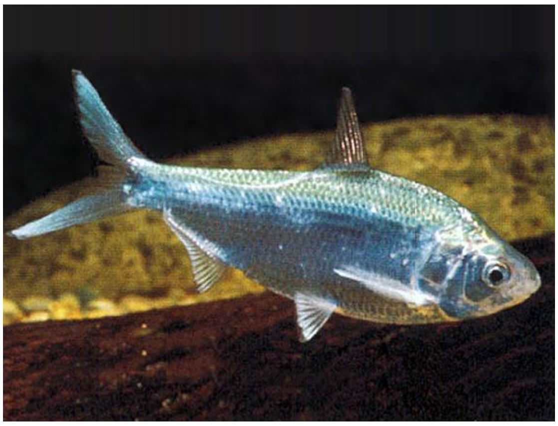
Design issues influenced by the timing of fish passage

- Consideration must be given to the types of baffles required to assist fish passage during:
  - periods of low flow (i.e. daily movement)
  - periods when fish migration is linked to a given time of year (if any)
  - periods when fish migration is triggered by flood events (if any).

Summary of sidewall baffle design (Photos by Gunther Schmida)

Crimson-spotted Rainbowfish

Common Archerfish



Bony Bream

Black Catfish

Grouping fish according to body length

- For the purpose of this document, fish species have been grouped into three body length (BL) categories.
- Small fish have a body length < 150 mm.
- Medium fish body length 150 to 400 mm.
- Large fish body length > 400 mm.
- What is defined as a 'large' fish is relative to the species of fish likely to inhabit the waters crossed by a culvert, not the species found along the full length of the waterway.

Recommended baffle width

- The baffle's protrusion width should be based on the largest of the target species.
- Small fish, at least 50 mm baffle width.
- Medium fish, at least 100 mm baffle width.
- Large fish, at least 200 mm baffle width.
- If larger migrating fish, with a body length greater than 400 mm, are to be expected to pass through a culvert, then the recommended baffle width is 300 mm.

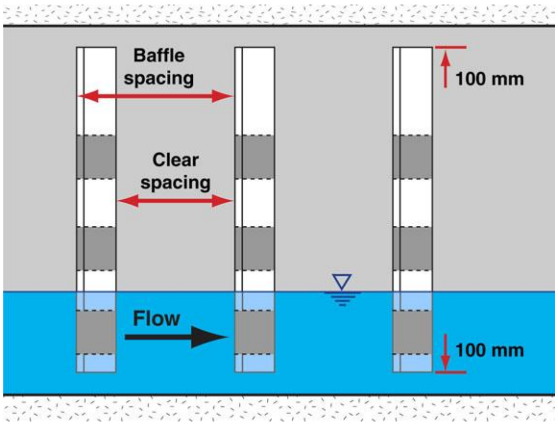
Assumed fish dimension (for the purpose of this numerical analysis)

- Based on an average of 70 species, the typical body length is likely to be 0.67 times the maximum body length of that species (excluding eels).
- Body thickness is assumed to be:
  - small fish body width < 20 mm.
  - medium fish body width < 40 mm.
  - large fish body width < 100 mm.
- The body width is not strictly critical.

Baffle clear spacing (L_C)

- Six (6) times the baffle width for baffle widths less than 100 mm
- Five (5) times the baffle width for baffle widths less than 200 mm
- Five (5) times the baffle width for baffle widths greater than, or equal to 200 mm, and flow velocity is less than 2 m/s.
- Four (4) times the baffle width for baffle widths greater than, or equal to 200 mm, and flow velocity is greater than 2 m/s.
- Four (4) times the baffle width on the culvert wingwalls.

Summary of baffle spacing



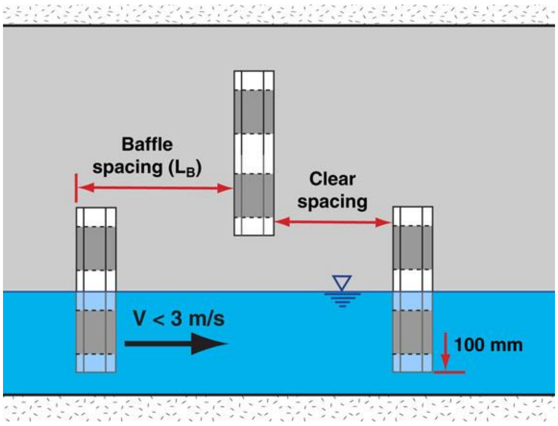
Full-height baffles

Full-height baffles

- Full-height baffles are placed at an even leading-edge to leading-edge spacing of L_B.

Note: The baffle spacing (L_B) is the clear spacing (L_C) plus the baffle depth (D_B).

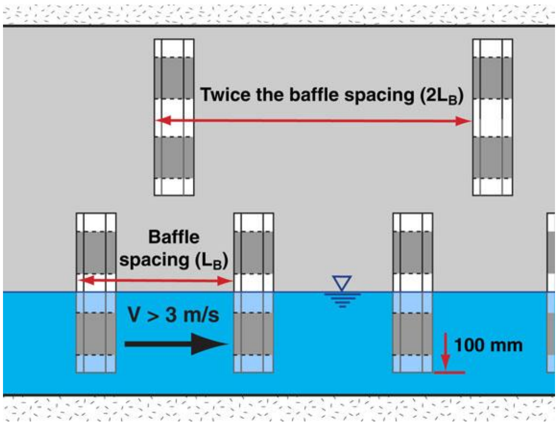
Note: The baffle depth (D_B) is the effective depth (side width) of the baffle measured in the direction of flow, which can be significant for the pre-cast concrete baffles.



Low velocity during low flows

Short-length sidewall baffles

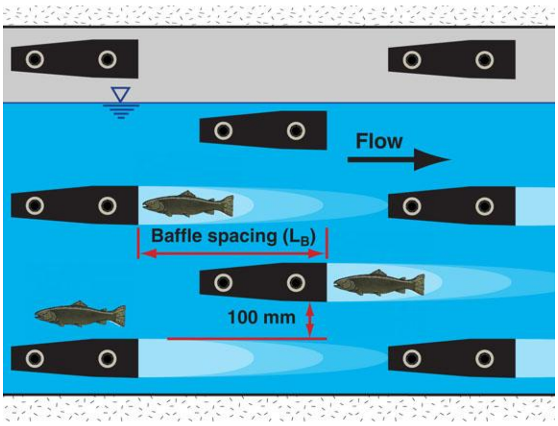
- If the average flow velocity of the culvert cell is less than 3 m/s when the water level is below the top of the lowest row of baffles (i.e. low flow condition), then:
  - the short-length baffles remain staggered in their position
  - two or more rows of baffles can be used
  - the spacing of baffles on any given row is twice the nominated baffle spacing ($2L_B$).



High velocity during low flows

High velocity during low flows

- If the average flow velocity of the culvert cell is greater than 3 m/s when the water level is below the top of the lowest row of baffles, then:
  - two or more rows of baffles can be used
  - the baffle spacing on the lowest row is the nominated baffle spacing (L_B)
  - the baffles on the higher rows is twice the nominated baffle spacing ($2L_B$).

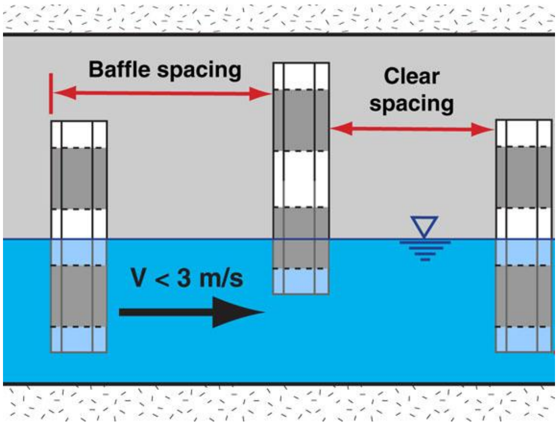


Sidewall roughness units (spoiler baffles)

Sidewall roughness units (spoiler baffles)

- The spacing of isolated roughness units along any given row is twice the nominated baffle spacing ($2L_B$).
- Thus the lateral spacing between two baffles in adjoining rows is the nominated baffle spacing (L_B).
- The clear vertical spacing between two baffles in adjoining rows is suggested to be 100 mm.

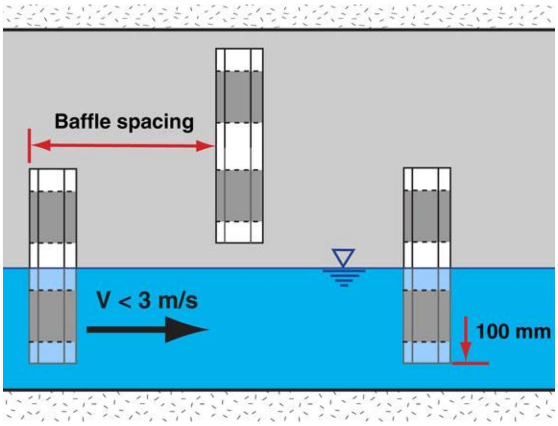
Summary of the vertical positioning of short-length baffles



Low-height culvert

Low-height culverts

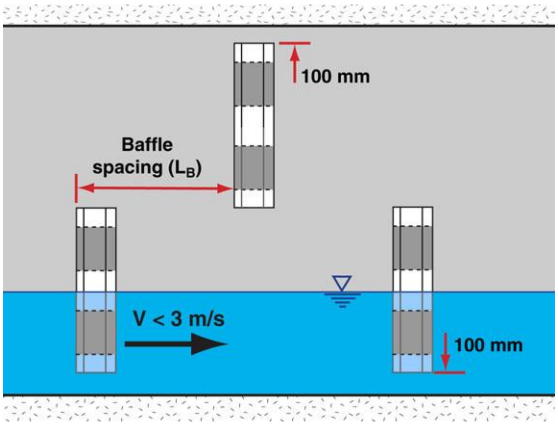
- Baffles staged in height:
  - first; 100 mm above the culvert floor, or the expected permanent sediment elevation, whichever the case may be
  - next; 100 mm below the roof.



Slightly higher culvert

Slightly higher culverts

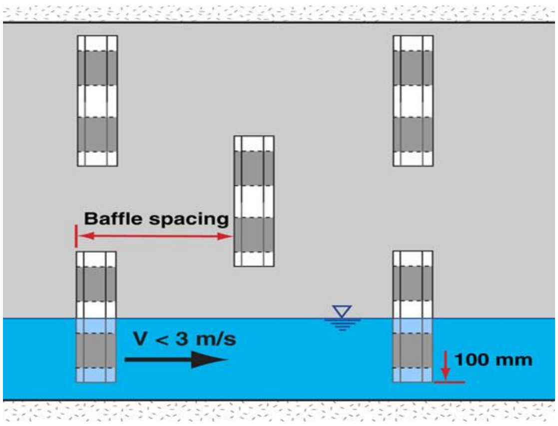
- Baffles staged in height:
  - first; 100 mm above the culvert floor, or the expected permanent sediment elevation, whichever the case may be
  - next; 100 mm below the roof.



A higher culvert

Even higher culverts

- Baffles staged in height:
  - first; 100 mm above the culvert floor, or the expected permanent sediment elevation, whichever the case may be
  - next; 100 mm below the roof.
- The upper row of baffles no higher than 200 mm above the lower row of baffles.



A tall culvert

Tall culverts

- The top row of baffles 100 mm below the roof.
- An upper row of baffles no higher than 200 mm above the immediate lower row of baffles.
- The bottom row of baffles 100 mm above the culvert floor, or the expected permanent sediment elevation, whichever the case may be.

Table 15.1 – Suggested suitability of baffle types in different waterways

Baffle type	Type of waterway				
	Clay based	Sand based	Gravel based	Rock based	Arid & semi-A.
Full-height section baffles	Yes	?	?	Yes	Yes
Short-length sidewall baffles	Yes	Yes	Yes	Yes	Yes
Sidewall roughness units (spoiler baffles)	Yes	Yes	Yes	Yes	Yes
Sidewall roughness panels	?	?	?	?	?
Porous modular units	?	**No**	**No**	?	?
Longitudinal baffles	?	?	?	?	?
Corner baffles	Yes	**No**	**No**	Yes	?
Floor baffles	?	**No**	**No**	Yes	?
Yes = Useful	**No** = Not recommended		‘?’ = Questionable value		

Table 15.2 – Suitability of baffles for various bed load and flood debris conditions

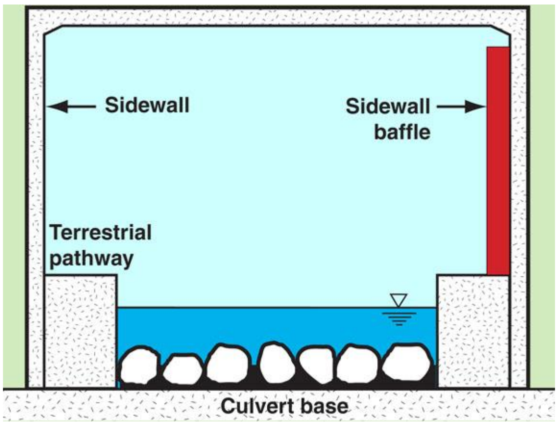
Baffle type	Movement of bed sediments and flood debris				
	Urban waterway	No sediment	Sediment movement	No flood debris	Flood debris
Full-height section baffles	Yes	Yes	?	Yes	?
Short-length sidewall baffles	Yes	Yes	Yes	Yes	Yes
Sidewall roughness units	Yes	Yes	Yes	Yes	Yes
Sidewall roughness panels	?	?	?	?	?
Porous modular units	?	Yes	**No**	Yes	**No**
Longitudinal baffles	?	?	?	?	?
Corner baffles	?	Yes	**No**	Yes	?
Floor baffles	?	Yes	**No**	Yes	?
Yes = Useful	**No** = Not recommended		‘?’ = Questionable value		

Table 15.3 – Suggested location of baffles within multi-cell culverts

Baffle type	Expected timing of fish passage				
	Daily all year	During low flows	Elevated flows	Flood events	Specific time of year
Sidewall baffles	Yes	?	Yes	Yes	Yes
Corner baffles	Yes	Yes	Yes	Yes	Yes
Floor baffles	Yes	Yes	Yes	?	Yes
Adjacent to waterway bank	Yes	?	Yes	Yes	Yes
Internal ‘dry’ cells	?	**No**	?	Yes	Yes
Internal ‘wet’ cells	Yes	Yes	Yes	?	Yes
Low-flow ‘wet’ cell	?	Yes	?	?	?
Yes = Useful	**No** = Not recommended		‘?’ = Questionable value		

The above table also appear in Appendix E in Part 2 of this publication.

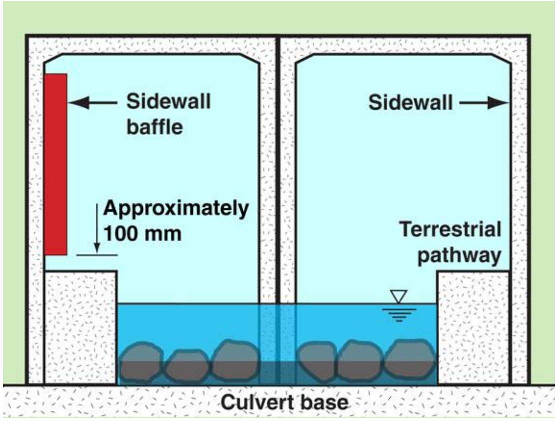
Positioning of baffles within single, twin-cell, and multi-cell culverts



Single cell culvert

Single cell culvert

- If the waterway is so narrow that a single cell culvert can be used to cross the channel, then sidewall baffles are only likely required along one side of the culvert.
- Designers need to confirm this requirement with the local Fisheries office.



Twin-cell culvert

Twin-cell culvert

- If the waterway is so narrow that a twin-cell culvert can be used to cross the channel, then sidewall baffles are only likely to be required along one side of the culvert.
- If a multi-cell culvert is wider than it is deep, then consideration should be given to sidewall baffles placed adjacent to each waterway bank.
- Designers should confirm this requirement with the local Fisheries office.

Multi-cell culverts:

Cell adjacent to the waterway bank [1]

- If fish passage is likely during flood events, then sidewall baffles should be located adjacent to both channel banks.
- These baffles would likely extend to near the roof (obvert) of the culvert cell.

Nominated 'dry' cells (but not above) [2]

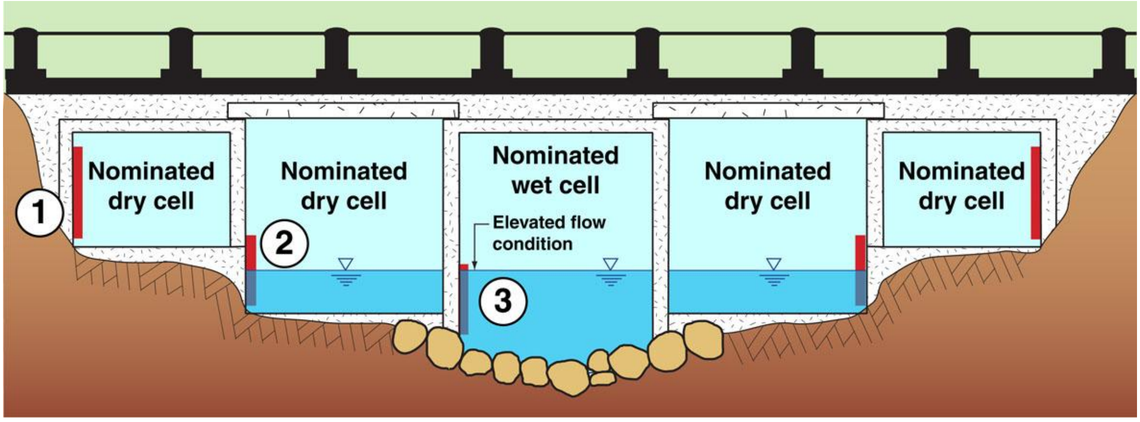
- If fish passage is likely during elevated flows (non-flood events), then sidewall baffles may need to be located within internal 'dry' cells if there is an elevation difference compared to the 'wet' cells (as shown in the example below).

Nominated 'wet' cells [3]

- If fish passage is likely on a day-to-day basis, then sidewall baffles may be required along one side of the nominated 'wet' cell.

Exceptions for low velocity cases

- An exception exists to all of the above; if the average flow velocity through the culvert is less than 0.3 m/s during any of these flow conditions (such as low flows), in which case, sidewall baffles are unlikely to be required for that particular flow condition.

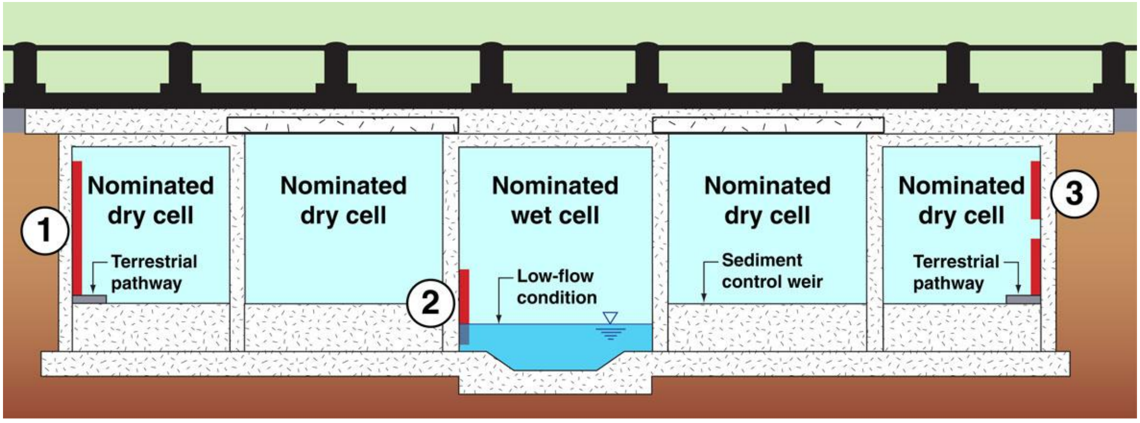


Positioning of baffles in multi-cell culverts

Culvert with sediment control weirs (Qld)

Multi-cell culvert with sediment control weirs

1. If fish passage is likely during flood events, then sidewall baffles should be located adjacent to both channel banks.
2. If fish passage is likely on a day-to-day basis, then sidewall baffles should be located on one side of the nominated 'wet' cell.
3. Alternatively, short-length sidewall baffles, or sidewall roughness units (spoiler baffles), can be used.

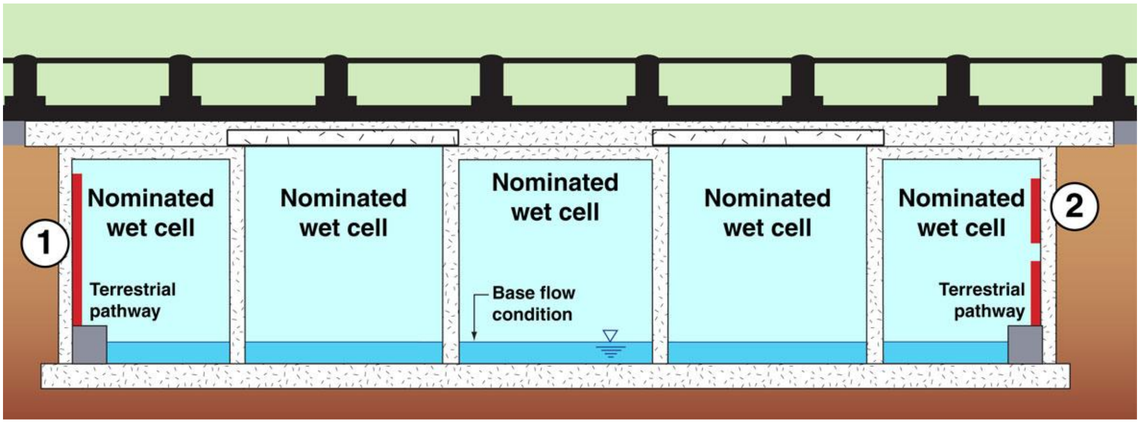


Multi-cell culvert with sediment control weirs

Multi-cell culvert with flat bed (NSW)

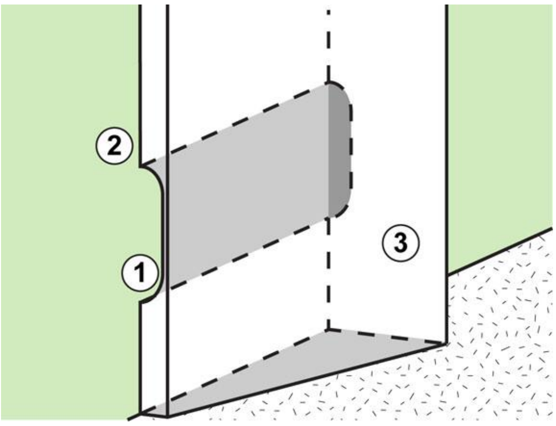
Recessed multi-cell culvert with flat bed

1. Sidewall baffles should be located adjacent to both channel banks.
2. Alternatively, short-length sidewall baffles, or sidewall roughness units (spoiler baffles), can be used.

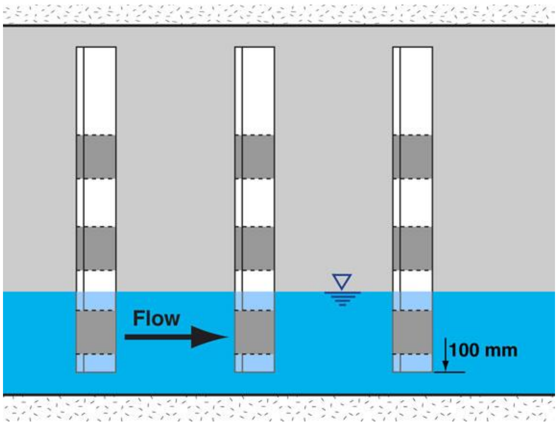


Recessed multi-cell culvert with flat bed

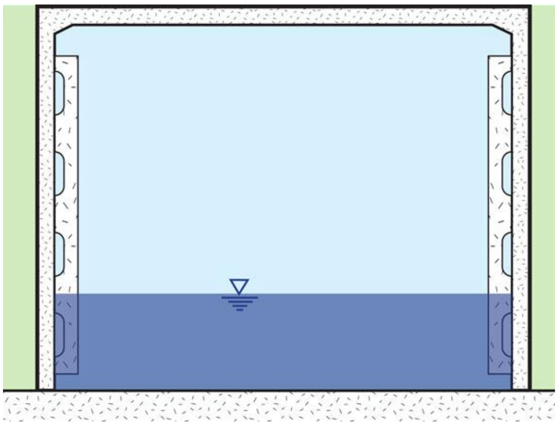
Pre-cast sidewall baffles



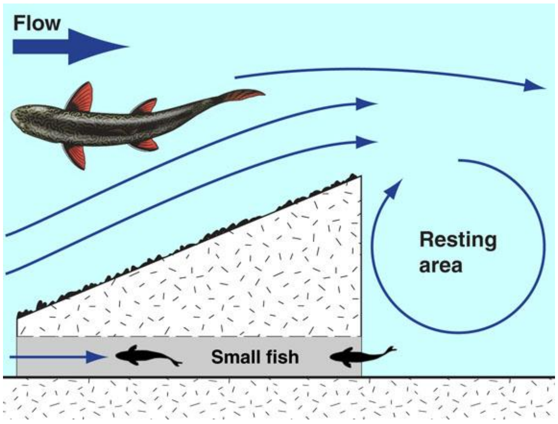
Pre-cast concrete baffle



Side view



Front view



Plan view

Introduction

- The author is unaware of any fish passage trials using such a baffle design.
- The baffle has a wedge shape to reduce the risk of trapping flood debris.

1. Isolated, low turbulence slots aid the passage of small fish.
2. The leading edge has the necessary thickness to make the pre-cast section durable.
3. The downstream baffle width should, at least, match the maximum body thickness of the target species.

Attributes

- A wedge-shaped baffle will produce a thinner overall boundary layer width compared to a square-edged baffle.
- Including narrow flow slots between the baffle and the culvert sidewall could potentially assist small fish to negotiate the baffles without needing to pass around the baffles.

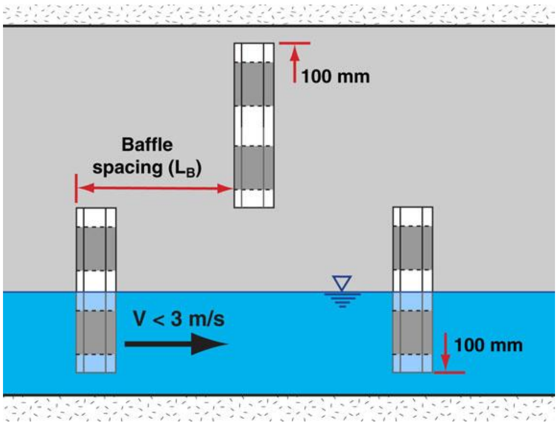
Advantages of pre-cast concrete baffles:

- Durable.
- Could provide fish passage for both small and large fish.
- Non-rusting (except for the possible fittings).

Disadvantages of pre-cast concrete baffles:

- High cost.
- The units will be heavy and difficult to install.
- Difficult to provide a suitable range of baffle lengths to match different culvert heights.

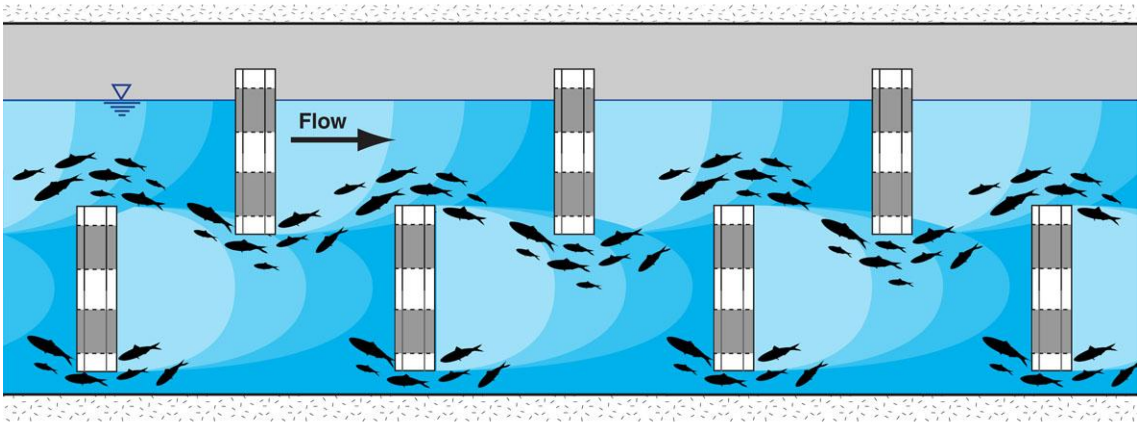
The hydraulic benefits provided by staggered baffles



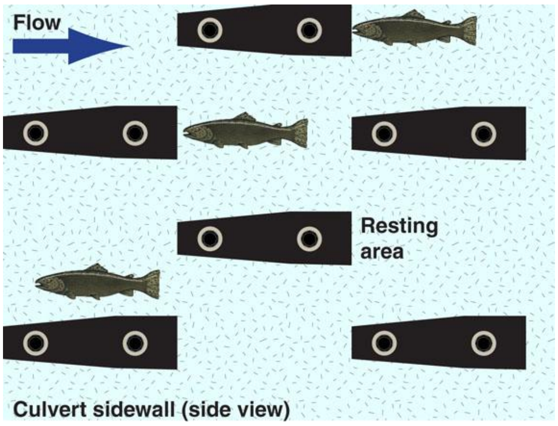
Short-length section baffles

Short-length sidewall baffles

- When fish are required to pass around a full-height baffle, they need to use their burst speed in order to enter a high-velocity region of the culvert.
- If it is accepted that fish have a burst speed of around 10BLPS (body lengths per second), then moving against flow velocities exceeding 3 m/s can be very difficult for small fish.
- Staggered baffles allow fish to swim totally within the boundary layer region that is formed adjacent to the culvert sidewall.



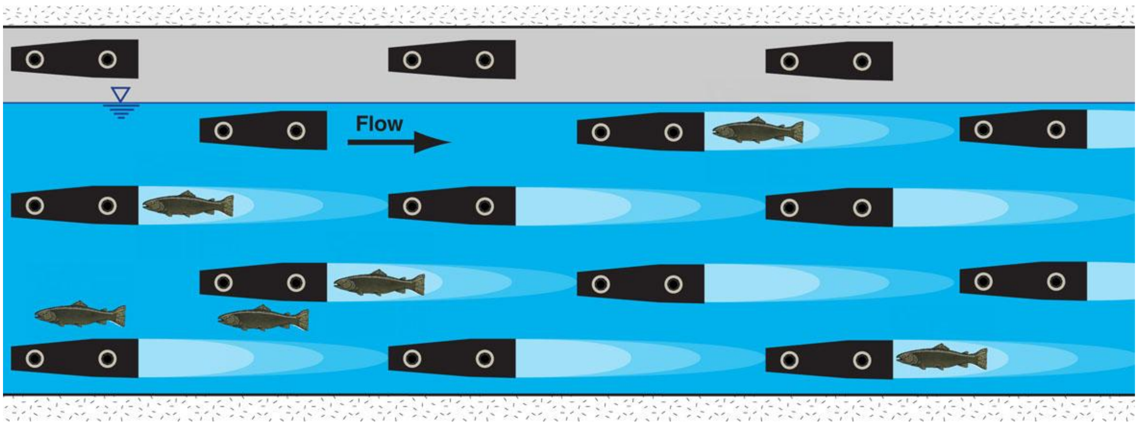
Low-velocity shadow zones



Sidewall roughness units

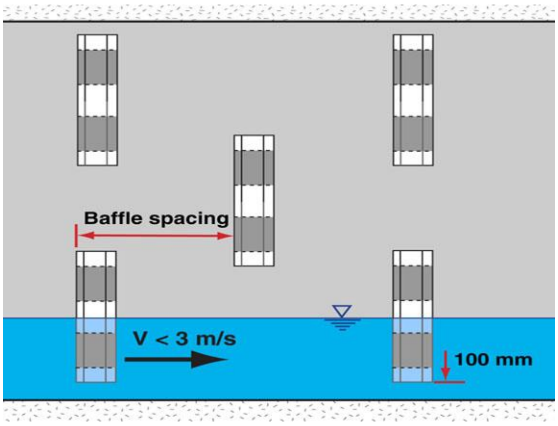
Sidewall roughness units (spoiler baffles)

- Sidewall roughness units not only allow fish to swim totally within the boundary layer region close to the sidewall, they also reduce the risk of capturing flood debris within the culvert.
- The exact location of each baffle is not critical, therefore the heavy steel reinforcing inside the culvert leg should not interfere with the attachment of each baffle.
- Also, the loss/damage of a few baffles will not cause fish passage to stop.



Low-velocity shadow zones

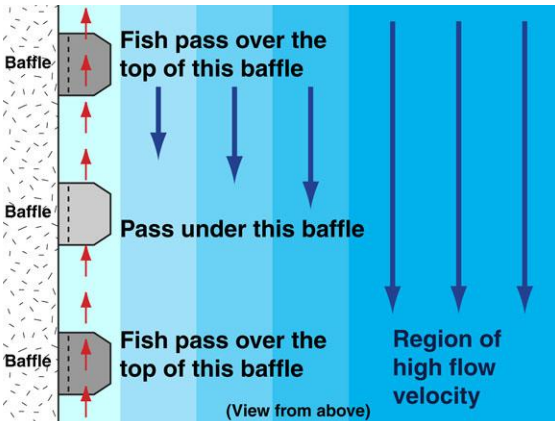
The hydraulic benefits provided by staggered baffles



Staggered short-length baffles (side view)

Alternative positioning of baffles

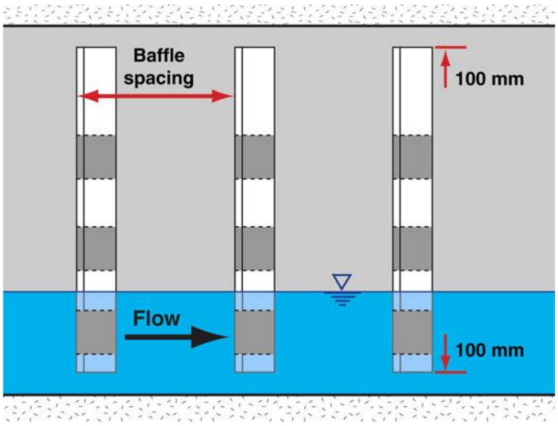
- There can be a wide variety of arrangements of staggered short-length baffles depending on the height of the culvert.



Possible fish passage (top view)

Fish passage between staggered baffles

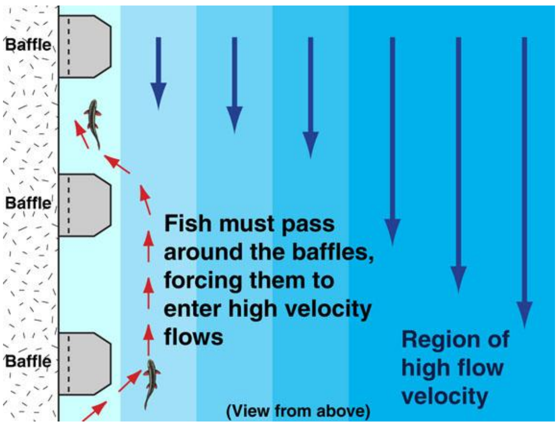
- The benefit of staggered baffles is that fish can stay within the boundary layer (and shadow zones) all the way through the culvert.
- Fish can pass over and under the short-length baffles, rather than swimming around the baffles.



Full-height baffle (side view)

Full-height baffle

- With full-height baffles, the baffles typically extend from near the bed, to near the culvert roof.



Fish passage past full-height baffles (top)

Fish passage past full-height baffles

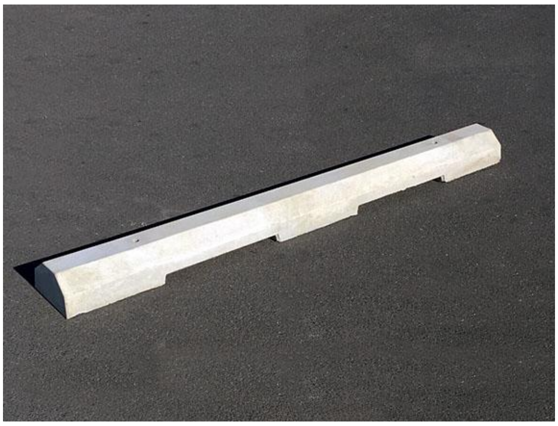
- With full-height baffles, fish are required to move into the higher velocity zone in order to pass around the baffles.
- This means fish are required to use their burst speed, which may be insufficient if the average flow velocity in the culvert exceeds, say 3.5 m/s.

Pre-cast parking stops (lateral thinking)

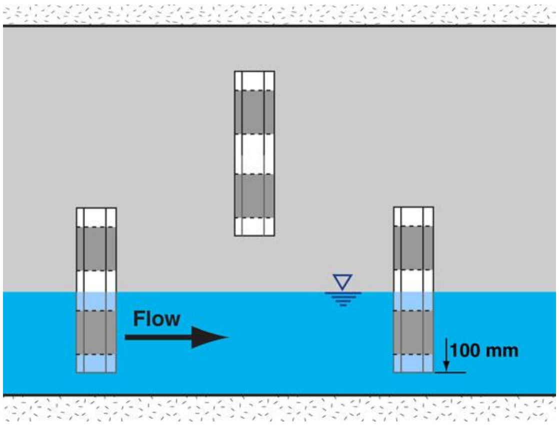
Absolute Concrete

Making use of existing pre-cast concrete units

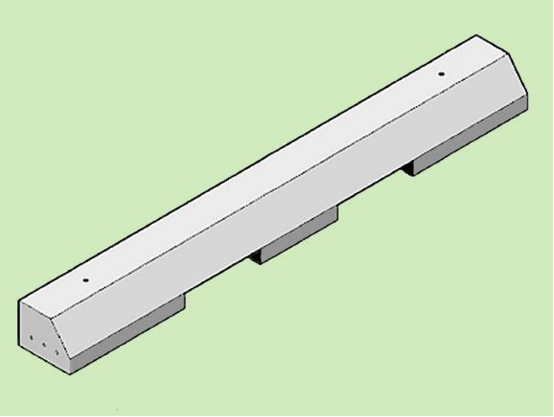
- Numerous existing pre-cast concrete traffic control units can do the equivalent job of sidewall baffles.



Bundaberg Concrete Casting



Typical placement along a sidewall



Cromwell Concrete

Enforcer Group Concrete Wheel Stop

Turner Vault Concrete Parking Stop

Wilbert Precast Inc.

Step 16 - Assess the need for improved lighting conditions (wet cells)

The big question: Is it needed?

Skylight installed into the grass verge

Skylights installed in a raised median (Qld)

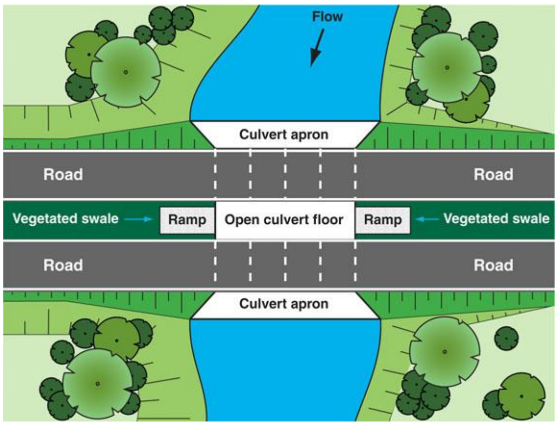
Introduction

- Again the author wishes to remind readers that he is a retired civil engineer that has specialised in fluid mechanics, not fish biology.
- The author's knowledge of the 'lighting' requirements of fishways is very limited.

My recommendations

- Given the above, the author's recommendations are:
  - if the road is more than two lanes wide, then consideration should be given to the inclusion of a skylight into at least one of the wet cells
  - if the road has a painted median, then consideration should be given to the possible inclusion of a stormwater inlet within the painted median (noting the importance of a high-grip treated surface of any inlet screen for bike safety reasons)—AustRoads should address this issue
  - if the roadway includes a raised median, then a skylight should be installed into the median above one or more of the wet cells
  - for divided roads, refer to discussion and examples over the page.

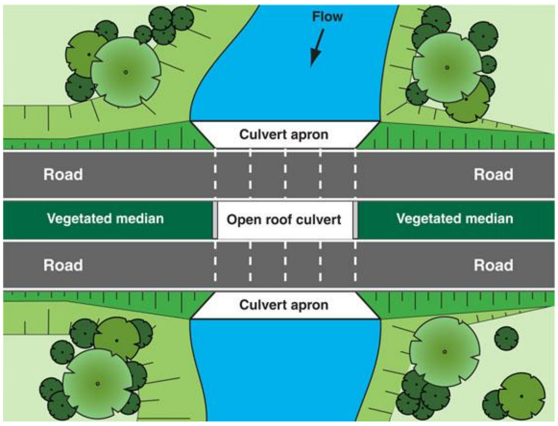
Dual carriageway roads



Trapezoidal channel formed in median

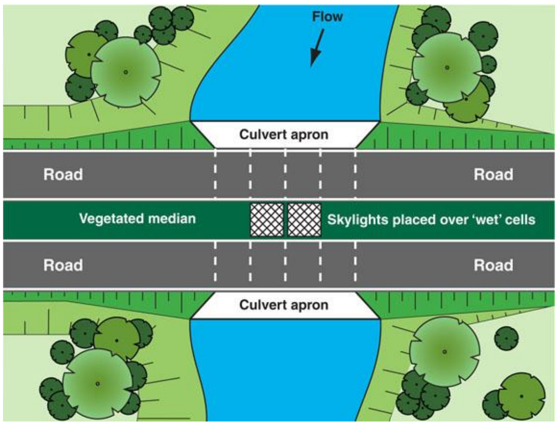
Dual carriageway roads

- In general, the wider the road, the longer the culvert; however, dual carriageways provide us with the opportunity to introduce 'resting' areas for fish.
- These resting areas can also help to improve lighting conditions within the culvert.
- The difficulty for designers is to achieve these outcomes without introducing excessive energy loss within the culvert, which would reduce the culvert's flow capacity.



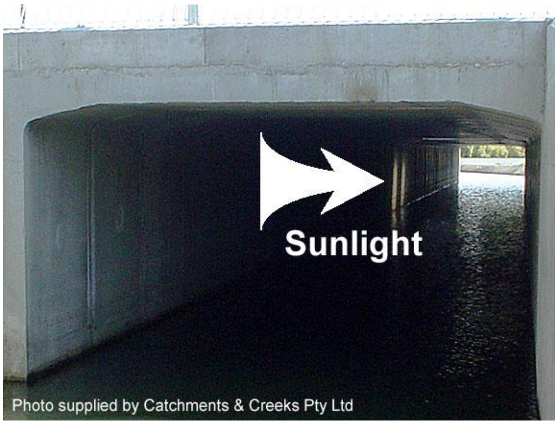
Open roof section within a long culvert

Open roof section within a long culvert



Skylights placed within the median

Skylights placed within the median (Qld)

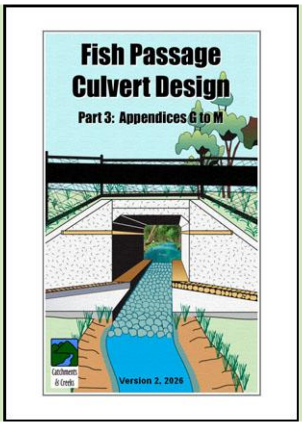


Light entering the culvert (Qld)

Skylights placed within the median (Qld)

Step 17: Assess the terrestrial passage requirements

Step 17 - Assess the terrestrial passage requirements



Fish Passage Culvert Design, Part 3

Queensland Transport, 2024

Elevated (dry) terrestrial pathway

Detailed discussion

- An expanded discussion on terrestrial passage is provided in Appendix J of Part 3 of this three-part document.

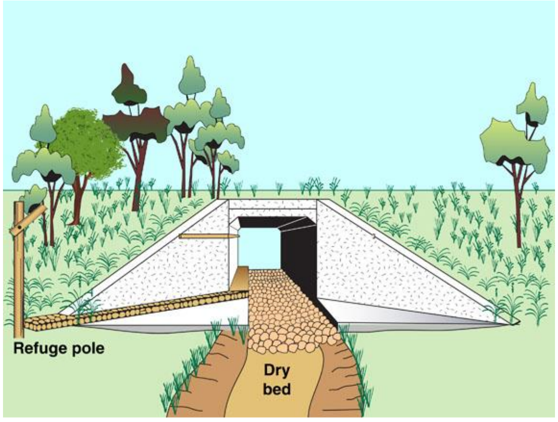
Reference document

Fauna Sensitive Transport Infrastructure Delivery – Chapter 6: Mitigation, The State of Queensland (Department of Transport and Main Roads) 2024.

Introduction

- The policies and focus of any fisheries office, or any fish passage guideline, cannot be limited to just the consideration of aquatic life.
- All agencies, and all designers, have a duty of care to consider the wider impact of their policies and designs on the greater environment, which includes terrestrial wildlife (terrestrial passage).
- Potential conflicts must be addressed, if not fully prevented.

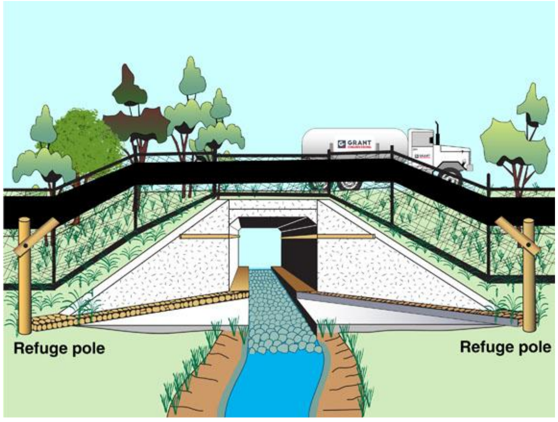
Introduction



Single cell culvert on an ephemeral creek

One side of the waterway channel

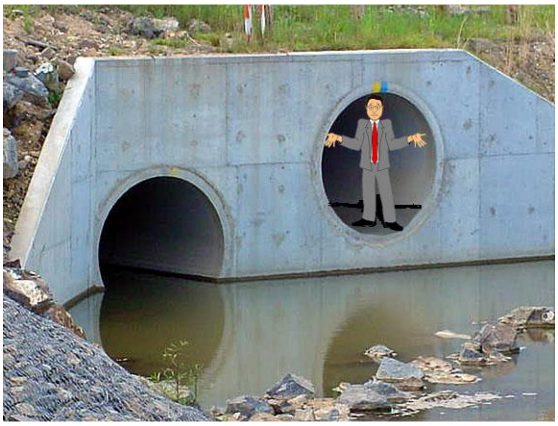
- Terrestrial pathways are generally only required on one side of a culvert if the culvert spans across:
  - an ephemeral waterway (i.e. a channel that is usually dry, in parts, during normal dry weather), or
  - a permanent waterway that has sufficient 'land bridges' (e.g. fallen trees, culverts or footbridges) that allow the target species to cross from bank to bank.



Single cell culvert on a wet creek

Both sides of the waterway channel

- Terrestrial pathways are typically required along both sides of a culvert if the culvert spans across a permanent waterway (i.e. a waterway that is usually flowing during normal dry-weather conditions).



'Wet' and 'dry' cells

Continuity of the 'dry' paths

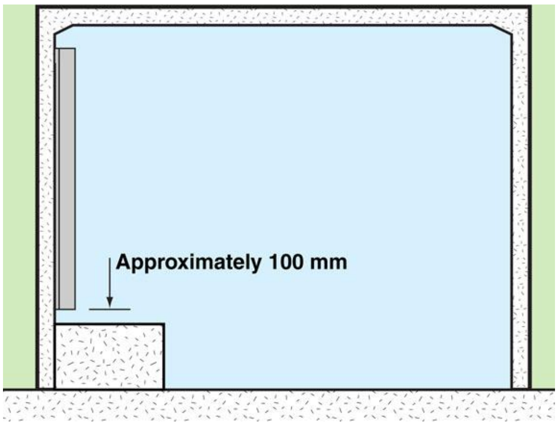
- It is essential for terrestrial pathways to have a continuous 'dry' pathway from bank to bank (through the culvert).
- This means that the dry pathway must extend to dry ground on both sides of the culvert.

Street light with shield (Qld)

Reducing artificial light at night

- Nearby street lighting should have shields attached to minimise light spilling onto sensitive areas.
- Culvert headwalls can be painted to reduce the impact of reflected light.

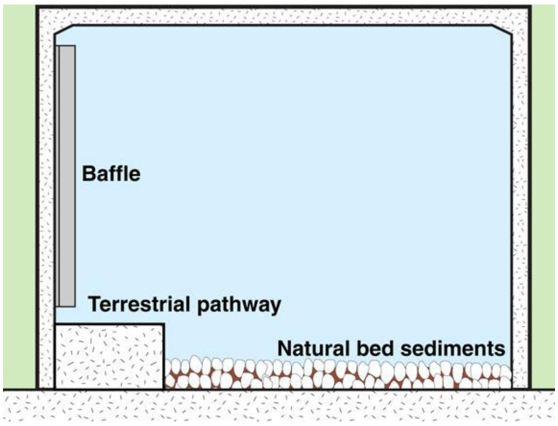
Integration of aquatic and terrestrial passage features



Single sidewall baffle

Basic design

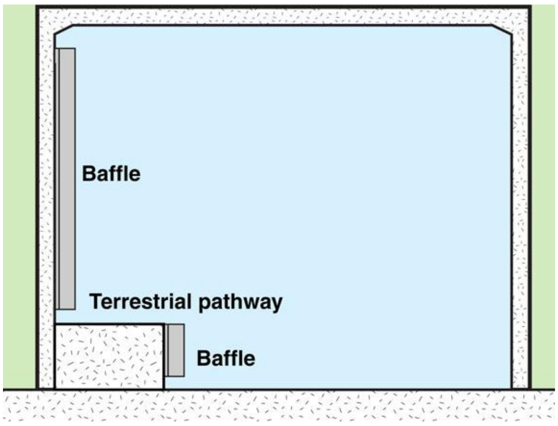
- Terrestrial pathways can be integrated into fish-friendly culverts.
- The dry terrestrial pathway should be set above the dry-weather flow.
- Minimum clear path width of 300 mm.
- Desirable clear path width of 500 mm in culvert cells at least 1800 mm wide.



Natural bed sediment

Inclusion of natural or introduced bed roughness

- The elevation of the dry pathway must take into account the hydraulic effects of:
  - added bed roughness
  - sediment deposition raising the effective bed elevation.



Baffles attached to the terrestrial pathway

Baffles placed on the side of the dry pathway

- If fish passage is expected during periods of zero or low flow, <u>and</u> bed roughness is not included, then consideration should be given to the placement of baffles on the side of the dry fauna pathway.

Baffles attached to the terrestrial pathway

Example

- An example of fish passage baffles attached to the side of the dry terrestrial fauna pathway.

Lizard runs

Access ramps (Qld)

Introduction

- 'Lizard runs', or elevated pathways, aim to provide dry passage for the smaller terrestrial fauna that would normally be preyed upon by larger animals.
- The use of flat planks is generally preferred to that of round poles.
- Access ramps to logs should be no steeper than 1V:5H.

Central elevated pathway (Qld)

Central pathways

- If the target species is koalas, then spacing from the floor, roof and sidewalls becomes important.
- Potential effects of debris blockage must be considered.
- Desirable:
  - minimum 3 m x 3 m cell dimensions
  - 1.5 m above the floor
  - 0.75 m clearance from the ceiling (1 m recommended by VicRoads, 2012)
  - position along centre of the cell.

Evidence of human activity in the culvert

Human use of terrestrial pathways

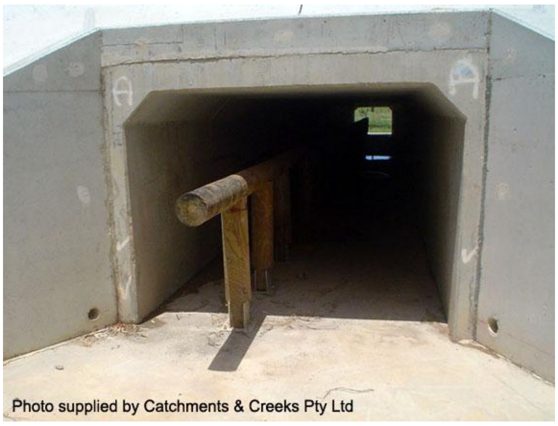
- Children should be discouraged (somehow) from using terrestrial pathways to cross under roads, or as 'hideaways'.

Lack of connectivity

Connection to the creek bank

- It is essential for terrestrial pathways to have a continuous dry pathway from bank to bank (through the culvert).
- Lizard runs must extend along the wingwalls to the creek bank.

Fauna passage furniture



Elevated pathway (Qld)

Introduction

- Fauna furniture can include constructed shelters and the rehabilitation of natural waterway features.
- This furniture can be installed on the culvert floor, its sidewalls, or built into the low-flow channel.
- Most of these features will be placed within the nominated dry cells, but of course, single-cell culverts are required to have both wet and dry features.

Non-use of flowering plants

Landscaping within the road reserve

- Plants in and around a road culvert can create habitat for native fauna, assist fauna movement, and reduce soil erosion.
- Plants placed outside the road reserve can consist of those that attract native fauna, for shelter or feeding.
- However, plants placed inside the road reserve should not attract fauna (native or non-native).
- Placing flowering plants in a road reserve will increase the risk of road kills.

Roosting (Qld)

Artificial shelters and roosts

- Waterway culverts are often used by lizards as habitat—the concrete headwall and wingwalls can act as roosting areas to gather the morning sun.
- Non-biodegradable shelters, including sections of pipe, can be used to mimic a log pile, with numerous options for small fauna to enter and exit.
- Where appropriate, the low-flow channel should include randomly placed boulders, some partially submerged, to act as roosting areas.

Elevated logs (lizard runs, Qld)

Elevated logs

- Elevated horizontal logs or log rails should be approximately 300 mm in diameter (width), set 1500 mm above the ground, and with a minimum 500 mm clearance from the ceiling.
- Access ramps should be no steeper than 1V:5H.
- Flat planks are preferred to round logs.

Traffic calming

Traffic calming on a rural road (Qld)

Introduction

- The risks to wildlife crossing roadways are influenced by a number of factors, including:
  - traffic volume
  - number of trafficable lanes
  - speed of the vehicles
  - distance of drivers' clear vision.
- Traffic calming is the process of managing the speed of traffic on a road to reduce these risks.

Traffic calming on a back road (Qld)

Traffic calming

- Unfortunately it is not practical to reduce vehicle speeds, or 'thin' the traffic on high-speed arterial roads due to the resulting safety risks to the road users.
- On low-speed back roads and urban roads, traffic calming can be used to slow vehicles as they approach a culvert crossing.
- Designers should refer to relevant guidelines in each state and territory, or to AustRoads publications.

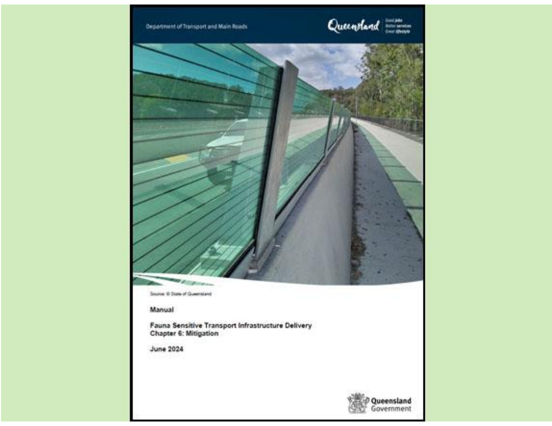
Traffic calming speed bump (Qld)

Warning sign (Qld)

Signage

- Roadside warning signs are intended to modify driver behaviour by warning them of an increased risk of confronting wildlife on a section of roadway.
- Enhanced signs may be larger than standard signs and include flashing lights.

Risk of predation

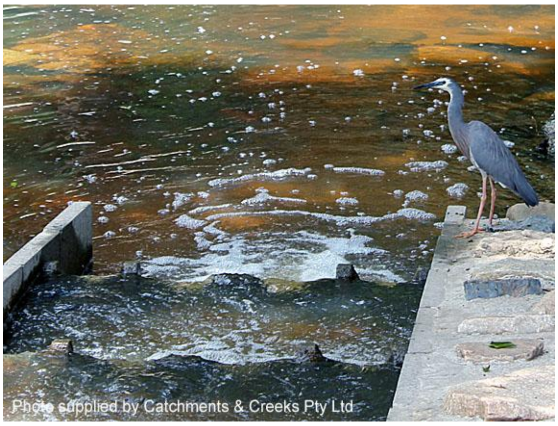


Queensland Transport, 2024

A concern raised by the author!

The Main Roads' document *Fauna Sensitive Transport Infrastructure Delivery – Chapter 6:* makes the following claim:

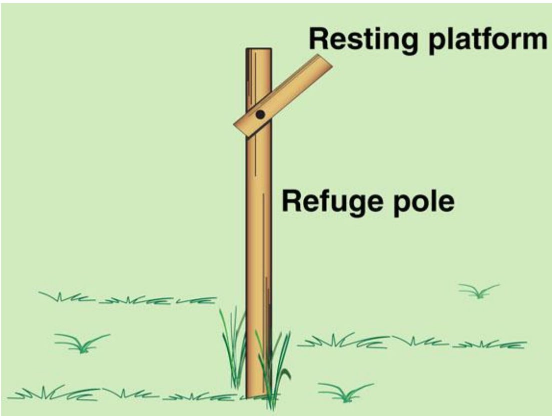
- 'There is a misconception that crossing structures are prey-traps for fauna because predators learn to preferentially hunt at those locations. Despite this assertion, there is no evidence that predators systematically use crossing structures in this way'.
- The author of this field guide questions the above statement!



White-faced heron waiting for dinner

My observations

- Over the past 25 years the author has travelled the country and photographed many fauna tunnels.
- The author has observed:
  - examples of kingfisher birds sitting in trees adjacent to fish barriers
  - fish-hunting birds standing next to fishways
  - many animal carcasses at the entry/exit of culverts.



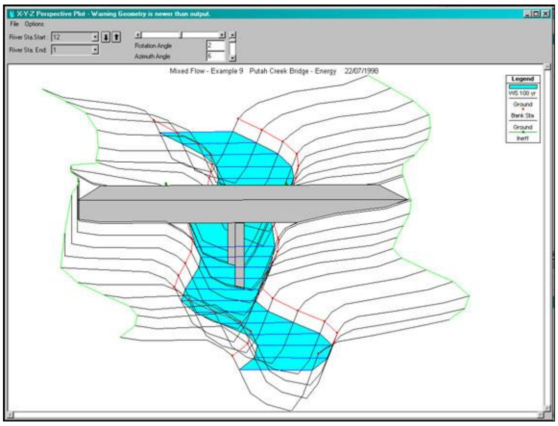
Refuge pole with resting platform

Refuge poles

- Refuge poles should have resting platforms to provide koalas refuge from predators.
- Refuge poles should be approximately 4 m tall and include a V-shaped resting platform at least 2.5 m from the ground.
- The author does not support the placement of refuge poles inside waterway culverts due to the high risk of trapping large woody debris; however, such a concern does not exist for fauna tunnels located outside floodplains.

Two-legged predators collecting at the culvert exit waiting to trap and tag fauna (Qld)

Step 18 - Hydraulic Analysis



HecRas numerical model

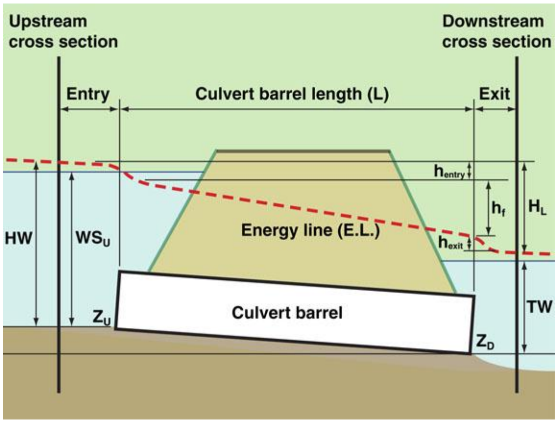
Introduction

- There is no particular stage in the design of a culvert where the hydraulic analysis (computer analysis) should start.
- However, if the analysis is started too early, then your efforts could become a waste of time caused by subsequent changes to the culvert's design.
- If the analysis is started too late, then the culvert design may progress too far before important flood control issues are identified.

Drowned outlet conditions (full culvert)

Traditional design procedures

- In the past, culvert analysis focused on the process of checking for inlet control and outlet control conditions (see over page).
- Fish-friendly culverts are unlikely to experience inlet control conditions, so the focus is now limited to an outlet control analysis.
- It is noted that if the outlet of the culvert is drowned during a flood, then inlet control conditions cannot exist at that flow condition.



Energy loss analysis (long-section)

Quick hydraulic check

- The following quick check can be carried out on culverts flowing full, but not overtopped.
- While the culvert is flowing full, but **not** overtopping, the following energy losses can be expected:
  - Entry loss . 0.5 $V^2/2g$
  - Friction loss . 0.2 $V^2/2g$
  - Exit loss . 0.7 to 1.0 $V^2/2g$
- **Total energy loss . 1.5 to 1.7 ($V^2/2g$)**

General hydraulic issues

100% debris blockage (Qld)

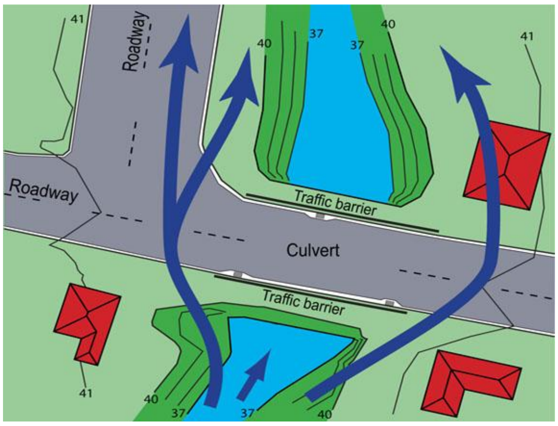
Consideration of debris blockages

- The hydraulic analysis should take appropriate consideration of likely debris blockage.
- The typical debris blockage allowance is 10% to 20% of the culvert flow area depending on the extent of vegetated waterways upstream of the culvert.
- Debris blockage is discussed in more detail in Appendix G in Part 3.

Debris blockage of traffic barrier (Qld)

Assumed hydraulic condition of fencing and traffic barriers during overtopping flows

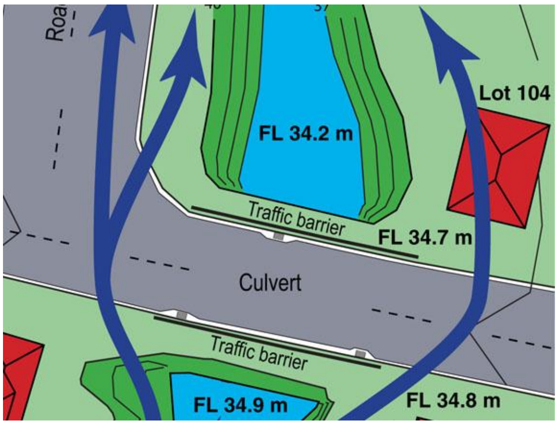
- Consideration should also be given to the likelihood of significant debris blockage of the culvert, roadway fences and crash barriers.



Travel path of bypass flows

Consideration of likely flow path of overtopping flows

- The flow path of overtopping and/or bypass flows must be considered.
- If the fencing or traffic barrier becomes fully blocked with flood debris, then can the overtopping flow bypass around the ends of the blockages?
- If flows pass around the traffic barriers, will these flows become blocked by, or cause damage to, private property fencing?



Floodwater passing around a home

Setting minimum floor levels upstream and downstream of a culvert

- If flood flows are likely to overtop a waterway culvert, then it may be this flood condition that should determine the minimum habitable floor level of homes that surround the culvert.
- In the above example, the minimum floor level for Lot 104 should be based on the actual flood level of 34.7 m, instead of the adjacent creek flood level of 34.2 m.

Inlet control conditions (Such flow conditions are not fish friendly)

Inlet control (looking downstream, Qld)

Inlet conditions on an 'inlet control' culvert

- Inlet control conditions exist when the culvert is undersized, and a hydraulic choke is triggered at the culvert's inlet.
- This flow condition usually means:
  - flow velocities are too high at the inlet to allow fish passage
  - turbulence inside the culvert is too high to allow fish passage.

Inlet control (looking upstream, Qld)

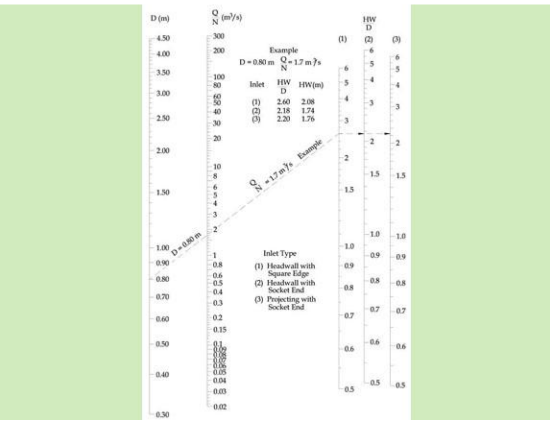
Outflow conditions on an 'inlet control' culvert

- Except in rare circumstances, inlet control can only occur when the outlet of the culvert is not drowned (i.e. the roof of the culvert cell is visible).
- Typically the downstream water level is low, the exit velocities are high, and the culvert is flowing partially full.

Inlet control (drowned inlet with vortices)

Description of photos

- All three of these images (left and above) were taken at the same location, which was a culvert on a private driveway.
- The top image shows the upstream water level almost at the elevation of the road.
- The middle image shows the high velocity jetting at the culvert outlet.
- The bottom image (left) shows eddies above each of the culvert cell inlets.



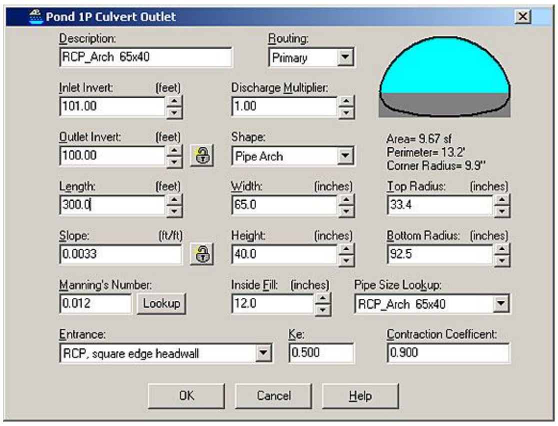
Inlet control flow chart

Outlet control conditions

- The hydraulic analysis of inlet control conditions is usually performed:
  - using a design chart (left) if performed manually, or
  - within the programming of a numerical model.
- An 'old' design rule involved checking the flow capacity for both inlet control and outlet control conditions, and to then adopting the lower of the two values—this rule should no longer be followed.

Outlet control conditions (Can be fish friendly)

Outlet control condition (Qld)



Commercial software

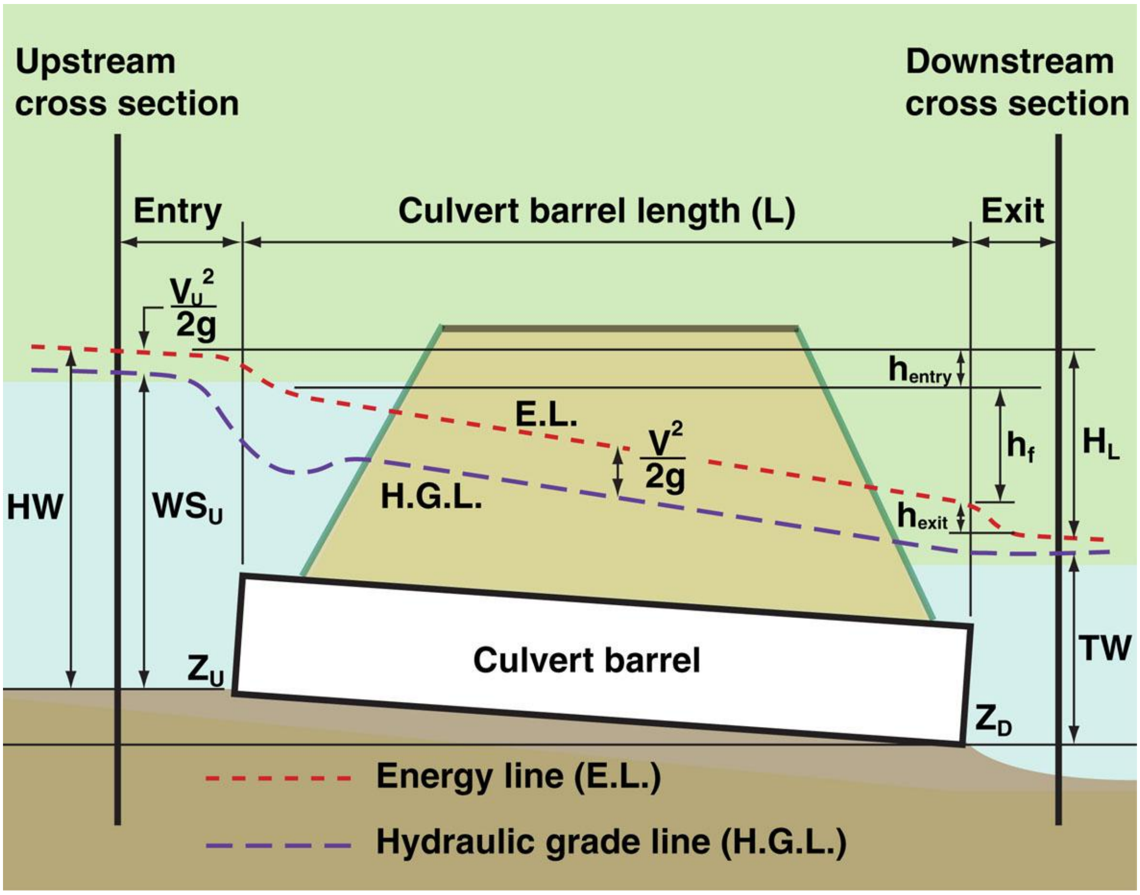
Introduction

- Outlet control conditions exist when subcritical partial-full flow, or full flow conditions exist throughout the culvert.
- Such flow conditions usually means:
  - water levels through the culvert are controlled (in-part) by tailwater conditions
  - if flow velocities are low enough for fish to enter the culvert, then they should be able to pass through the culvert provided suitable surface roughness exists through the culvert.

Hydraulic analysis

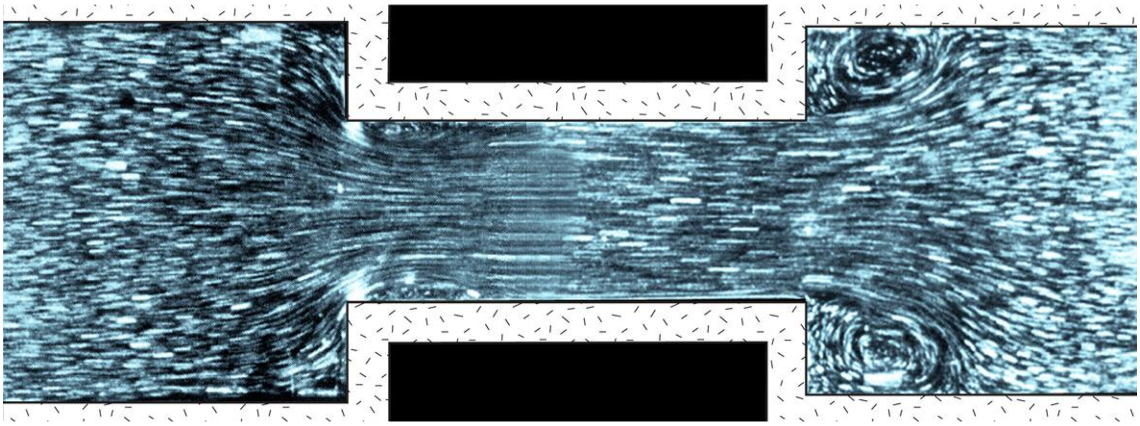
- The hydraulic analysis of outlet controlled culverts is usually conducted within commercial software packages.
- Hand calculations (not addressed here) involve an assessment of:
  - outlet loss (flow expansion loss)
  - friction loss within the culvert
  - inlet loss (based on the geometry).

(Designers should be able to calculate along the E.L., then back along the H.G.L. and return to the starting value.)



Energy line (EL) and hydraulic grade line (HGL) for outlet control conditions

Components of energy loss



Flows into, and out-of, a short-barrel culvert (equivalent to a 'long orifice')

Entrance Loss Coefficient

Entrance losses are computed as a function of the **velocity head** inside the culvert at the upstream end. The entrance loss for the culvert is computed as:

$$h_{en} = k_{en}\frac{V_{en}^2}{2g}$$

Where: h_{en} = Energy loss due to the entrance

k_{en} = Entrance loss coefficient

V_{en} = Flow velocity inside the culvert at the entrance

g = Acceleration due to gravity

HecRas analysis

Entrance loss (inlet loss)

- In theory, the entrance loss coefficient should be applied to the 'change in velocity head', similar to the exit loss.

$$H_{en} = k_{en}.(V_{en}^2/2g - V_{us}^2/2g) \qquad (18.1)$$

- However, for many culverts. the upstream velocity (V_{us}) is much slower than the culvert velocity, so it can be ignored.

$$h_f = L\left(\frac{Qn}{AR^{2/3}}\right)^2$$

Where: h_f = friction loss

L = culvert length

Q = flow rate in the culvert

n = Manning's roughness coefficient

A = area of flow

R = hydraulic radius

HecRas analysis (metric)

Friction loss

- In a fish-friendly culvert, the analysis of the friction loss can be a complex process.
- Designated 'wet' cells can have a surface roughness different from designated 'dry' cells.
- Also, the bed roughness can be different from the sidewalls and the cell roof.

Exit Loss Coefficient

Exit losses are computed as a coefficient times the change in velocity head from just inside the culvert, at the downstream end, to the cross section just downstream of the culvert. The equation for computing exit losses is as follows:

$$h_{ex} = k_{ex}\left(\frac{\alpha_{ex}V_{ex}^2}{2g} - \frac{\alpha_2 V_2^2}{2g}\right)$$

Where: h_{ex} = Energy loss due to exit

k_{ex} = Exit loss coefficient

V_{ex} = Velocity inside of culvert at exit

V_2 = Velocity outside of culvert at downstream cross section

HecRas analysis

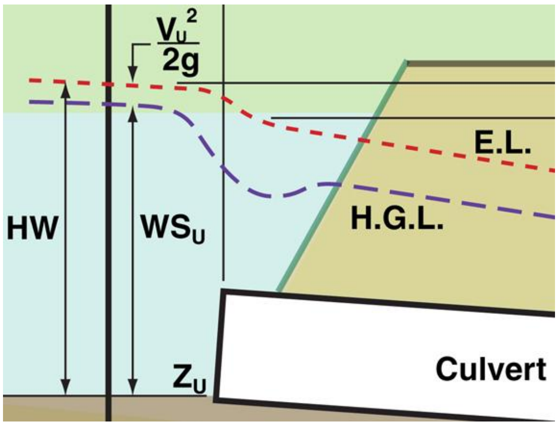
Exit loss

- The exit loss coefficient is applied to the absolute change in velocity head at the outlet.
- For hand calculations:

$$H_{ex} = k_{ex}.(V_{ex}^2/2g - V_{ds}^2/2g) \qquad (18.2)$$

- Caution; the downstream velocity (V_{ds}) must be assessed with care—flow expansion is unlikely to extend very far into the floodplain, if at all.

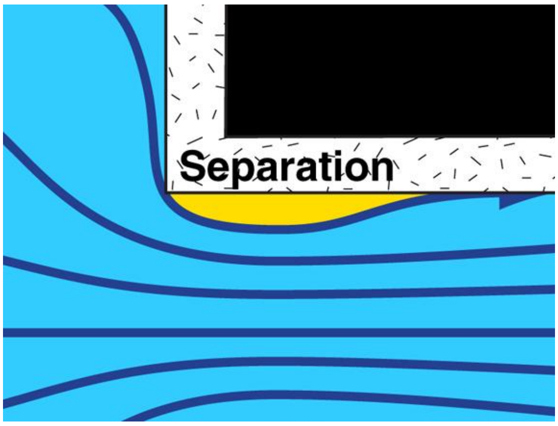
Understanding energy losses due to flow contraction



Gradual energy loss at culvert entry

Introduction

- The first thing to note about the entry loss (inlet loss) is the fact that it is a gradual energy loss that occurs over a distance of around 5 to 10 times the equivalent cell diameter (i.e. 5–10D).
- However, in a numerical analysis it is usually assumed that the entry loss is a sudden loss that occurs solely at the culvert inlet.
- If the length of the culvert is less than 10D, then the full entry loss may not occur.



Stream lines cannot turn 90-degrees

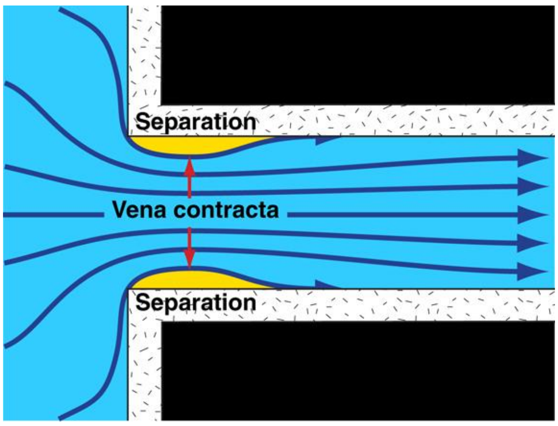
The momentum effect

- Water has mass, which means it experiences the effects of inertia and momentum.
- Flows can approach a culvert inlet from a wide range of directions, even if the upstream channel is close to the same width as the culvert.
- Flows moving parallel with the headwall cannot suddenly turn 90-degrees in order to enter the culvert, and so flow separation occurs just inside the inlet.

Inlet of a multi-cell box culvert (Qld)

The effect of internal culvert walls (legs)

- Given the relatively narrow width of the legs of a box culvert, it would seem reasonable that these legs would not contribute significantly to the flow contraction, but this is not the case.
- If the leading face of these internal walls is relatively flat, then a 'bow wave' can form (as shown left), which can generate the usual box culvert inflow contraction and energy loss.



Streamline cannot turn 90-degrees

Vena contracta

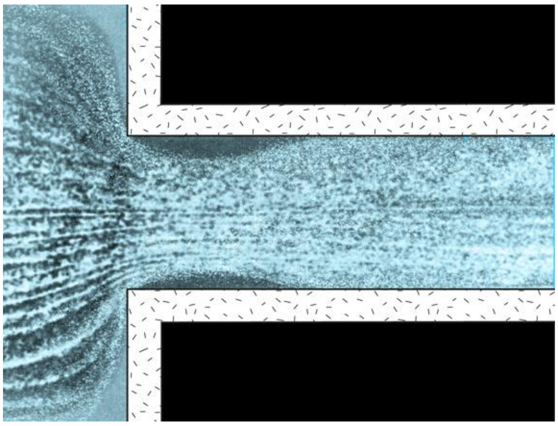
- In most cases, a water flow can contract to a smaller flow area without significant energy loss.
- However, at the inlet of a culvert, the effects of momentum can cause the flow to contract beyond the size of the conduit (vena contracta), which causes the inflow to experience a degree of flow expansion after the vena contracta.
- It is this flow expansion that causes most of the energy loss at the culvert's entrance.

Inlet hydraulics

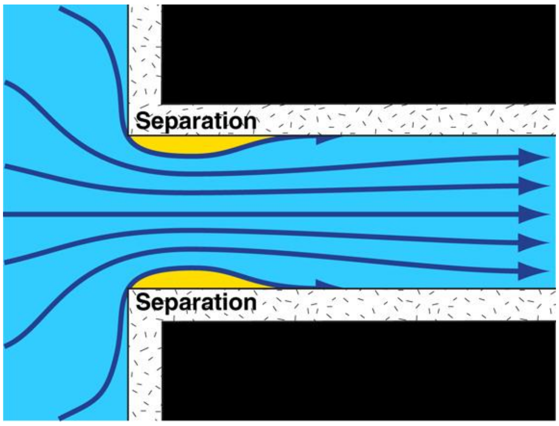
Inlet flush with a straight headwall (NSW)

Flush headwall

- A flush headwall without wingwalls has the potential for significant flow contraction and entry loss.
- In some cases the banks of the upstream watercourse may act like wingwalls, but the shape and position of these stream banks can vary with time, and should not be considered as a substitute for formal wingwalls.
- **Entry loss coefficient typically = 0.5**



Stream lines for square-edged entry

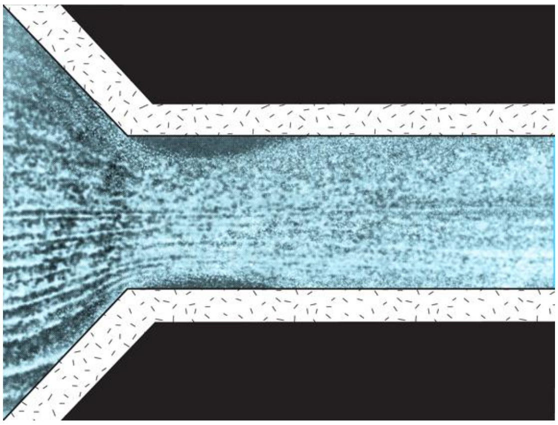


Square-edged culvert entry

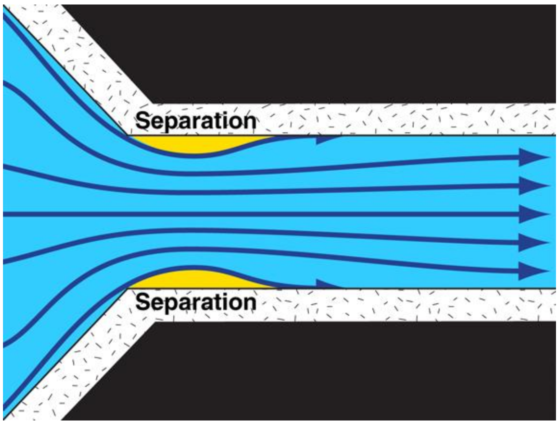
Angled wingwalls (Qld)

Angled wingwalls

- Angled wingwalls can help to direct flows into a culvert, but significant flow separation should still be expected.
- The vena contracta is not as narrow as the case for a flush headwall.
- **Entry loss coefficient typically = 0.4**



Stream lines for wingwall entry



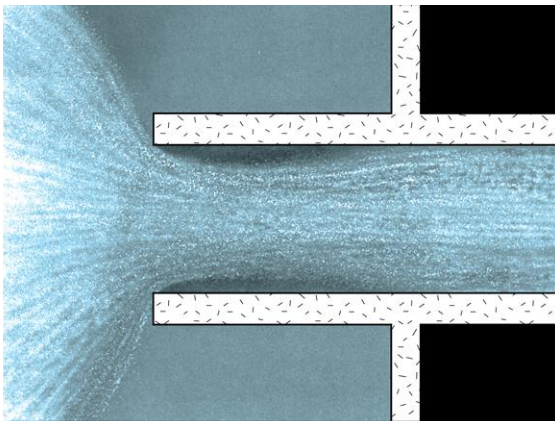
Culvert inlet with angled wingwalls

Inlet hydraulics

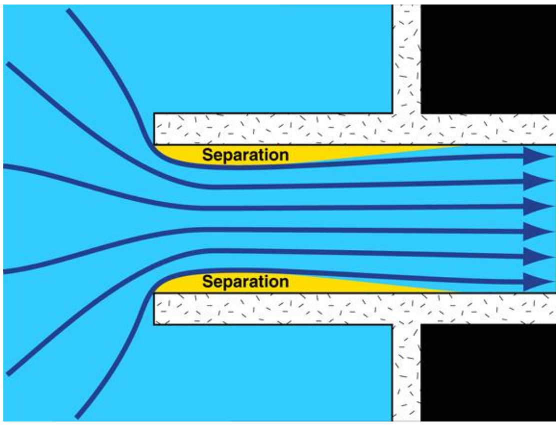
Projected pipe inlet (Qld)

Projected inlet

- Projecting a culvert inlet can result in significant energy loss at the inlet; **however**, designers need to be careful if they wish to nominate a projected inlet.
- The skewed culvert shown (below) would not experience the adverse effects of a projected box culvert because the:
  - outer cells sit flush with the wingwalls
  - internal legs would not experience the same flow separation shown below.
- **Entry loss coefficient typically = 0.7**



Stream lines for a projected inlet

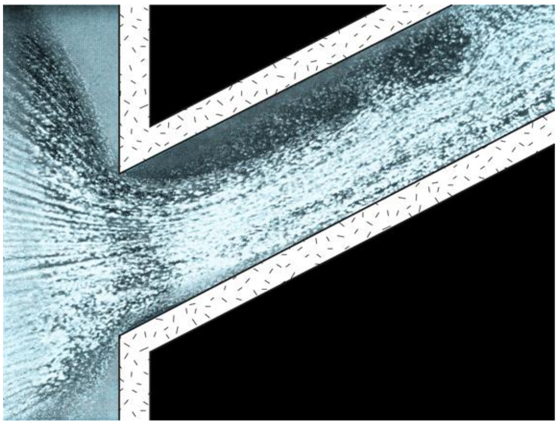


Flow separation on a projected inlet

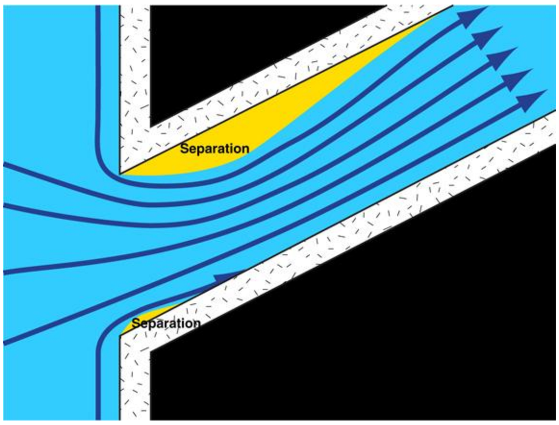
Projected inlets (Qld)

Skewed culvert inlet

- In general, the entry loss coefficients of skewed culverts are equal to those adopted for 'flush headwall' (square edge) culverts.
- The width of the vena contracta for a skewed culvert is similar to that of a square-edged culvert.
- **Entry loss coefficient typically = 0.5**

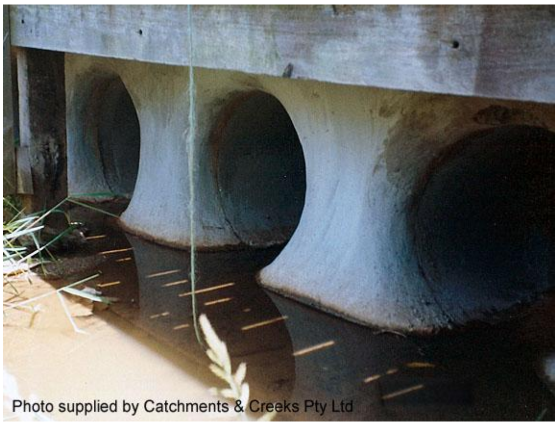


Stream lines on a skewed inlet



Flow separation at a skewed inlet

Minimising entry loss

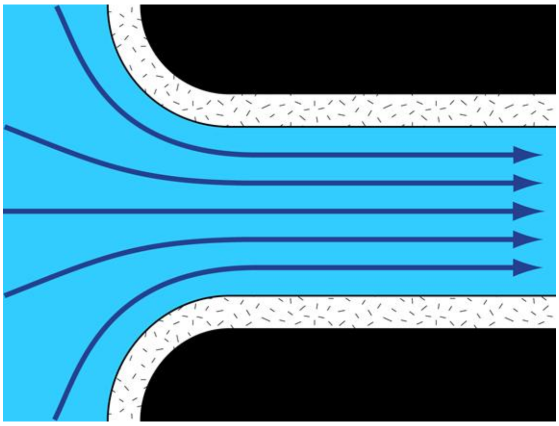


Rounded inlet (Qld)

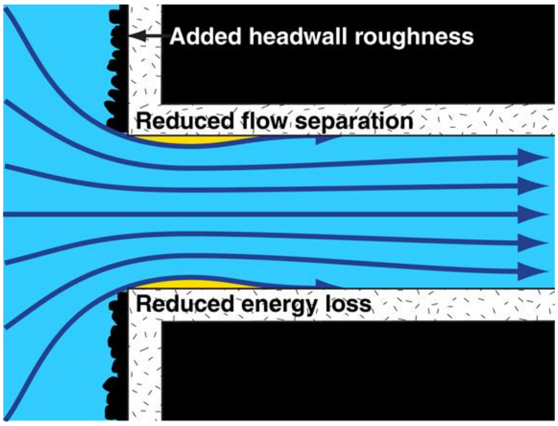
Rounded inlet

- The recommended radius of this curved surface is = D/12.
- On box culverts, both the culvert legs and the top deck (roof) should be rounded.
- Smooth entry conditions can reduce the entrance loss coefficient from 0.5 down to 0.2.
- A minimum 0.2 coefficient will exist because of the energy required to build the boundary layer within the barrel.
- **Entry loss coefficient typically = 0.2–0.5**

Rounded box culvert leg (Qld)



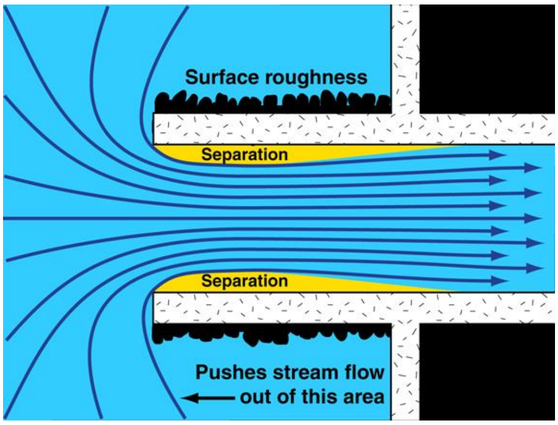
Stream lines on a rounded culvert entry



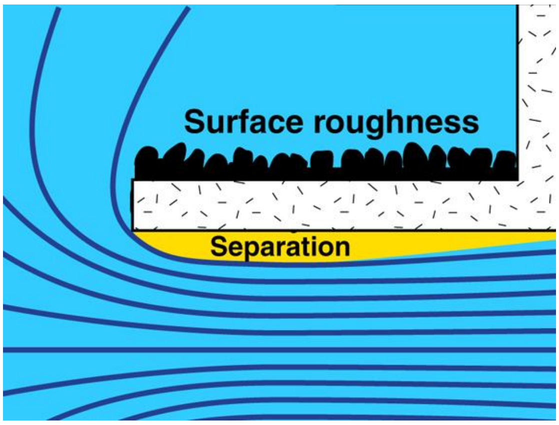
Added surface roughness

Added surface roughness

- Introducing significant surface roughness to the headwall can:
  - slow flow velocities adjacent to these roughened surfaces
  - push high flow velocity stream flows away from the headwall
  - reduce the degree of flow separation
  - reduce the entry loss.
- **Entry loss coefficient typically = 0.3–0.5**



Added surface roughness



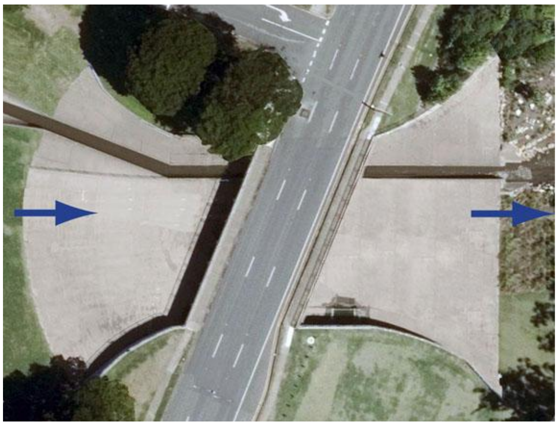
Effect on stream lines

Minimum energy structures

Cornwall St, Greenslopes, Brisbane, Qld

Introduction

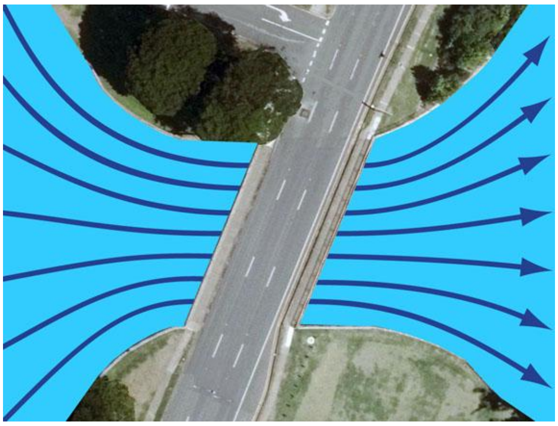
- The concept of a 'minimum energy structure' is largely an academic exercise.
- In practice, an equivalent outcome could be achieved at 60% of the cost just using a low energy loss inlet.
- In theory this design procedure can minimise the width of the culvert, and thus the cost of the culvert.
- However, in practice, the width of the culvert is usually determined by the width of commercially available box cells.



Minimum energy culvert (Qld)

Entry loss

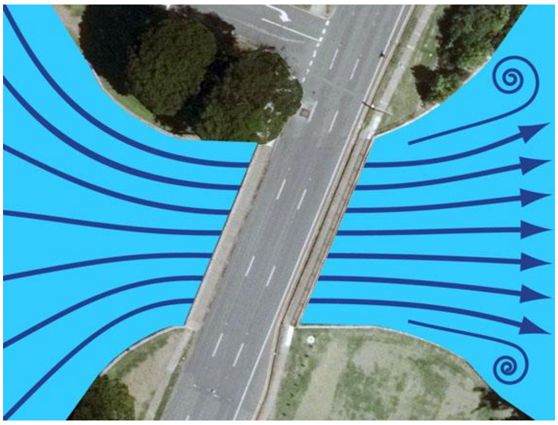
- In general, the minimum entry loss is considered to be $0.2(V^2/2g)$ because of the energy required to build the boundary layer within the barrel of the culvert.
- Thus, the increased friction loss that results from boundary layer development is treated as part of the entry loss.
- This means the large entry of an ideal minimum energy structure can be replaced with a smaller D/12 curved entry.
- **Entry loss coefficient typically = 0.2**



Flow conditions of an 'ideal fluid'

Exit loss

- The real problem with these designs is that a 'specific energy' analysis of the flow net is based on the movement of an 'ideal fluid'.
- The analysis does not take into account the effects of friction loss along the sidewalls, which can lead to flow separation.
- During minor flows, when flow velocities are relatively low, the type of flow expansion shown (left) can occur.

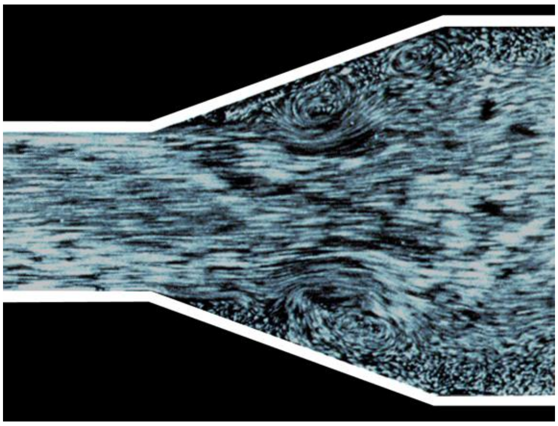


Flow conditions of a real fluid

Flow separation at the culvert exit

- However, during major flows, when flow velocities are high, outlet jetting and flow separation should be expected.
- This means that the exit loss from the culvert will not be close to zero (as in the ideal case), but can be as much as a standard culvert outlet (depending of the flow velocity).
- **Assume an exit loss coefficient typically = 0.5**

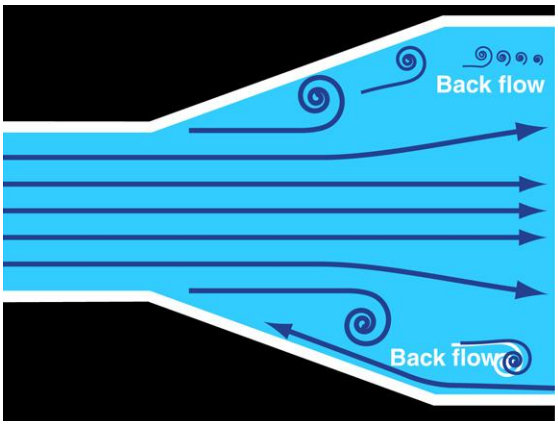
Flow expansion at culvert outlets



Stream lines at flow expansion

Introduction

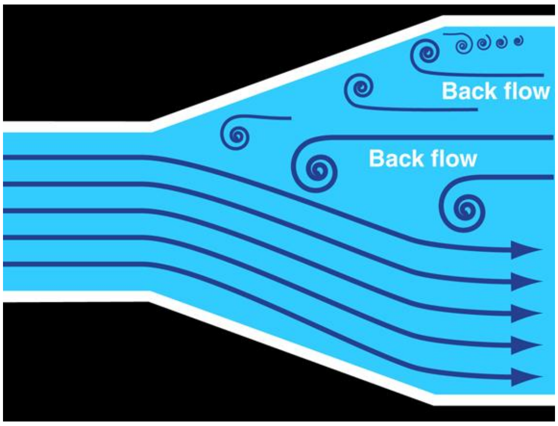
- It is very difficult to expand the flows exiting from a culvert without generating a significant energy loss.
- Flow separation is largely governed by the velocity and/or Froude Number of the outlet jet.
- For the flow velocities that are typically found at a waterway culvert, flow separation and energy loss should always be expected.



Typical flow separation and outlet jetting

Outlet jetting

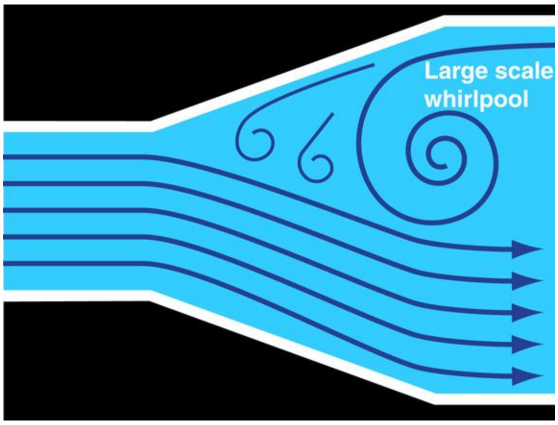
- Outlet jetting is something that should be expected.
- The type of outlet that would prevent flow separation would be so gradual in its expansion that it would make the outlet structure impractical.
- Designing the outlet based on a specific energy analysis will **not** prevent the likely occurrence of flow separation.
- Further discussion is presented in Step 19.



Asymmetric flow separation

Asymmetric flow conditions

- During a flood event, the outlet jet can move from side to side as flow conditions change, as flood debris collects in different locations, or as backwater conditions become more two-dimensional.
- If the outlet jet moves all the way to one side of the outlet channel, then significant bank erosion can occur.

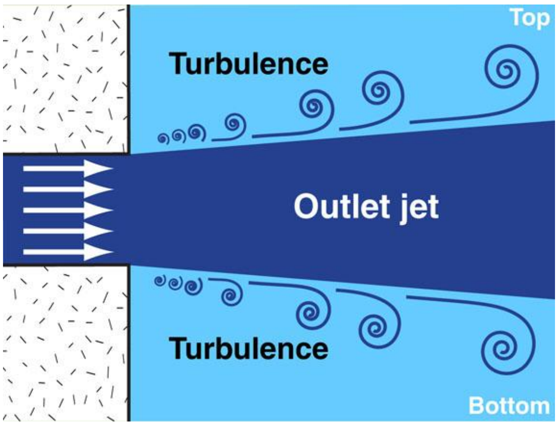


Alternative flow separation

Outlet whirlpools

- Whirlpools form easily when either a near-square, or circular, body of water exists adjacent to a flow expansion.
- Whirlpools are almost always circular, but exceptions do occur.
- Whirlpools can occur at culvert outlets and at sudden expansions within an open channel.
- The formation of a whirlpool can harm fish passage.

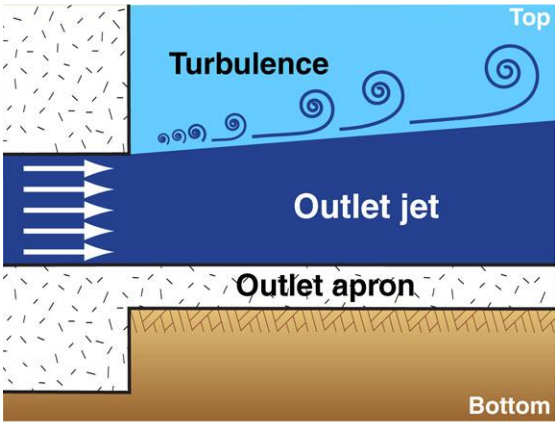
Understanding energy losses due to flow expansion



Side view of an elevated pipe outlet

Introduction

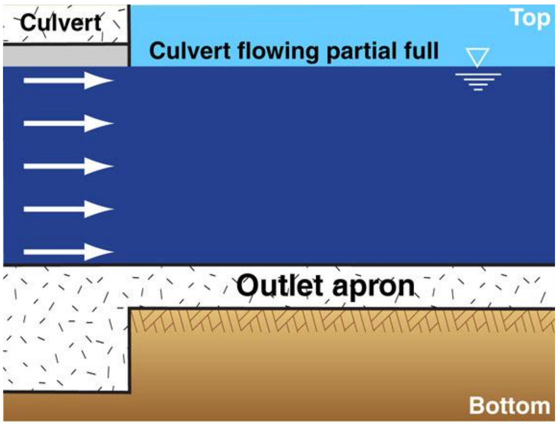
- During flow expansion, energy loss occurs for two main reasons:
  - inefficiencies associated with the transfer of energy (velocity) from the outlet jet into the surrounding water (i.e. turbulence), and
  - energy lost in forming and dissipating eddies.
- The more 'work' that the outlet jet does on the receiving water body, the greater the energy loss.



Side view of a bed-level culvert outlet

Culvert with a stable outlet apron and creek bed

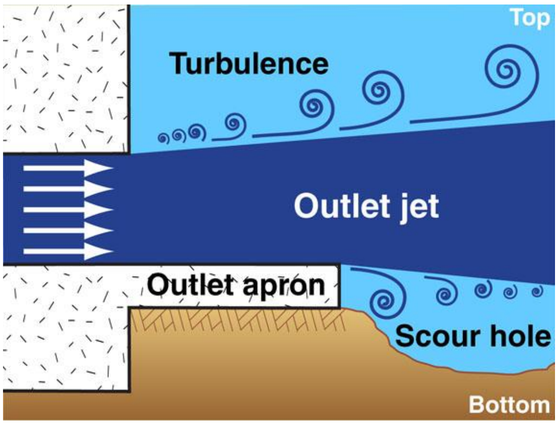
- In the example shown above, the pipe outlet is discharging well above the bed of the waterbody, thus flow expansion occurs all around the outlet jet.
- Exit loss coefficient = 1.0
- In the example shown left, the culvert jet expands only on three sides (left, upwards, and right); however, there is increased friction along the bed.
- Expected exit loss coefficient = 0.7



Side view of a partial-full culvert outlet

Exit loss with stable outlet bed and free surface flow

- In this example, the culvert is flowing partially-full (i.e. open channel flow), and the culvert has a stable outlet bed, which means flow expansion only occurs on two sides of the outlet jet.
- The jet expands to the left and right, but not upwards or downwards; however, there is increased friction along the bed.
- Expected exit loss coefficient = 0.5–0.6



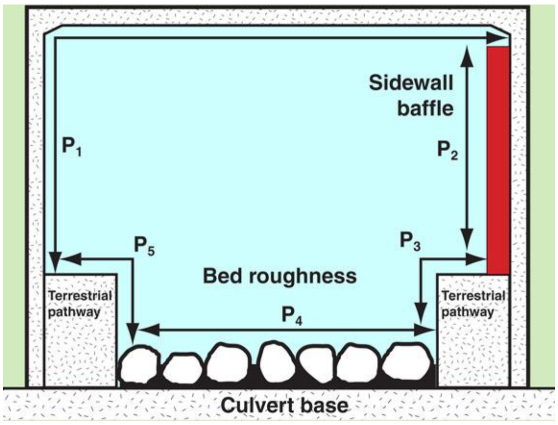
Culvert outlet with scour hole

Exit loss with restricted flow expansion

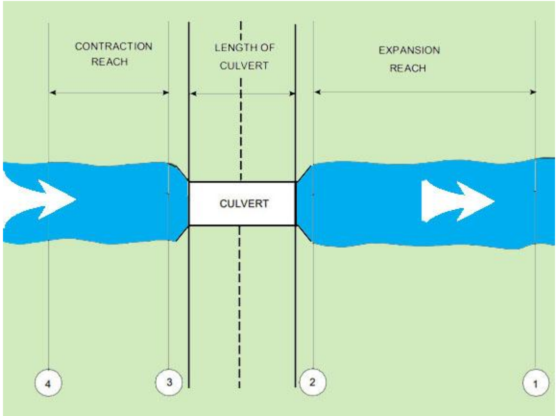
- During a flood event, it is possible for the culvert outlet to initially have a stable, flat, outlet bed, but as the flood progresses, a deep scour hole can be formed downstream of the concrete apron.
- In some cases, this scour hole may be backfilled with sediment by the time a post-flood inspection occurs.
- The existence of this scour hole means that flow expansion, and energy loss, can occur on all four sides of the outlet jet.
- Expected exit loss coefficient = 1.0

Hydraulic analysis of complex culvert cells

Sidewall baffles with roughened bed (NSW)



Complex surface roughness



HecRas culvert cross-sections

Flood debris blockage (Qld)

Introduction

- In modern, fish-friendly culverts, dealing with surface friction becomes a complex issue.
- Some commercial software programs allow the user to adopt multiple Manning's roughness values.
- Critically, the combined roughness of a cell flowing full can be different from that of a partial-full flow condition, which may be used to confirm fish passage conditions.

Determining a uniform Manning's roughness for a complex culvert cell

- Independent of whether the culvert cell is flowing full, or partial-full, a composite roughness value can be estimated from Equation 18.3.

$$n = \left(\sum \left[P_i . n_i^{3/2} \right] / P\right)^{2/3} \quad (18.3)$$

where:

n = composite Manning's roughness

P_i = wetted perimeter of sector (i)

n_i = Manning's roughness of sector (i)

P = wetted perimeter of total flow area

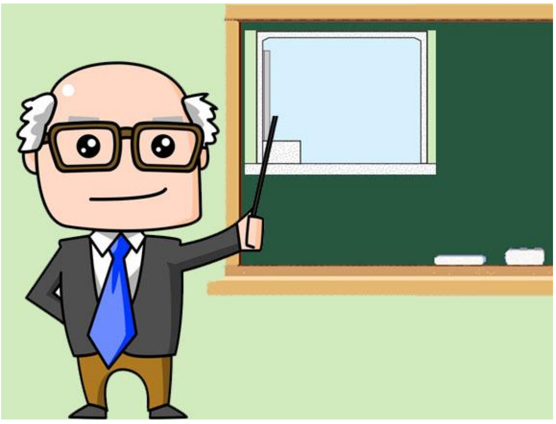
Location of cross-section XS1

- HecRas uses four cross-sections to model a culvert.
- Cross-section 1 (XS1) should be located where the flow has expanded to the maximum useable channel width.
- An expansion ratio of 1:4 would be a reasonable assumption.
- This does not mean that flow velocities will be uniform across the channel—only that all the flow is in a downstream direction, with no back-flow currents.

Consideration of debris blockages

- The typical debris blockage allowance is 10% to 20% of the culvert flow area depending on the extent of vegetated waterways upstream of the culvert.
- Debris blockage is discussed in more detail in Appendix G in Part 3.

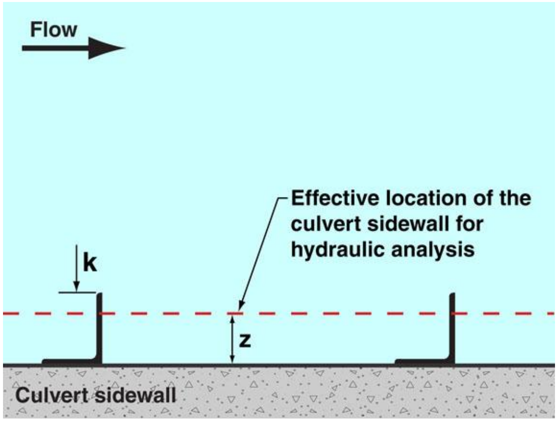
Determining the effective width and depth of a culvert cell



Hydraulics professor

Introduction

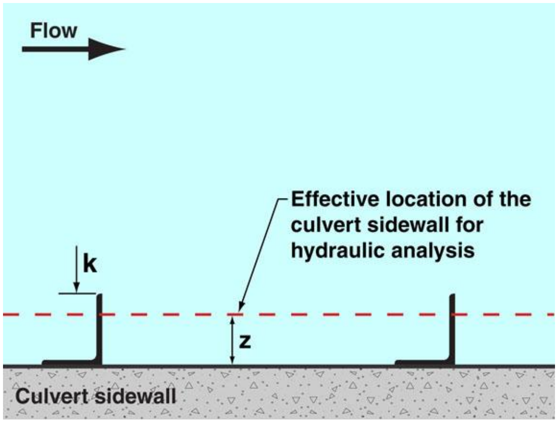
- The two hydraulic issues discussed on this page are:
  - the effective flow width changes caused by the introduction of sidewall baffles
  - the effective Manning's roughness of a baffled sidewall.



Effective width of dead water zone (z)

The effective flow width changes caused by the introduction of sidewall baffles

- Ideally, the hydraulic analysis of a baffled culvert cell must assume that any continuous dead water region formed between the baffles, is excluded from the effective flow area.
- This means that the effective width (W) must be reduced by the distance 'z' determined from an appropriate formula.
- However, in a typical culvert analysis, this correction is usually not performed.



Effective width of dead water zone (z)

Hydraulics

- If the parameter 'z' is taken as the effective position of the culvert sidewall (as used in hydraulic analysis), and 'k' is the projected width of the baffles, and 'L' is the spacing of the baffles, then the parameter 'z' can be determined from Table 18.1 (same as Table F5 in Part 2).

where:

- L is equivalent to L_B (baffle spacing)
- k is equivalent to W_B (baffle width)
- z = reduction in effective flow width.

Table 18.1 – Values of parameter 'z'

L/k (L_B/W_B)	10	6	5	4	< 4
z/k (z/W_B)	0.40	0.62	0.77	1.0	1.0

Surface roughness of culvert cells

Smooth concrete surface (NT)

Concrete surfaces

- Manning's roughness for smooth pre-cast concrete is:

n = 0.013

Corrugated pipe culvert (NSW)

Corrugated surface

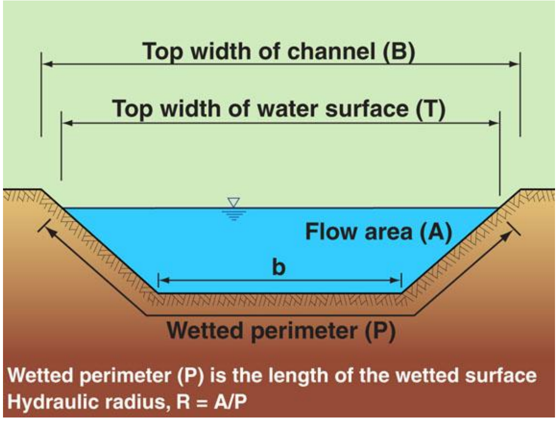
- Manning's roughness for corrugated stormwater pipe is:

n = 0.024

Table 18.2 – Recommended Manning's roughness values for conduits

Pipe type	Recommended "n"	Typical range of values
Reinforced concrete	0.013	0.011 to 0.013
Fibre reinforced concrete	0.011	0.010 to 0.011
Corrugated metal	0.024	0.016 to 0.024
uPVC	0.009	0.008 to 0.009
Black Brute or HDPE	0.013	0.009 to 0.015

Manning's roughness of rock-lined surfaces



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:

$$V = (1/n) \cdot R^{2/3} \cdot S^{1/2} \qquad (18.4)$$

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 effective Manning's roughness of rock-lined surfaces depends on:
  - average rock size (d_{50})
  - the distribution of rock sizes, defined in this case by a 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 'whitewater' (not directly considered here).

Manning's roughness in deep water

- The Strickler equation for deep water may be presented in the modified form:

$$n = ((d_{50})^{1/6})/21.1 \qquad (18.5)$$

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

$$n = ((d_{90})^{1/6})/26.0 \qquad (18.6)$$

  - d_{50} = rock size for which 50% of rocks (by weight) are smaller [m]
  - d_{90} = rock size for which 90% of rocks (by weight) 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 below.

$$n = \frac{{d_{90}}^{1/6}}{26(1 - 0.3593^{m})} \qquad (18.7)$$

  - $m = [(R/d_{90})(d_{50}/d_{90})]^{0.7}$
  - 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.

Rock roughness – Rounded river bed rock

Rounded river rock

Description of rock

- Natural, rounded river rock.

Rock placement (NSW)

Hydraulic properties of natural river rock

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

Table 18.3 – Manning's roughness for rock-lined surfaces in shallow water

d_{50}/d_{90}	d_{50}/d_{90} = 0.2					d_{50}/d_{90} = 0.3				
d_{50} (mm)	50	100	200	300	400	50	100	200	300	400
R (mm)	Channel bed Manning's roughness (n)					Channel bed Manning's roughness (n)				
200	0.12	0.21	0.38	0.53	0.67	0.07	0.12	0.21	0.29	0.37
300	0.10	0.17	0.30	0.40	0.51	0.06	0.10	0.16	0.22	0.28
400	0.08	0.14	0.24	0.33	0.42	0.05	0.08	0.14	0.19	0.23
500	0.07	0.12	0.21	0.29	0.37	0.05	0.07	0.12	0.16	0.20
600	0.07	0.11	0.19	0.26	0.32	0.04	0.07	0.11	0.15	0.18
700	0.06	0.10	0.17	0.23	0.29	0.04	0.06	0.10	0.13	0.17
800	0.06	0.09	0.16	0.21	0.27	0.04	0.06	0.09	0.12	0.15
900	0.06	0.09	0.15	0.20	0.25	0.04	0.06	0.09	0.11	0.14
1000	0.05	0.08	0.14	0.19	0.23	0.04	0.05	0.08	0.11	0.13
1200	0.05	0.08	0.12	0.17	0.21	0.03	0.05	0.07	0.10	0.12
1400	0.05	0.07	0.11	0.15	0.19	0.03	0.05	0.07	0.09	0.11
1600	0.04	0.07	0.10	0.14	0.18	0.03	0.04	0.06	0.08	0.10
1800	0.04	0.06	0.10	0.13	0.16	0.03	0.04	0.06	0.08	0.10
2000	0.04	0.06	0.09	0.12	0.15	0.03	0.04	0.06	0.08	0.09

Rock roughness – Quarry rock

Fractured quarry rock (Qld)

Description of rock

- Fractured, angular quarry rock.

Loose rock placement (SA)

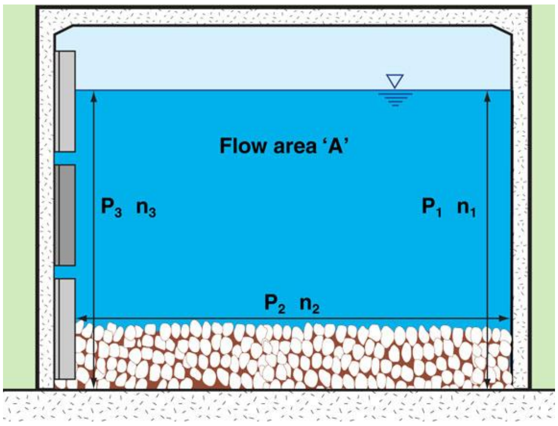
Hydraulic properties of quarried rock

- The relative roughness (d_{50}/d_{90}) of quarried rock is commonly in the range 0.5 to 0.8.

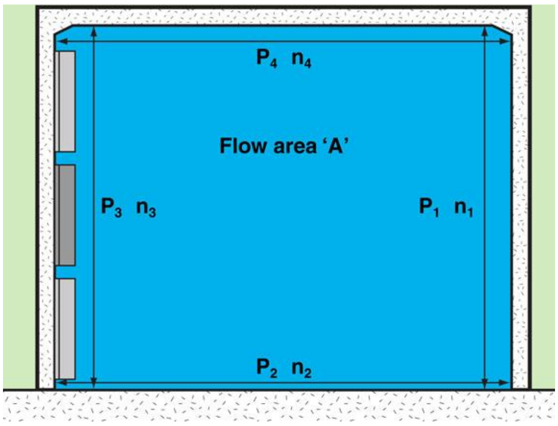
Table 18.4 – Manning's roughness for rock-lined surfaces in shallow water

d_{50}/d_{90}	d_{50}/d_{90} = 0.5					d_{50}/d_{90} = 0.8				
d_{50} (mm)	50	100	200	300	400	50	100	200	300	400
R (mm)	Channel bed Manning's roughness (n)					Channel bed Manning's roughness (n)				
200	0.04	0.06	0.10	0.14	0.17	0.03	0.04	0.06	0.08	0.09
300	0.04	0.05	0.08	0.11	0.14	0.03	0.03	0.05	0.06	0.08
400	0.03	0.05	0.07	0.09	0.12	0.03	0.03	0.04	0.05	0.07
500	0.03	0.04	0.06	0.08	0.10	0.03	0.03	0.04	0.05	0.06
600	0.03	0.04	0.06	0.08	0.09	0.03	0.03	0.04	0.05	0.05
700	0.03	0.04	0.05	0.07	0.09	0.03	0.03	0.04	0.04	0.05
800	0.03	0.04	0.05	0.07	0.08	0.03	0.03	0.04	0.04	0.05
900	0.03	0.04	0.05	0.06	0.08	0.03	0.03	0.04	0.04	0.05
1000	0.03	0.03	0.05	0.06	0.07	0.03	0.03	0.03	0.04	0.05
1200	0.03	0.03	0.04	0.06	0.07	0.03	0.03	0.03	0.04	0.04
1400	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
1600	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
1800	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
2000	0.03	0.03	0.04	0.05	0.05	0.03	0.03	0.03	0.03	0.04

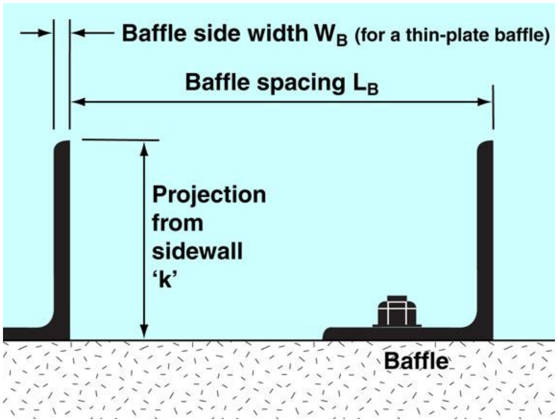
Effective Manning's roughness of a baffled sidewall



Partial-full flow conditions



Culvert flowing full



Terminology

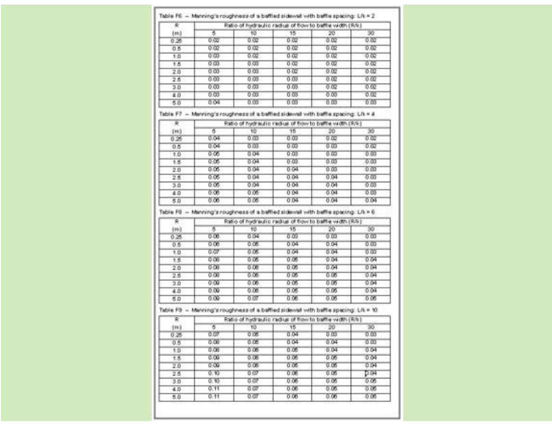


Table 18.5 to 18.8 (over page)

Introduction

- The following analysis is based on Knight, D.W. and Macdonald, J.A., 1979. *Hydraulic Resistance of Artificial Strip Roughness*. ASCE Vol 105 HY6, June 1979, pp675-690. American Society of Civil Engineers, USA.
- Knight and Macdonald (1979) developed the following Manning's roughness equation (Equation 18.8)

$$n = (R1/6) / 19.0*\log10 [C*(R/k)] \qquad (18.8)$$

Equation parameters

n = Manning's roughness of the baffled sidewall

R = Hydraulic roughness of the culvert cell = A/P [m]

A = Cross-sectional area of the water flow within the culvert cell [m2]

P = Wetted perimeter of the water flow within the culvert cell [m]

C = Equation parameter than depends on the baffle spacing term (k/L)

L = The horizontal spacing of the baffles = L_B [m]

k = The projected width of the baffles [m]

Equation parameter 'C'

- The relationship between the equation parameter (C) and the inverse of the baffle spacing term (k/L) is given by:

$$C = 116*(k/L)\ 2 - 27.4*(k/L) + 2.422 \qquad (18.9)$$

Manning's roughness of a baffled sidewall

- The Manning's roughness for a culvert sidewall lined with rectangular, two-dimensional (strip) roughness units as determine from the work of Knight and Macdonald (1979) is presented in tables 18.5 to 18.8 (same as tables F6 to F9 in Appendix F in Part 2 of this document).

Table 18.5 – Manning's roughness of a baffled sidewall with baffle spacing: L/k = 2

R (m)	Ratio of hydraulic radius of flow to baffle width (R/k)				
	5	10	15	20	30
0.25	0.02	0.02	0.02	0.02	0.02
0.5	0.02	0.02	0.02	0.02	0.02
1.0	0.03	0.02	0.02	0.02	0.02
1.5	0.03	0.03	0.02	0.02	0.02
2.0	0.03	0.03	0.02	0.02	0.02
2.5	0.03	0.03	0.03	0.02	0.02
3.0	0.03	0.03	0.03	0.02	0.02
4.0	0.03	0.03	0.03	0.03	0.02
5.0	0.04	0.03	0.03	0.03	0.03

Table 18.6 – Manning's roughness of a baffled sidewall with baffle spacing: L/k = 4

R (m)	Ratio of hydraulic radius of flow to baffle width (R/k)				
	5	10	15	20	30
0.25	0.04	0.03	0.03	0.02	0.02
0.5	0.04	0.03	0.03	0.03	0.02
1.0	0.05	0.04	0.03	0.03	0.03
1.5	0.05	0.04	0.03	0.03	0.03
2.0	0.05	0.04	0.04	0.03	0.03
2.5	0.05	0.04	0.04	0.04	0.03
3.0	0.05	0.04	0.04	0.04	0.03
4.0	0.06	0.05	0.04	0.04	0.03
5.0	0.06	0.05	0.04	0.04	0.04

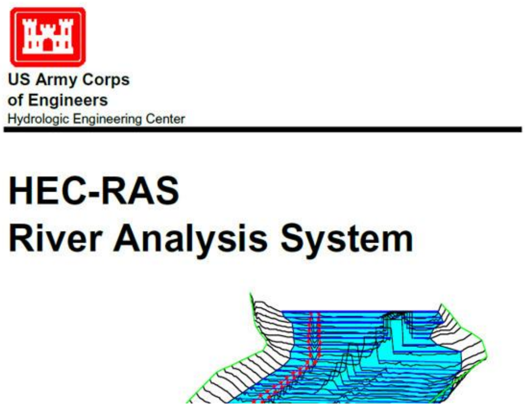
Table 18.7 – Manning's roughness of a baffled sidewall with baffle spacing: L/k = 6

R (m)	Ratio of hydraulic radius of flow to baffle width (R/k)				
	5	10	15	20	30
0.25	0.06	0.04	0.03	0.03	0.03
0.5	0.06	0.05	0.04	0.04	0.03
1.0	0.07	0.05	0.04	0.04	0.03
1.5	0.08	0.05	0.05	0.04	0.04
2.0	0.08	0.06	0.05	0.04	0.04
2.5	0.08	0.06	0.05	0.05	0.04
3.0	0.09	0.06	0.05	0.05	0.04
4.0	0.09	0.06	0.05	0.05	0.04
5.0	0.09	0.07	0.06	0.05	0.05

Table 18.8 – Manning's roughness of a baffled sidewall with baffle spacing: L/k = 10

R (m)	Ratio of hydraulic radius of flow to baffle width (R/k)				
	5	10	15	20	30
0.25	0.07	0.05	0.04	0.03	0.03
0.5	0.08	0.05	0.04	0.04	0.03
1.0	0.08	0.06	0.05	0.04	0.04
1.5	0.09	0.06	0.05	0.05	0.04
2.0	0.09	0.06	0.05	0.05	0.04
2.5	0.10	0.07	0.06	0.05	0.04
3.0	0.10	0.07	0.06	0.05	0.05
4.0	0.11	0.07	0.06	0.05	0.05
5.0	0.11	0.07	0.06	0.06	0.05

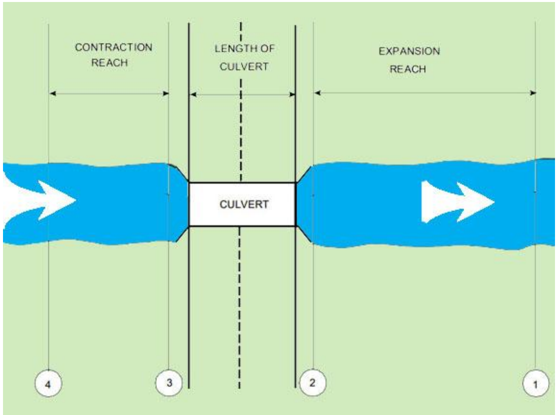
Numerical modelling – HecRas overview



HecRas, River Analysis System

Introduction

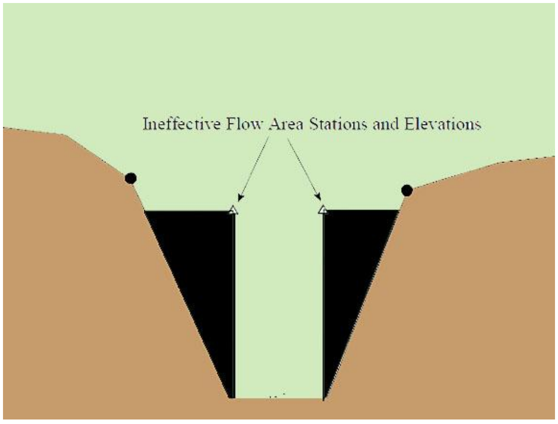
- HecRas computes losses in three parts.
- The first part consists of losses that occur in the reach immediately downstream from the culvert.
- The second part consists of losses that occur as flow travels into, through, and out of the culvert.
- The third part consists of losses that occur in the reach immediately upstream of the culvert.



HecRas culvert cross-sections

Location of cross-section XS1

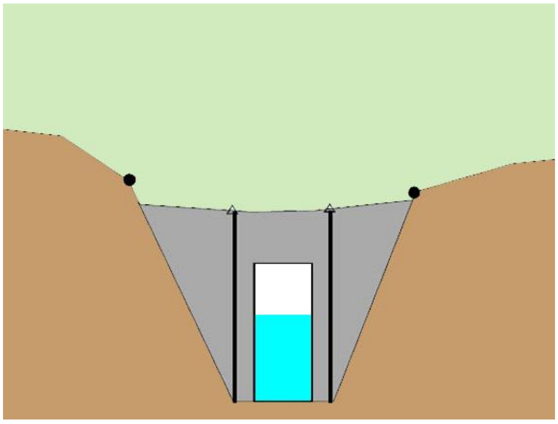
- HecRas uses four cross-sections to model a culvert.
- Cross-section 1 (XS1) should be located where the flow has expanded to the maximum useable channel width.
- An expansion ratio of 1:4 would be a reasonable assumption.
- This does not mean that flow velocities will be uniform across the channel—only that all the flow is in a downstream direction, with no back-flow currents.



Ineffective flow area option, XS2

Location of cross-section XS2

- Cross-section 2 (XS2) is located a short distance downstream from the culvert exit.
- The cross-section does not include any of the culvert structure or embankments.
- It should represent the physical shape of the channel just downstream of the culvert.
- The ineffective flow area option is used to correct the active flow area just downstream of the culvert.



Ineffective flow area option, XS3

Location of cross-section XS3

- Cross-section 3 (XS3) is located a short distance upstream of the culvert entrance.
- It should be located far enough upstream from the culvert to contain the abrupt contraction of flow—the more gradual contraction of flow occurs between XS3 and XS4.
- Cross-section 4 (XS4) is located at a point where flow has not yet begun to contract.
- A contraction ratio of 1:1 is a reasonable assumption.

Step 19 - Culvert Outlet

Decorative culvert headwall (Qld)

Small private culvert without headwall

Recessed culvert without aprons (NSW)

Introduction

- In its simplest form, a culvert outlet consists of just an outlet apron followed by a rock pad; however, there can be several arrangements of a culvert outlet, including:
  - with or without a headwall
  - with or without an outlet apron
  - with or without a cut-off wall
  - baffles placed on the wingwalls
  - a rock-lined scour control pad
  - downstream recessed rock check dam.

With or without a headwall

- Designers can choose a conventional concrete headwall, or a decorative headwall, usually consisting of grouted rock, slate, or artificial rock.
- On small culverts, the headwall can be replaced with stacked rock.
- The decision to move away from a traditional headwall is usually based on aesthetics, but the designer needs to be sure that future erosion issues will not undermine the culvert.

With or without an outlet apron

- Inlet and outlet aprons can perform the following tasks:
  - reduce the risk of culvert undermining
  - provide a solid surface so maintenance personnel can inspect the culvert.
- A recessed culvert that allows sediments to settle on the culvert floor can still have a formal apron system that eventually becomes covered in sediment.

Components of an outlet structure

Culvert with apron but no cut-off wall

Cut-off wall

- Cut-off walls are useful for preventing migrating head-cut erosion from undermining the culvert.
- Head-cut erosion is a lowering of the downstream channel bed, which was triggered well-downstream of the culvert, but has now migrated up the channel to the culvert.
- Guidelines typically specify a 600 mm or 1000 mm deep cut-off wall depending on the channel stability.

Wingwall baffles (Qld)

Wingwall baffles

- Sidewall baffles are usually required on the outlet wingwalls, as well as on the inlet wingwalls.
- It is the author's recommendation that the spacing of these baffles is four (4) times the baffle width.

Culvert outlet with rock pad (NSW)

Outlet scour pads (rock pads)

- The design of outlet rock pads is presented in the next design step, Step 20.
- The purpose of an outlet rock pad is not to dissipate energy, but instead to:
  - build desirable boundary layer conditions before the flow is released into the downstream channel
  - reduce the risk of bed erosion undermining the outlet apron.

Recessed rock check dam (NT)

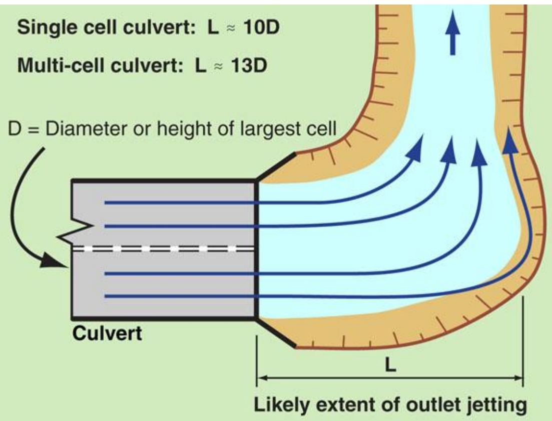
Recessed rock check dams

- Outlet rock pads cannot prevent the adverse effects of outlet jetting.
- Outlet jetting is likely to occur if the average velocity through any of the culvert cells exceeds 2 m/s.
- Outlet jets can travel 10 to 13 times the equivalent jet diameter downstream of the culvert.
- Recessed rock check dams can help to prevent bed lowering caused by outlet jetting (if such erosion is likely to occur).

Controlling the downstream erosion risk

Outlet bed erosion (SA)

Looking downstream from a culvert (Qld)



Outlet jetting and bank erosion

Elevated pipe culvert (NSW)

Introduction

- The outlet structure of a culvert cannot prevent channel erosion that has been triggered by an action downstream of the culvert.
- Culverts can be used to prevent head-cut erosion from migrating past the culvert.
- Outlet jetting from the culvert (which should not occur in fish-friendly culverts) can cause bed erosion immediately downstream of the apron or rock pad, as well as bank erosion well-downstream of the culvert.

The risk of bed erosion downstream of the rock pad

- If the culvert has high velocity outflows during flood events, then bed erosion should be expected downstream of the rock pad.
- Rock pads are not designed to prevent all forms of bed erosion, but instead to make sure such erosion occurs well-downstream of the culvert, so that the erosion does not endanger the culvert.

The risk of bank erosion downstream of the outlet (outlet jetting)

- If the channel changes direction downstream of the culvert, and if the culvert experiences outlet jetting, then this jetting can cause erosion on any channel bank that is:
  - aligned with the culvert
  - located less than 10 to 13 times the equivalent cell diameter (or cell height) downstream of the culvert outlet (measured from the headwall, not the apron).

Protection from bed erosion migrating up the channel

- If the channel bed downstream of the culvert lowers over time, then a fish-friendly recessed culvert can slowly turn into a fish barrier with a waterfall slowly forming at the outlet of the pipes, or along the edge of the outlet apron.
- Figures 19.1 to 19.8 show the critical bed location, the placement of a recessed rock check dam (IF needed), and the potential damage caused by severe flood events.

Recessed culverts – Potential downstream bed erosion

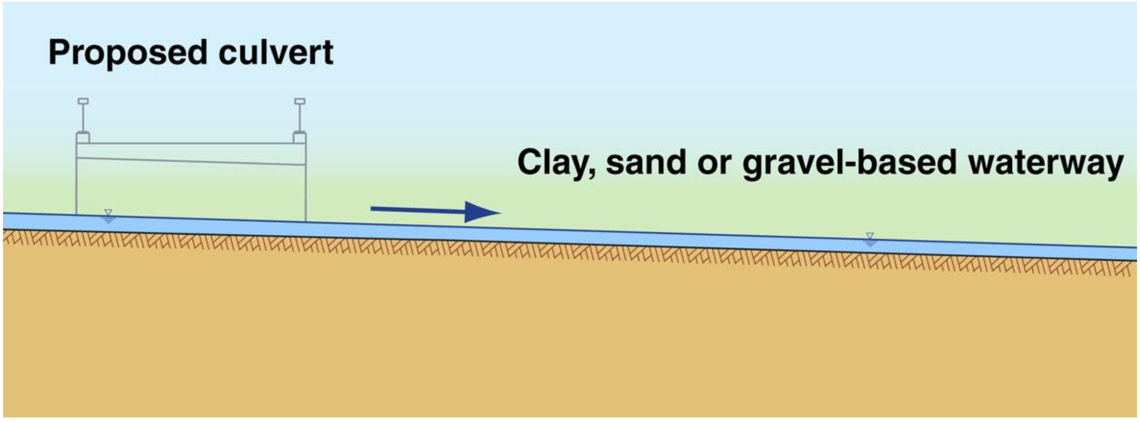


Figure 19.1 – Pre-culvert flow conditions

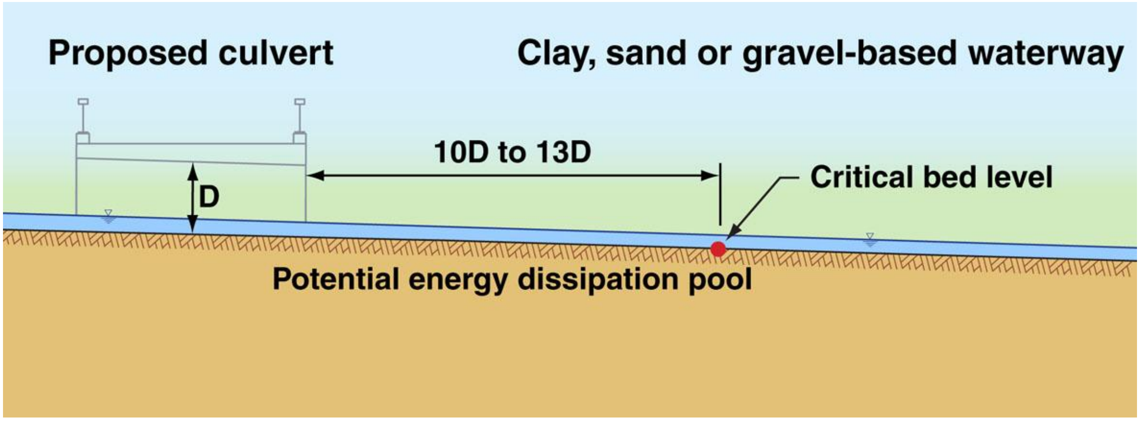
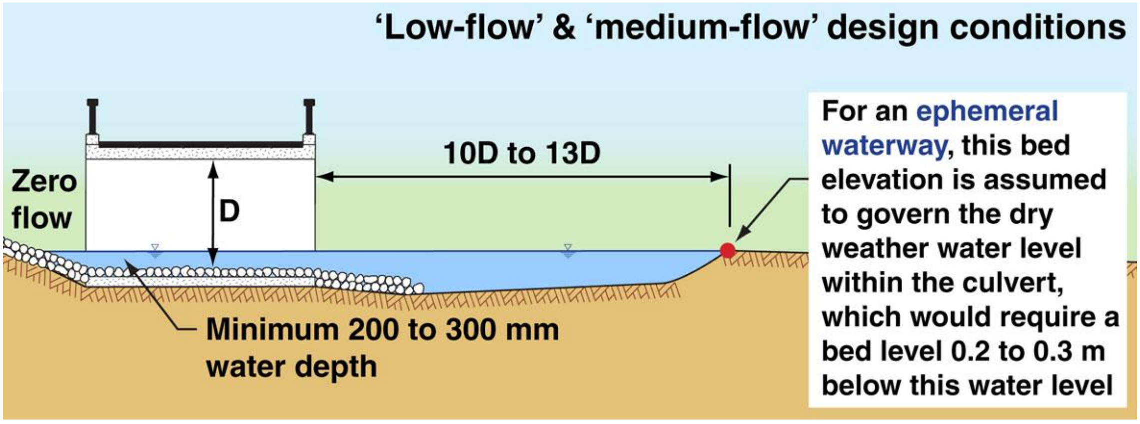
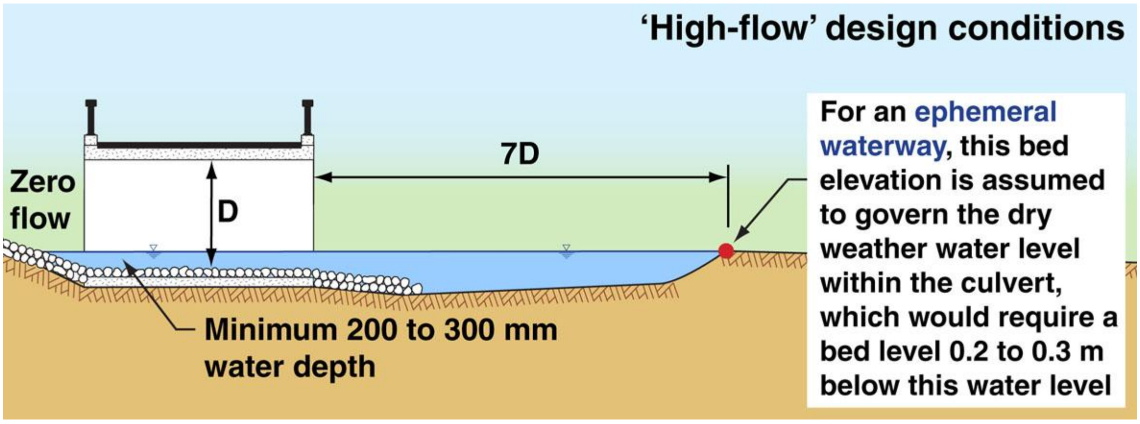


Figure 19.2 – Expected extent of outlet jetting

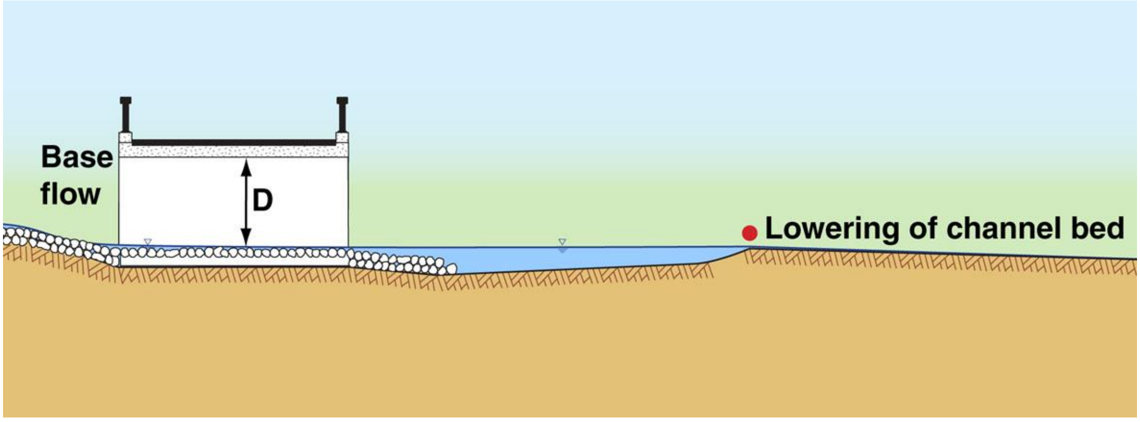


19.3 – Critical distance if the hydraulic analysis is based on a 1 in 10 year design event



19.4 – Critical distance if the hydraulic analysis is based on a 1 in 50 year design event

Recessed culverts – Potential downstream bed erosion



19.5 – Potential lowering of water levels if bed erosion occurs

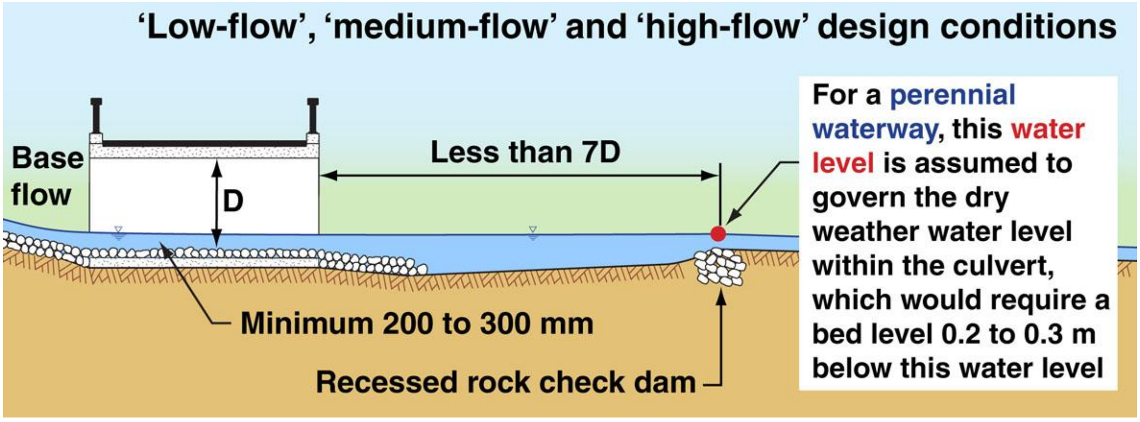


Figure 19.6 – The placement of a recessed rock check dam

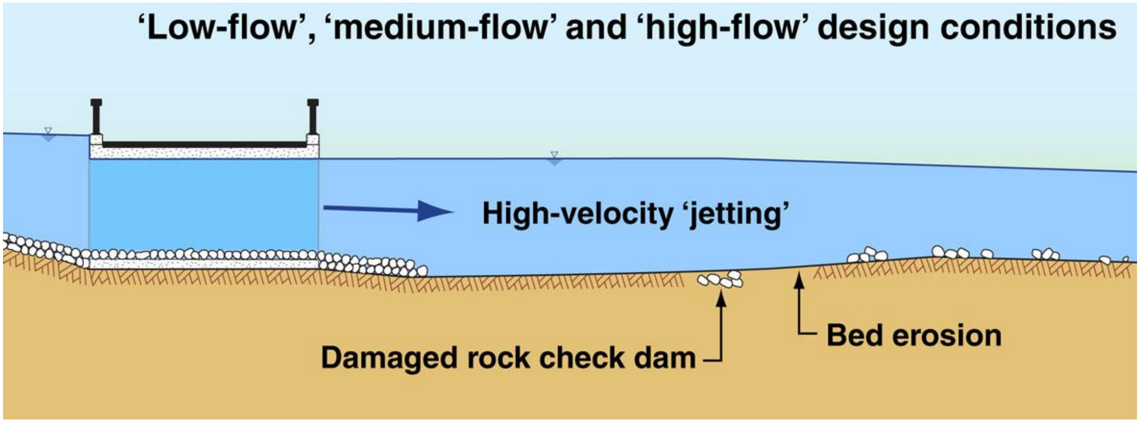


Figure 19.7 – Potential 'failure' condition

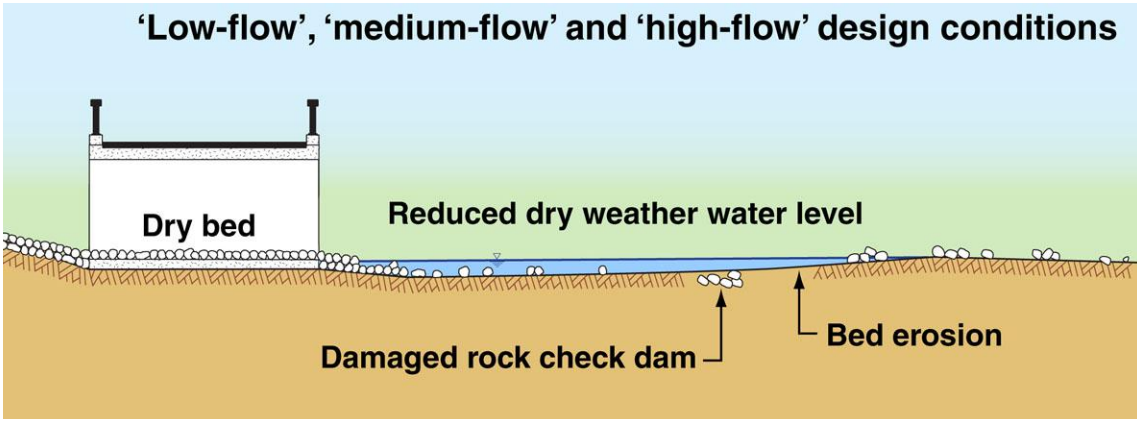


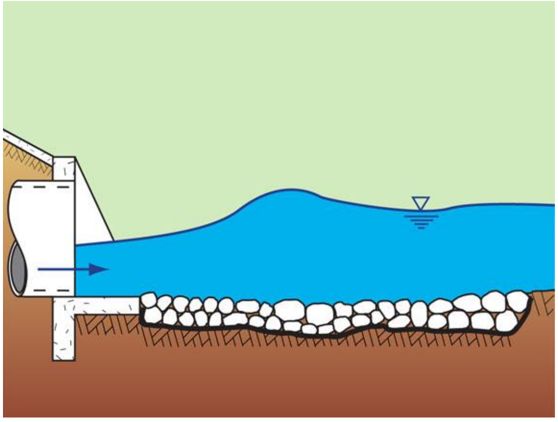
Figure 19.8 – Resulting outcome of poor downstream channel bed stability

Energy dissipation systems

Rock pad outlet (Qld)

Introduction

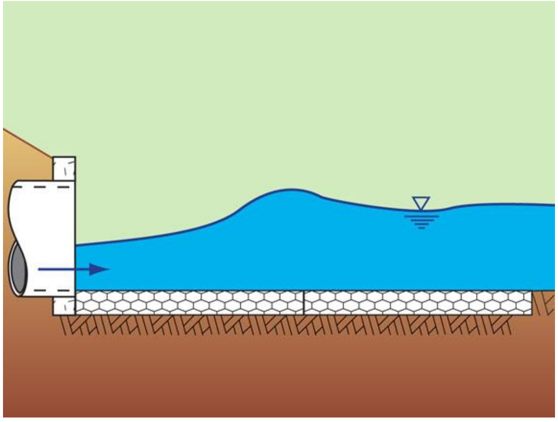
- There are a variety of energy dissipation structures that can be placed on a culvert outlet.
- Of all of these energy dissipation systems, only the rock pad outlet is considered to be fish friendly.
- In theory, a fish-friendly culvert should not require an energy dissipation system.



Rock pad outlet

Rock pad outlets

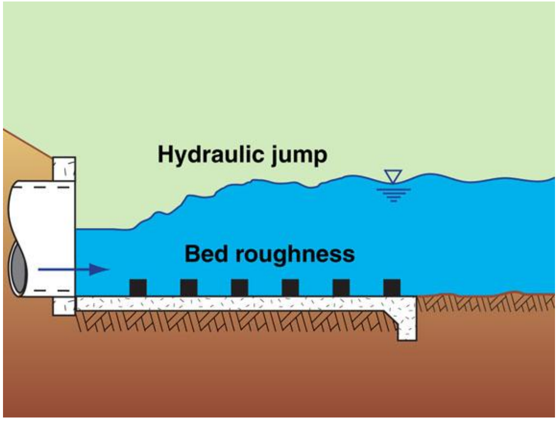
- References for the design of rock pads can be found in:
  - Step 20 of this document
  - Catchments and Creeks (2024) *Use of Rock in Waterway Engineering*
  - *Queensland Urban Drainage Manual* (2017) Institute of Public Works Engineering.



Rock mattress outlet

Rock mattress outlets

- Design references: Valletine, Hattersely & Cornish (1961), Queensland Transport (1975).
- Not recommended by the author because of poor durability, mattress failures, and loss of rocks.

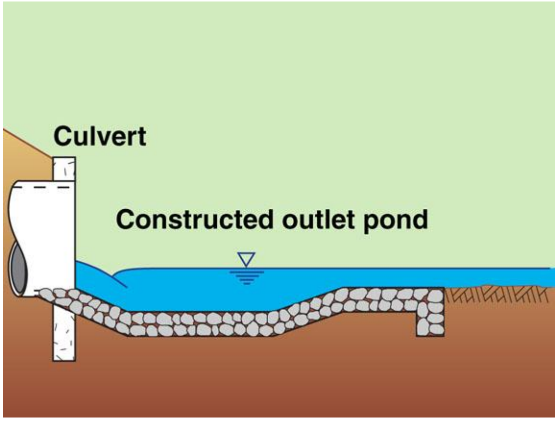


Forced hydraulic jump basin

Forced hydraulic jump basins

- Design references: U.S. Dept. of Transport (1983)

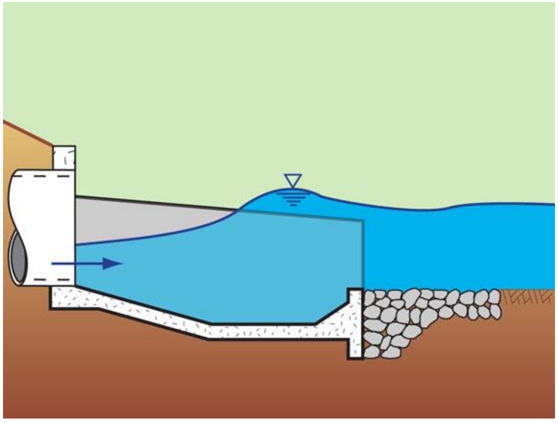
Energy dissipation systems



Riprap basin

Riprap basins

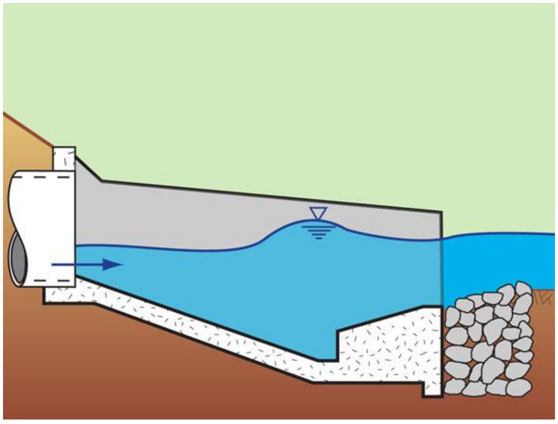
- Design references: ASCE (1992), U.S. Dept. of Transport (1983).
- Suitable for culverts operating under inlet control conditions with a low tailwater.



Single pipe plunge pool outlet structure

Single pipe plunge pool outlet structures

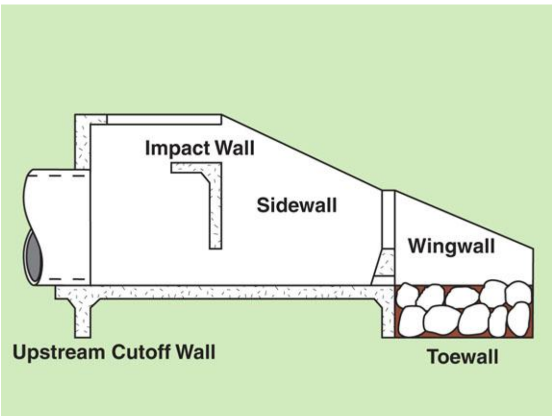
- Design references: Argue (1960), Queensland Transport (1975).
- Suitable for culverts operating under inlet control conditions with a low tailwater.



Twin pipe plunge pool outlet structure

Twin pipe plunge pool outlet structures

- Design references: O'Loughlin (1960), Queensland Transport (1975).
- Suitable for culverts operating under inlet control conditions with a low tailwater.

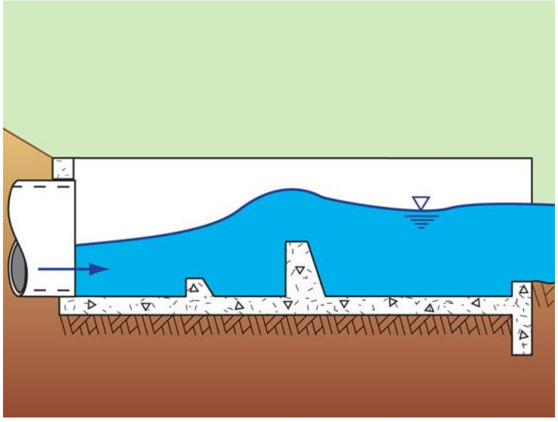


USBR Type VI impact basin

USBR Type VI impact basins

- Design references: Peterka (1984), Meredith (1975), U.S. Soil Conservation, Rice & Kadavy (1991), U.S. Dept. of Transport (1983), Standing Committee on Rivers and Catchments (1991).
- Designed for high-velocity outlets.

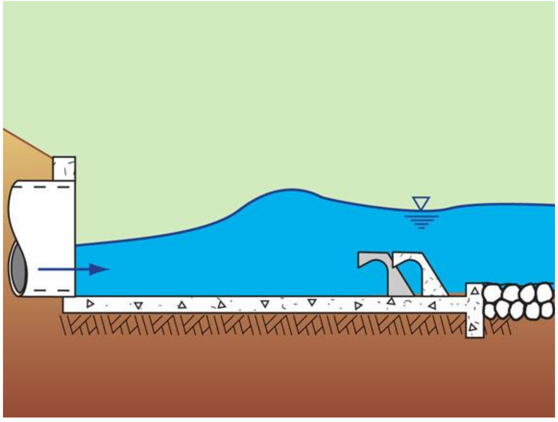
Energy dissipation systems



Contra Costa energy dissipater

Contra Costa energy dissipaters

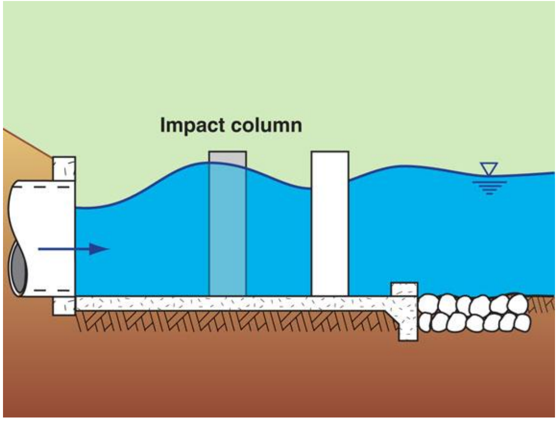
- Design references: Keim (1962), U.S. Dept. of Transport (1983).



Hook dissipater

Hook dissipaters

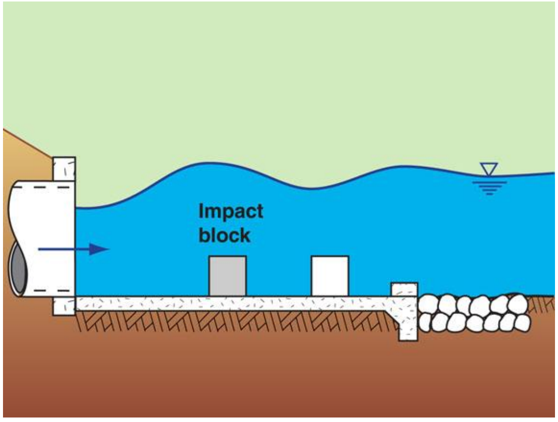
- Why would you ever design such a structure?
- The dissipater's performance has one unique feature that is not even worth discussing.



Impact columns

Impact columns

- Design references: Brisbane City Council (2003), Smith & Yu (1966).

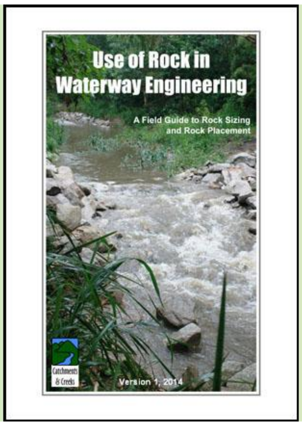


Impact basin

Impact basins

- Design guidelines are expected to appear in a future *Catchments and Creeks* Energy Dissipation field guide.

Step 20 - Erosion Control at the Outlet

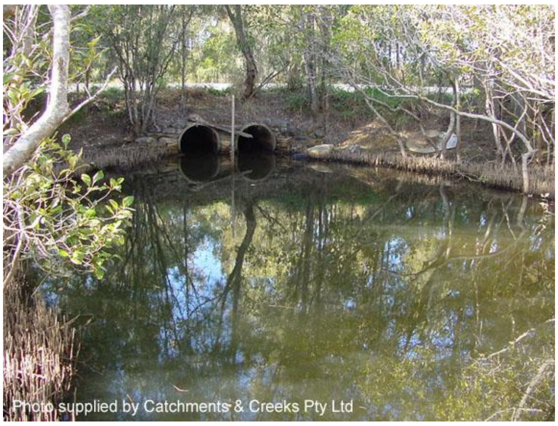


Catchments & Creeks Pty Ltd, 2024

Reference document:

Use of Rock in Waterway Engineering, Catchments & Creeks Pty Ltd, 2024, Brisbane Queensland.

Version 7, 2024.



Outlet scour hole (pool) on a tidal culvert

Assessing the need for scour control

- Scour control is essential on most waterway crossings to:
  - minimise damage to the culvert
  - minimise damage to the waterway channel
  - minimise loss of riparian vegetation resulting from bank erosion
  - maintain desirable low-flow water levels through the crossing.
- Outlet erosion normally results in the formation of an outlet scour hole.

Multi-cell box culvert outlet (Qld)

Length of the rock pad

- The minimum pad length (L) is based on practicality issues and will not necessarily prevent all bed scour.
- During high tailwater conditions, or when the culvert is operating under 'outlet control' conditions, bed and bank erosion can occur well-downstream of the outlet.
- When the outlet is fully or partially drowned (i.e. high tailwater) then 'jetting' from the outlet can transfer energy well-downstream of the rock pad.

Hydraulics of culvert outlets

Culvert discharge with very low tailwater

Outlet flow conditions

- The hydraulics of culvert outlets change with changing tailwater conditions.
- Some design guidelines provide different rock pad outlet dimensions for low tailwater conditions, as compared to a high tailwater condition.

Culvert discharge with low tailwater (NSW)

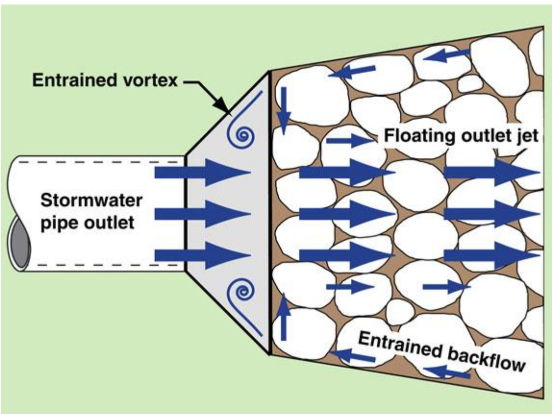
Low tailwater flow conditions

- During low tailwater conditions, discharges tend to 'spill' from the culvert cells, spreading the flow energy over a wider pathway than during high tailwater.
- Energy dissipation is more efficient, and the required length of the rock pad is smaller than would be required for a high tailwater condition.
- The rock pad lengths (L) presented within the following pages typically reflects this low tailwater condition.

Outlet jetting during high tailwater (NSW)

High tailwater flow conditions

- During high tailwater conditions, discharges from the cells tend to 'float' along the surface of the water.
- During these conditions it is common for high velocity outlet jets to travel a distance of between 10 and 15 times the jet depth (i.e. approx twice the nominal rock pad length, L) before there is a significant reduction in the central core flow velocity.
- Consequently, the existence of a rock pad may not necessarily enhance energy dissipation.

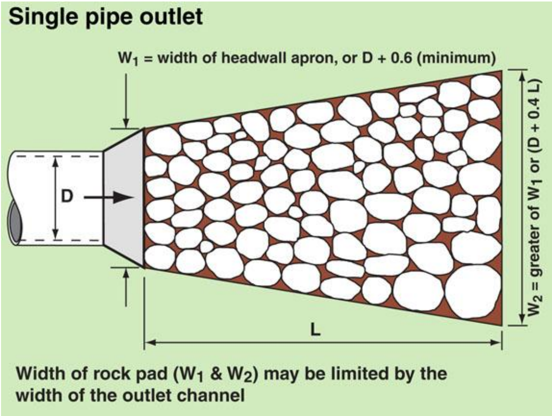


Example of entrained outlet vortices

Purpose of headwalls on culvert outlets

- Headwalls can provide the following benefits:
  - reduce the risk of erosion undermining the outlet (if a cut-off wall is included)
  - reduce the risk of rock displacement within outlet structures
  - reduce the risk of 'entrained vortices' eroding the channel banks adjacent to the outlet.

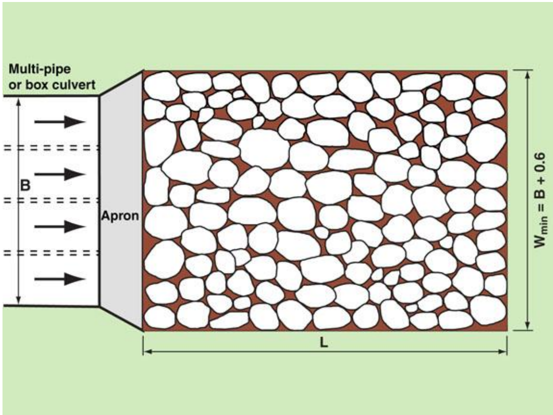
Rock pad outlet structures



Single cell culvert rock pad

Single cell culverts

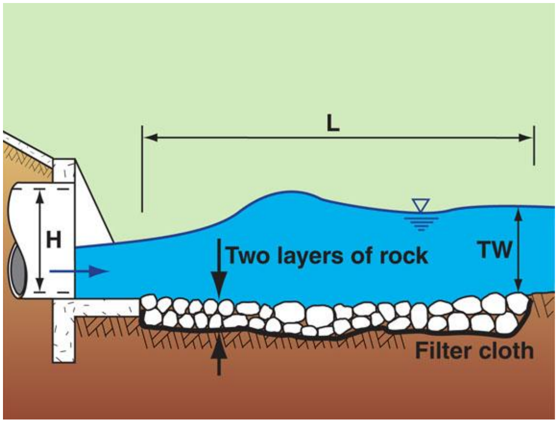
- The recommended mean (d_{50}) rock size for a single cell culvert is presented in Figure 20.1.
- A **36% increase** in rock size is recommended if rounded rocks are used instead of angular rock.



Multi-cell culvert rock pad

Multi-cell culverts

- The recommended mean (d_{50}) rock size for multi-cell culverts is presented in Figure 20.2 and tables 20.2 and 20.3.
- The values presented in tables 20.2 to 20.3 have been rounded up to the next 100 mm increment in consideration of the limited availability of rock sizes and the high variability of expected outcomes.
- A **36% increase** in rock size is recommended if rounded rocks are used instead of angular rock.



Rock pad dimension terminology

Minimum depth of rock pad

- The thickness of the rock pad should be based on at least two layers of rock.
- This typically results in an overall pad thickness as presented in Table 20.1.

Table 20.1 – Minimum thickness (T) of rock pad

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

Note: d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller.

Rock sizing charts

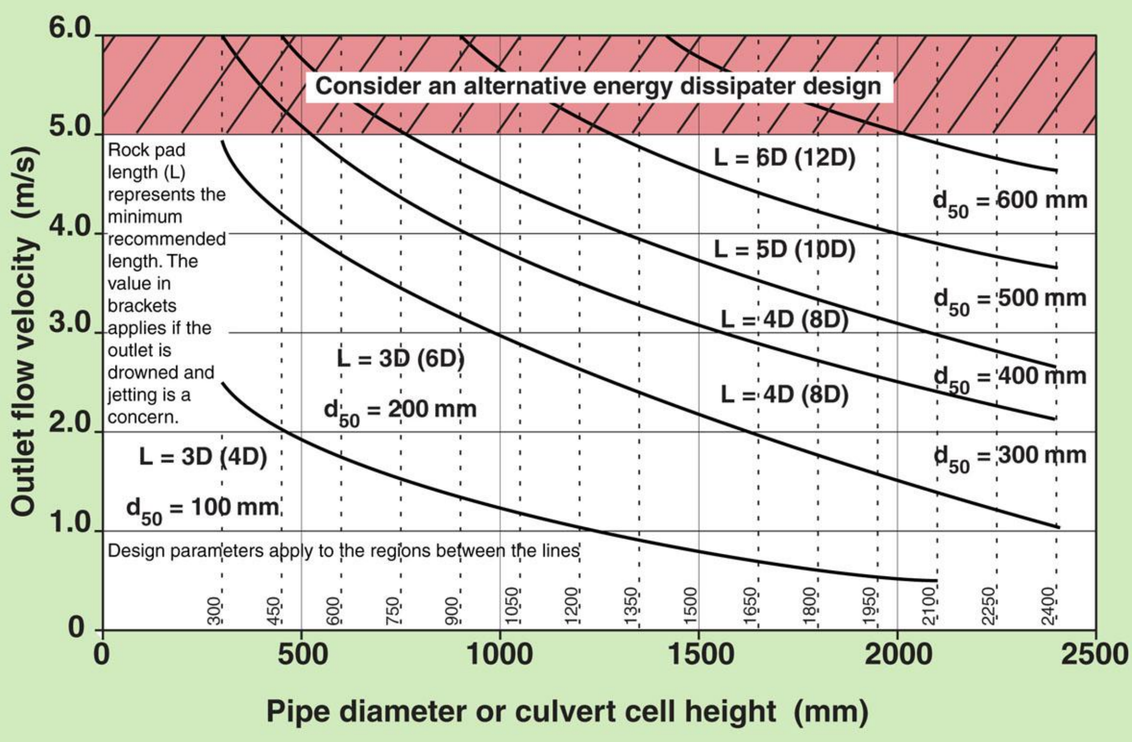


Figure 20.1 – Sizing rock for a single cell culvert outlet rock pad

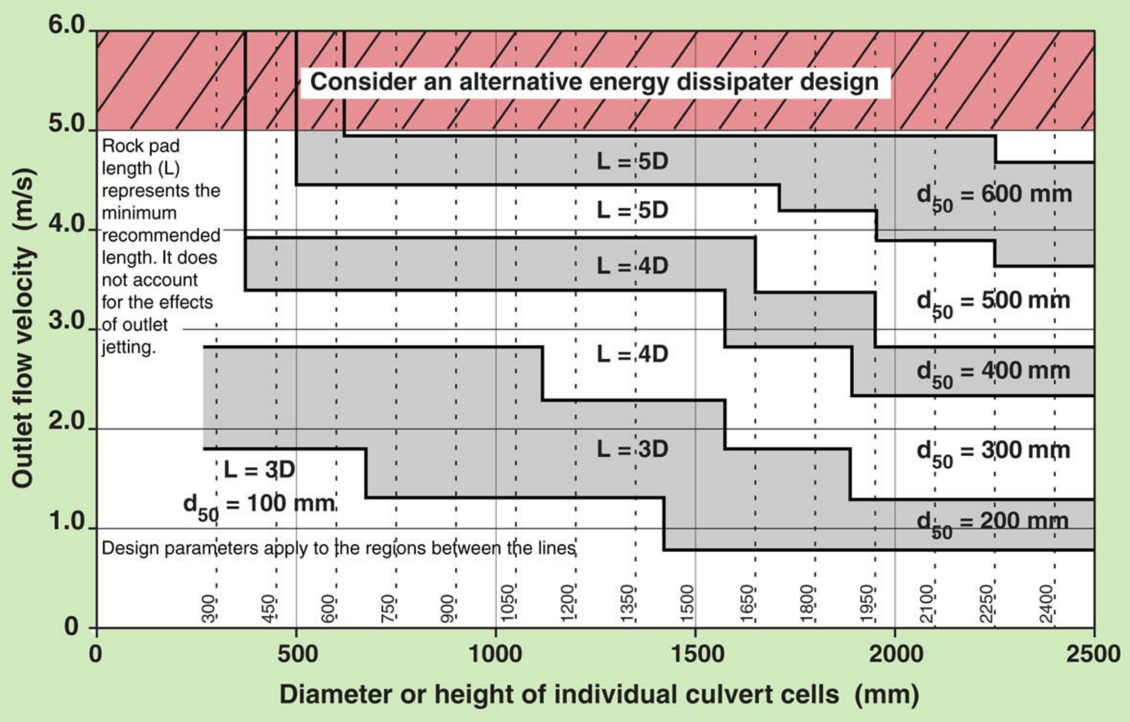


Figure 20.2 – Sizing rock for a multi-cell culvert outlet rock pad

Table 20.2 – Mean rock size, d_{50} (mm) for culvert outlet scour protection

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	300	375	450	525	600	750	900
0.50	100	100	100	100	100	100	100
1.00	100	100	100	100	100	100	100
1.50	100	100	100	100	100	200	200
2.00	200	200	200	200	200	200	200
2.50	200	200	200	200	200	200	200
3.00	300	300	300	300	300	300	300
3.50	300	400	400	400	400	400	400
3.75	300	400	400	400	400	400	400
4.00	300	400	500	500	500	500	500
4.25	300	400	500	500	500	500	500
4.50	300	400	500	600	600	600	600
4.75	300	400	500	600	600	600	600
5.00	300	400	500	600	600	700	700
5.25	300	400	500	600	600	800	800
5.50	300	400	500	600	600	800	800
5.75	300	400	500	600	600	800	871
6.00	300	400	500	600	600	800	900

Table 20.3 – Mean rock size, d_{50} (mm) for culvert outlet scour protection

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	1050	1200	1350	1500	1800	2100	2400
0.50	100	100	100	100	100	100	100
1.00	100	100	200	200	200	200	200
1.50	200	200	200	200	200	300	300
2.00	200	200	200	200	300	300	300
2.50	200	300	300	300	300	400	400
3.00	300	300	300	300	400	500	500
3.50	400	400	400	400	500	500	500
3.75	400	400	400	400	500	500	600
4.00	500	500	500	500	500	600	600
4.25	500	500	500	500	600	600	600
4.50	600	600	600	600	600	600	600
4.75	600	600	600	600	600	600	700
5.00	700	700	700	700	700	700	700
5.25	900	900	900	900	900	900	900
5.50	900	900	900	900	900	900	900
5.75	900	900	900	900	900	900	900
6.00	1000	1000	1000	1000	1000	1000	1000

Table 20.4 – Minimum length of rock pad relative to cell height (L/H) for culvert outlet protection [1,2]

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	300	375	450	525	600	750	900
0.50	3	3	3	3	3	3	3
1.00	3	3	3	3	3	3	3
1.50	3	3	3	3	3	3	3
2.00	3	3	3	3	3	3	3
2.50	3	3	3	3	3	3	3
3.00	3	3	3	3	3	3	3
3.50	3	3	3	3	3	4	4
3.75	3	3	3	3	4	4	4
4.00	3	3	3	4	4	4	4
4.25	3	3	4	4	4	4	4
4.50	3	4	4	4	4	4	4
4.75	3	4	4	4	4	4	5
5.00	4	4	4	4	4	4	5
5.25	4	4	4	4	4	5	5
5.50	4	4	4	6	6	6	6
5.75	4	4	6	6	6	6	6
6.00	4	6	6	6	6	6	6

Table 20.5 – Minimum length of rock pad relative to cell height (L/H) for culvert outlet protection [1,2]

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	1050	1200	1350	1500	1800	2100	2400
0.50	3	3	3	3	3	3	3
1.00	3	3	3	3	3	3	4
1.50	3	3	3	3	3	4	4
2.00	3	3	3	3	4	4	4
2.50	3	4	4	4	4	4	4
3.00	4	4	4	4	4	4	4
3.50	4	4	4	4	5	5	5
3.75	4	4	4	4	5	5	5
4.00	4	4	5	5	5	5	5
4.25	4	5	5	5	5	5	5
4.50	5	5	5	5	5	5	5
4.75	5	5	5	5	5	5	5
5.00	5	5	5	5	6	6	
5.25	6	6	6	6	6	6	
5.50	6	6	6	6	6		
5.75	6	6	6	6	6		
6.00	6	6	6	6	6		

[1] Values represent the recommended minimum length of rock protection to prevent significant scour; however, some degree of soil erosion should be expected downstream of the rock protection.

[2] Under high tailwater conditions (TW > D/2) outlet jetting may extend beyond the rock protection during high tailwater conditions resulting in bed and/or bank erosion downstream of the rock protection. Extending the length of the rock protection will not necessarily reduce the risk of downstream bank erosion under high tailwater conditions.

Common construction problems

Displacement of rock pad

Inadequate rock size

- Rock of inadequate size can readily be displaced downstream of the culvert potentially causing the formation of a scour hole.

Placement on dispersive soils (below)

- Outlet scour protection often fails when placed directly on a dispersive soil.
- The formation of a cut-off wall at the downstream end of the concrete apron can reduce the risk of structural failure, especially if placed on a dispersive soil.

Undermining of culvert

Same culvert outlet eight years later

Inappropriate rock placement

Poor placement of rock

- If the rock sits above the invert of the culvert, then:
  - sediment is likely to collect within the culvert, and
  - the outlet 'jet' can be deflected towards the creek banks.
- The rocks need to be recessed such that the upper surface of the rocks is level with the concrete apron.

Bank erosion well-downstream of culvert

Outlet jetting

- During periods of high tailwater, or when the culvert is operating under 'outlet control' conditions, the outlet jet can float along the water surface with minimal energy dissipation.
- Floating outlet jets can travel a distance of around 10 to 15 times their diameter (pipe culverts), or effective flow depth (box culverts), depending on the exit velocity of the jets and the spacing between the jets (two outlet jets in close proximity to each other can join into a single, larger jet).

Step 21: Safety issues

Step 21 - Safety Issues

Broken arm

Safety hazards

- The potential injuries a person may experience if swept through a culvert can include:
  - physical harm, such as broken bones
  - short or long-term psychological trauma
  - permanent brain damage
  - drowning
  - death.

Unstable ground

Dangerous waters

Factors of influence

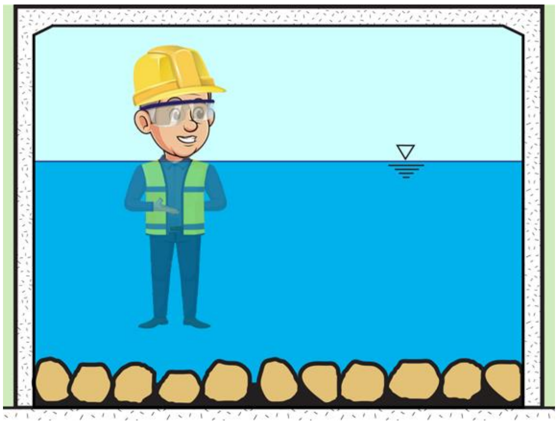
- The hazards experienced by persons passing through a culvert can be influenced by factors such as:
  - ambient lighting conditions (time of day)
  - depth and velocity of flow
  - the rate of rise in water level
  - stability of the ground surface upstream of the culvert, such as the edge of a bank
  - the presence of large, submerged, or sharp debris trapped at the entrance to the culvert
  - the presence of large, submerged, or sharp objects within the culvert, such as fish passage baffles
  - the presence of large, submerged, or sharp objects at the culvert outlet, possibly associated with energy dissipation measures
  - the person’s footwear and clothing (e.g. the drag caused by loose or heavy clothing).

Risk management options

Safe waters (NSW)

Safe creek banks (constructed channel)

Warning sign (NSW)



Good headroom

Risk management options

- The safety risks associated with waterway culverts can be managed, but not necessarily eliminated, through the use of appropriate design and management techniques, including:
  - designing flow conditions so that the waters do not present a risk of injury or death (first priority)
  - shaping the waterway banks in a manner that minimises the risk of a person accidentally falling or slipping into the waters (high priority)
  - designing or shaping the land and environments, in and around a culvert, in a manner that discourages an adult or child wanting to enter, or play in, the waterway during a storm or flood event (high priority)
  - designing systems that allow a person to readily exit a drain or waterway before they are swept into a culvert
  - designing long culverts in a manner that maximises the likelihood of the culvert flowing partially full (i.e. not submerged) during a storm or flood event
  - erecting warning signs to alert people of potential dangers
  - erecting external barriers (e.g. fencing) to limit the entry of persons into the upstream waters
  - erecting in-channel screens, or catch-poles, upstream of the culvert
  - erecting inlet safety screens on the culvert (generally considered the least preferred option due to increased flooding risks, and the safety hazards associated with the increased flood risk)
  - public education programs.

Long culverts

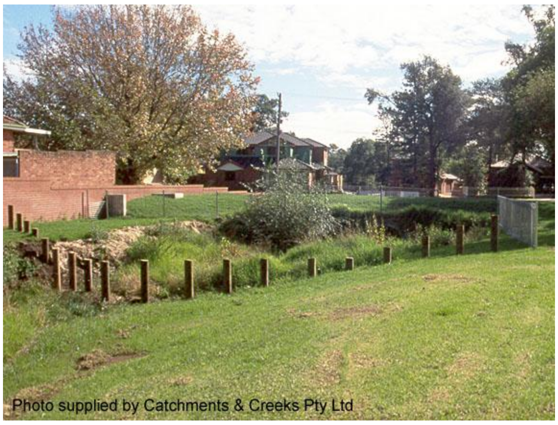
- Unless otherwise agreed, a 'long culvert' is a culvert with a flow travel time in excess of 10 seconds.
- Wherever possible, the potential 'headroom' within a flowing culvert should be maximised for the purpose of reducing the risk of a person being fully submerged as they pass through a culvert.
- Unfortunately, existing services, such as sewerage and water supply pipes, passing over the culvert often limits the height of the culvert's obvert (roof).

Mitigating safety risks associated with waterway culverts

Safety message

Teaching engineering solutions

Pile field (NSW)



Safety poles (NSW)

Introduction

- The first rule of safety management is:

If you cannot make it safe, then make the safety risks obvious

- Most water safety events result from an 'unexpected event', whether that 'event' is a change in flow conditions, or an action that caused the person to enter or fall into the water.
- Management aims should be (i) to remove the risk, if practical, or (ii) to prevent an event from being unexpected.

The four ways of solving a problem

- When looking for a solution to a safety risk, consideration should be given to the four basic options:
  - Remove yourself from the problem.
  - Remove the problem from yourself.
  - Change the outcome of the problem.
  - Change your response to the problem.
- The placement of an inlet safety screen on a waterway culvert should be considered one of the least preferred design options due to debris and flooding risks.

Pile fields

- Pile fields have been used for a variety of purposes in waterways, including:
  - debris collection
  - debris impact poles
  - human safety (to reduce the risk of a person being swept into a culvert)
  - flow diversion system (to guide flows around a channel bend)
  - a buried erosion control system (to limit the extent of bed erosion)
  - outlet energy dissipation.

Safety poles

- Safety poles are similar to a pile field, but simply placed in an arc around the culvert entrance.
- The purpose of safety poles is to give a person something to grab and hold onto, instead of being swept into the culvert.
- Consequently, the diameter of the poles should not exceed 300 mm.

Safety systems installed upstream of culverts

Safety rope (Tas)

Safety ropes

- Safety ropes can be placed across a waterway upstream of a culvert.

Anchor point for a floating curtain (NSW)

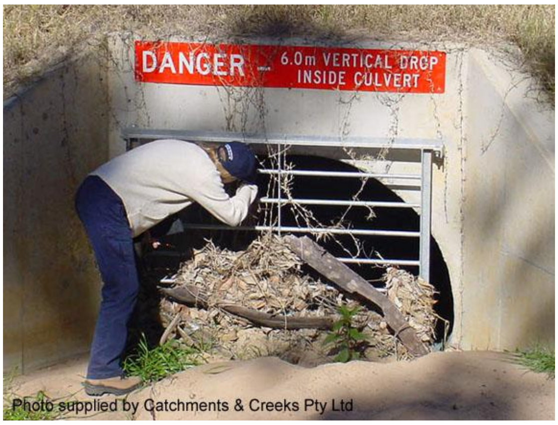
Floating debris curtains

- Floating debris curtains can provide the same benefits as safety ropes, but they can also:
  - trap floating debris
  - direct floating debris into a gross pollutant trap (SQID) located on one side of the channel
  - help guide a floating person to one side of the channel.

Trash rack (ACT)

Trash racks

- Trash racks of various designs have been used in urban drains for many years as part of stormwater treatment systems.
- These trash racks are used in non-fish habitat regions of the urban drainage system.



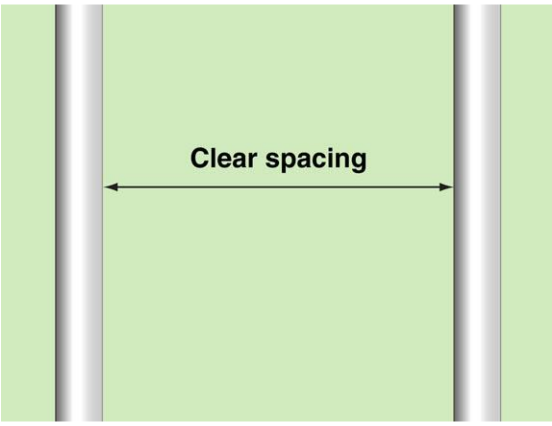
Inspection of an inlet safety screen (Qld)

Inlet safety screens

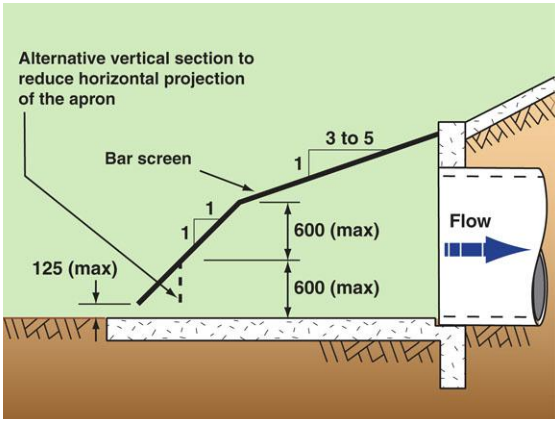
- Inlet safety screens should, in most cases, be considered as a last resort treatment option.
- However, if the safety risks are high, then such screens may be considered essential.
- Ideally, the screen should not be placed flush with the headwall.

Inlet safety screens – Design information

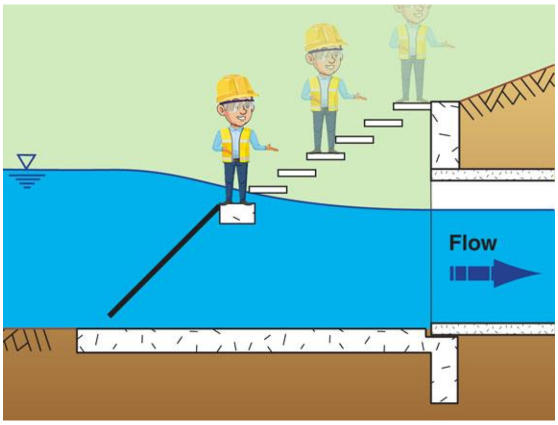
Parabolic inlet screen (Qld)



Clear bar spacing



One possible screen profile (V < 1 m/s)



Inlet screen with step-like egress

Inlet safety screens

- Several studies have been performed on inlet screens and their design.
- Critical design features are:
  - variable slope of the screen with elevation
  - clear spacing of bottom edge from the apron bed
  - clear bar spacing
  - regular horizontal bar to allow egress of a trapped person (maximum 600 mm spacing).

Clear bar spacing

- The clear spacing of bars is based on the head size of the youngest child that is likely to interact with the bars.
- The recommended maximum clear spacing of vertical bars is:
  - 100 mm for pool safety fencing (a crawling child)
  - 125 mm for inlet screens (older than a crawling child)
  - 150 mm for outlet screens (a pre-teen child).

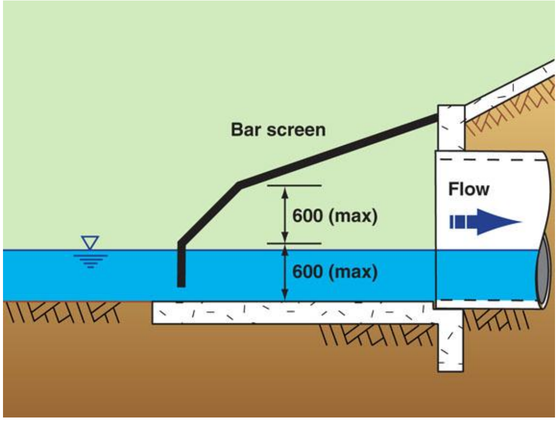
Slope of the screen

- Vertical (less than, or equal to, 600 mm with an approach velocity < 1 m/s)
- 45-degrees (600 to 1200 mm with an approach velocity < 1 m/s)
- 1:3 to 1:5 (V:H) (> 1200 mm with an approach velocity < 1 m/s)
- 45-degrees (less than, or equal to, 600 mm with an approach velocity **> 1 m/s**)
- 1:3 to 1:5 (V:H) (> 600 mm with an approach velocity **> 1 m/s**)

Providing safe egress

- An important design feature of pool safety fencing is the large spacing of the horizontal bars in order to prevent a child climbing over the pool fence and entering the pool.
- However, for inlet safety screens, the aim should be to allow a person to climb the screen, thus removing themselves from the dangerous waters.
- The recommended maximum inclined spacing of horizontal support bars is 600 mm.

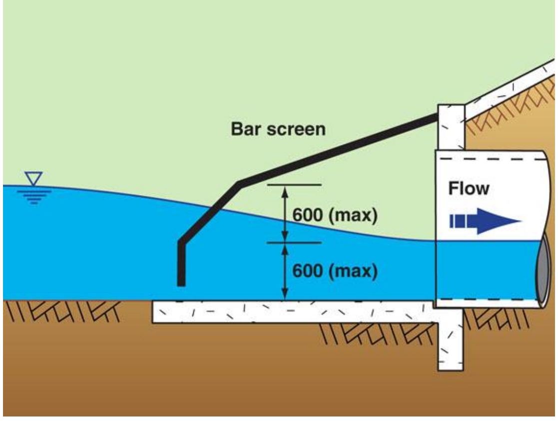
Inlet safety screens – Design information



Low flow

Minimal curvature of the approaching water surface

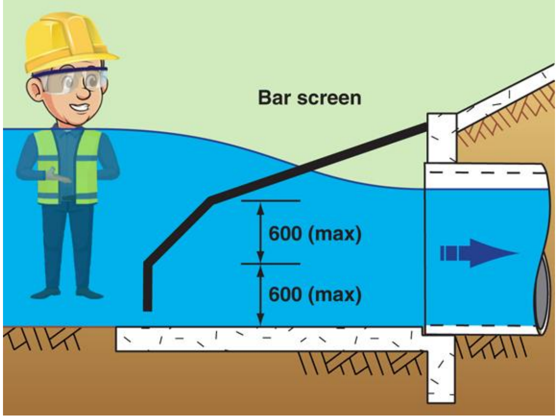
- In order to prevent a person from being held against the bar screen by high-velocity water pressure, the water surface should approach the screen at an angle far greater than 90-degrees.
- If the approach velocity is less than 1 m/s, then the water surface can approach the screen at 90-degrees up to a maximum height of 600 mm.



Medium flow

Mild curvature of the approaching water surface

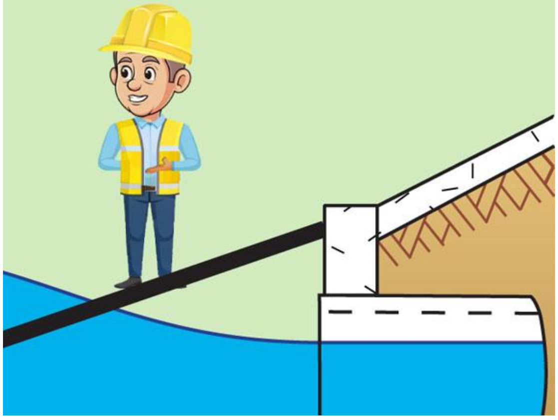
- As the inflow rate increases, there is a draw-down effect that causes the water surface to curve.
- The inlet screen should extend from the headwall such that the approach velocity does not exceed 1 m/s.
- A screen slope of 45-degrees is usually required in order to prevent the water surface from approaching the screen at 90-degrees.



High flow

Significant curvature of the approaching water surface

- As the inflow rate increases even further, the curvature of the water surface also increases, and the slope of the inlet screen needs to flatten to 1 in 3, or even 1 in 5, in order to achieve safe conditions.

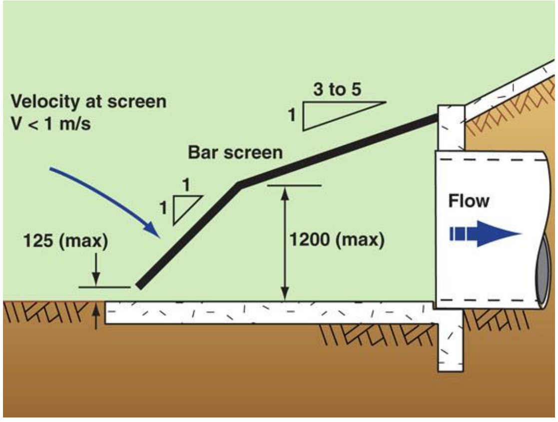


Safe approach angle of water surface

Safe approach angle of water surface

- The water surface should not be allowed to approach the inlet screen at an angle of 90-degrees.
- An approach angle of around 135-degrees would be ideal.

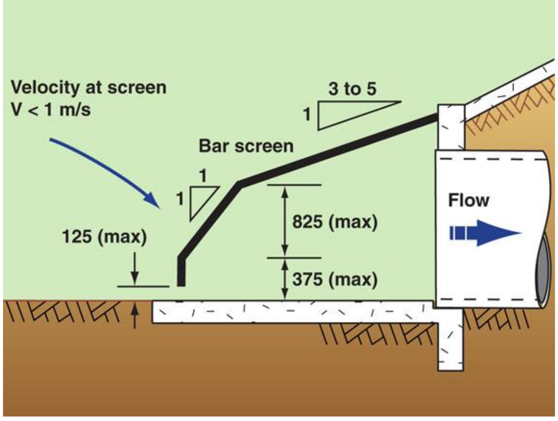
‘Parabolic’ inlet screens



Full sloping leading edge (V < 1 m/s)

Full sloping leading edge

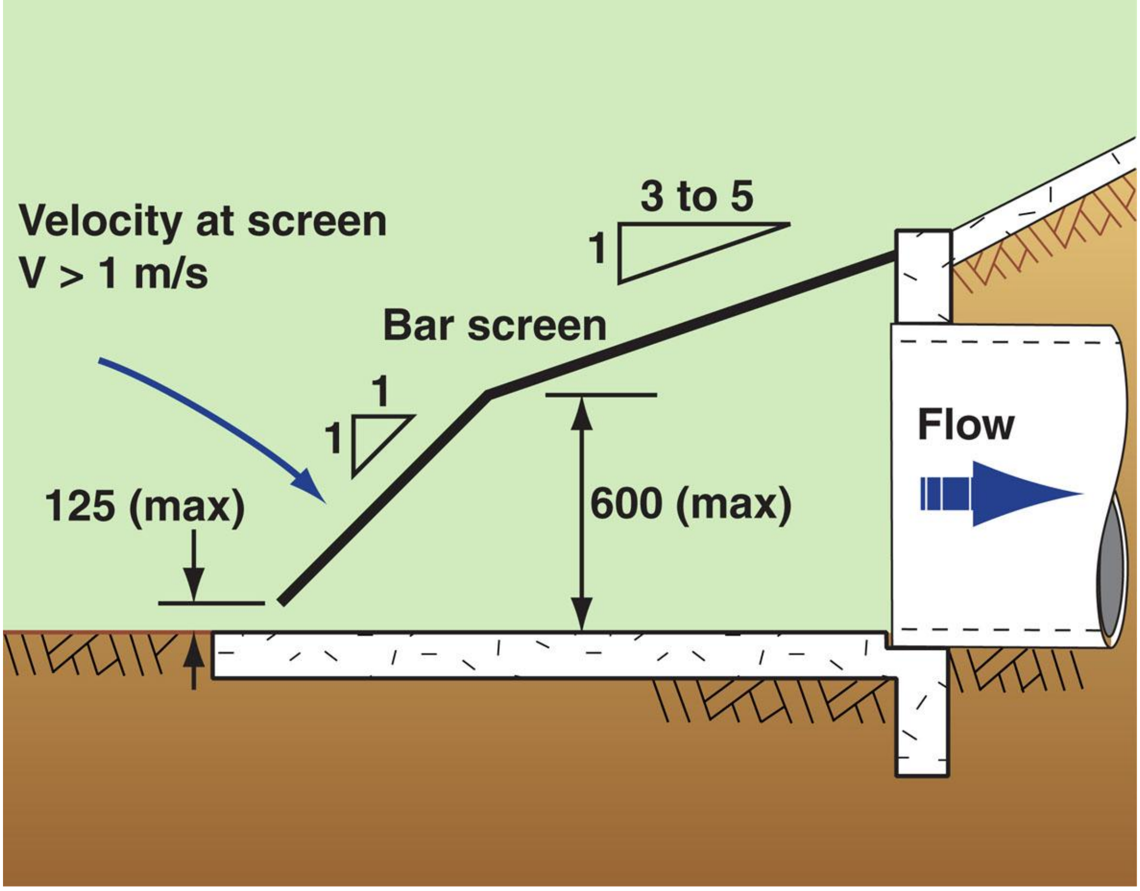
- If the approach velocity can be reduced to under 1 m/s, then a screen slope of 45-degrees can exist up to a height of 1200 mm.



Vertical leading edge (V < 1 m/s)

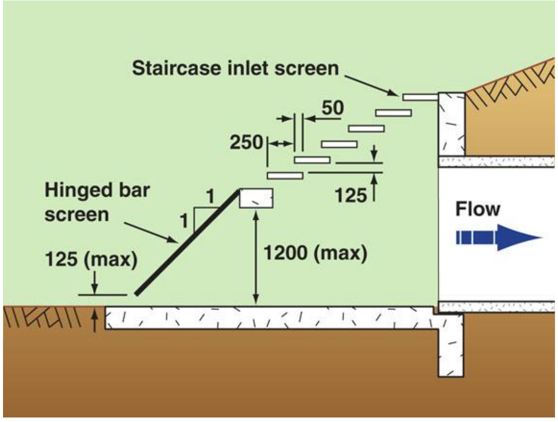
Vertical leading edge

- If the approach velocity can be reduced to under 1 m/s, then a vertical screen can be used up to a height of 600 mm.
- Some guidelines specify a maximum vertical component of 375 mm (left).
- Designers should refer to their local design standards.



Recommended bar screen gradients for approach velocities exceeding 1 m/s

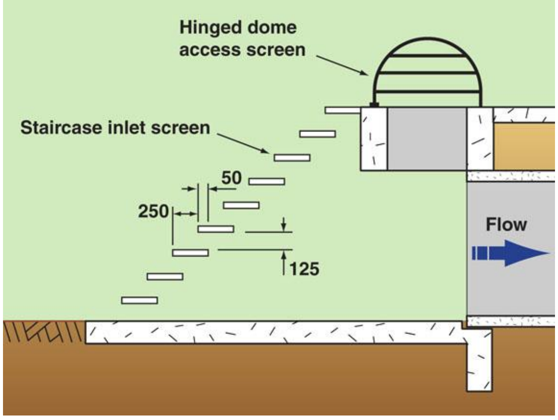
Inlet safety screens – Design variations



Bar screen with upper staircase screen

Staircase screens

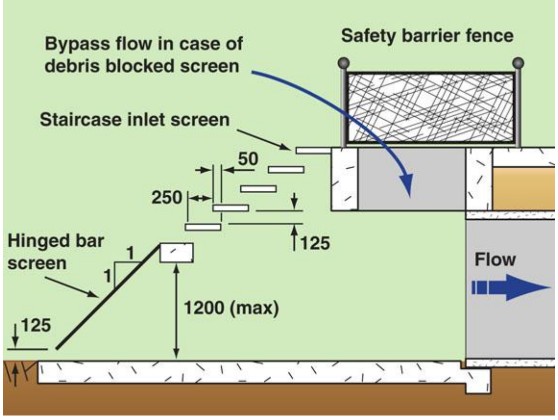
- A bit of lateral thinking can result in an inlet screen taking on the form of a staircase, which can be used by persons to egress the dangerous waters.



Staircase screen with dome inlet

Dome inlet screens

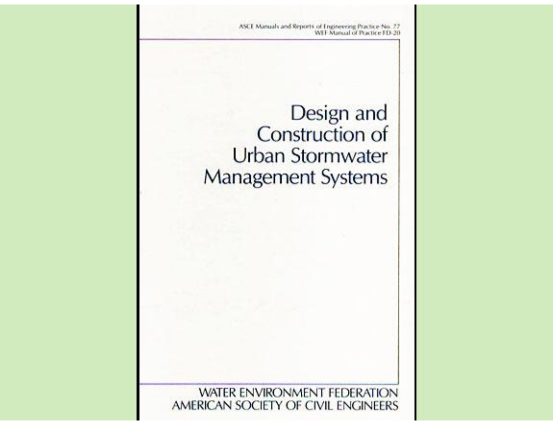
- Hinged dome inlet screens can be placed over access chambers, which can allow maintenance access behind the screen and into the culvert.



Complex culvert inlet screen

Complex culvert inlet screens

- A variety of culvert inlet designs can be achieved in order to satisfy local issues.
- However, inlet safety screens should, in most cases, only be considered as a last resort because of:
  - the risk of the blocked screen becoming a fish barrier
  - increased flood risk
  - increased safety risk to road users due to increased risk of overtopping flows.



ASCE, 1992

Additional design reference:

Guidance on the design of trash racks is provided in '*Design and Construction of Urban Stormwater Management Systems'* (ASCE, 1992).

- Hard copy book.
- ISBN 0-87262-855-8.
- ISBN 1-881369-21-8.

Inlet safety screens – Screen slope

Vertical inlet screen (Qld)

Vertical inlet screen

- Less than 600 mm high.
- Less than 1 m/s approach velocity.

45-degree inlet screen (Qld)

45-degree inlet screen

- Less than 1200 mm high.
- Less than 1 m/s approach velocity.

Parabolic inlet screen (Qld)

Parabolic inlet screen

- Approach velocity greater than 1 m/s

Complex inlet screen (Gold Coast, Qld)

Complex inlet screen

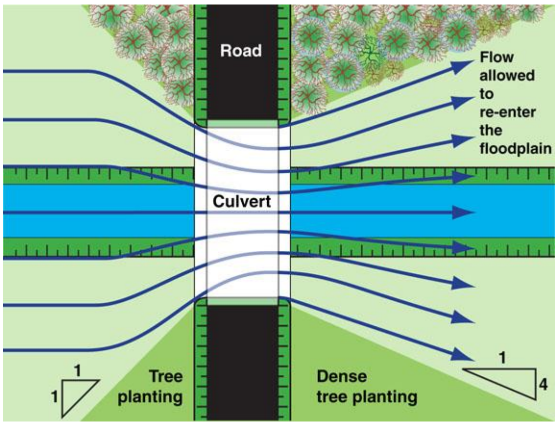
- Emphasis on several options for safe egress given the high public access to the area.

Step 22 - Landscaping

Non-use of flowering plants

Landscaping within the road reserve

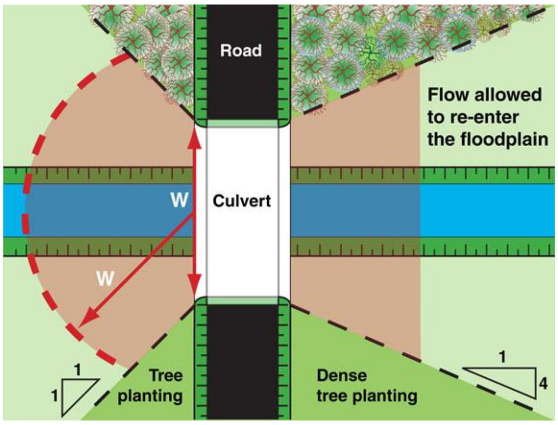
- Plants in and around a road culvert can create habitat for native fauna, assist fauna movement, and reduce soil erosion.
- Plants placed outside the road reserve can consist of those that attract native fauna, for shelter or feeding.
- However, plants placed inside the road reserve should not consist of those that attract fauna (native or non-native).
- Placing flowering plants in a road reserve will increase the risk of road kills.



Ideal flow conditions through a culvert

Riparian vegetation upstream of a culvert

- Riparian plants located near a culvert can:
  - aid fish passage during flood events
  - aid terrestrial passage by providing cover and protection from predators.
- However, these same plants can significantly affect flood levels and increase the risk of debris blockage.
- The 'critical' hydraulic region lies in an arc stretching out from the culvert inlet (refer to Step 23).

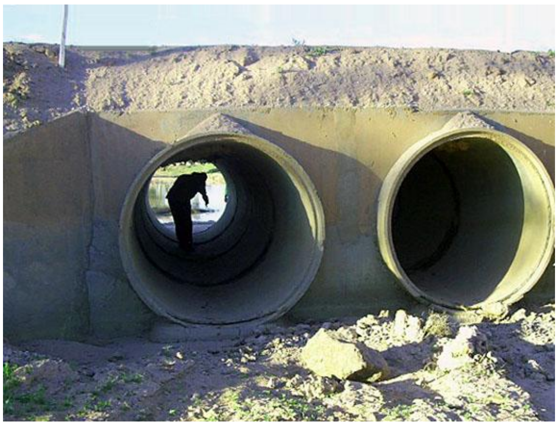


Critical planting zones marked in red

Riparian vegetation downstream of a culvert

- Riparian plants located downstream of a culvert can:
  - aid fish passage during flood events
  - aid terrestrial passage by providing cover and protection from predators.
- Similar to the upstream region, there are regions where dense planting can benefit the culvert hydraulics, and regions where the increased energy loss can cause a rise in local flood levels (refer to Step 23).

Step 23 - Maintenance Access



Post-flood culvert inspection (Qld)

Introduction

- The focus of this document is on the design of waterway culverts that accommodates the need for fish passage.
- The document does not present detailed discussion on the construction or maintenance of waterway culverts.
- The focus of this design step is not on the actual maintenance of culverts, but on the design issues that can affect the maintenance of culverts.

Post-flood screen clearing (NT)

Safety issues

- There are two key issues:
  - the provision of safe access
  - the provision of a safe work environment.
- The primary safety issue is the risk of a maintenance worker becoming pinned against a grate or bar screen while trying to remove flood debris from a culvert inlet.
- Removing flood debris can cause flow velocities to increase, which can act against the maintenance workers.

Missing person search (USA)

Safety of emergency workers

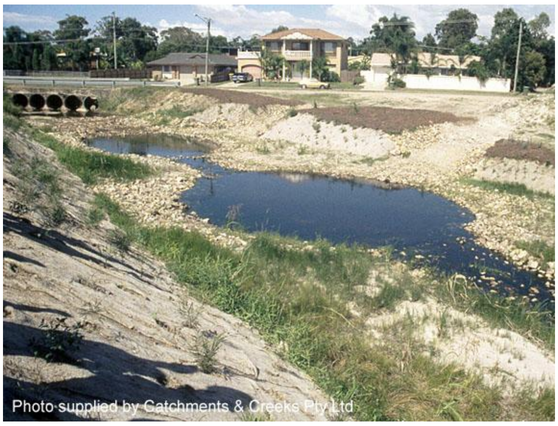
- Emergency and maintenance personnel may need to access a culvert for a wide variety of reasons.
- Obviously, culvert designers cannot think of every possible issue, and cannot prevent accidents that are beyond the influence of the culvert design, but the provision of safe physical access to a culvert inlet and/or outlet, is something that all designers should consider.

Maintenance access ramps

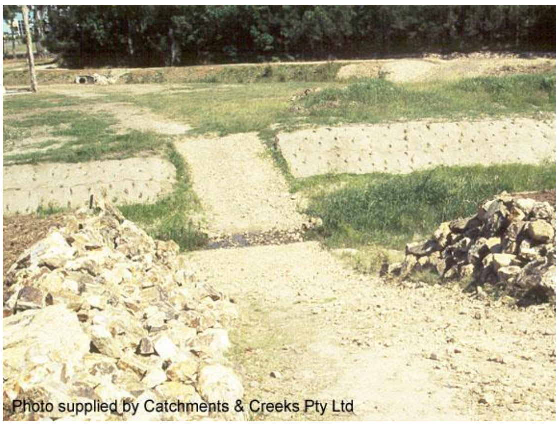
Temporary access ramp (Qld)

Access ramps

- In most government bodies, set funds are allocated to each individual branch of any government agency.
- The funds available for capital works (i.e. culvert construction) are different from the funds available for maintenance activities.
- If a culvert needs an access ramp in order to maintain the structure, then the cost of constructing this access should be carried by the capital works budget, not the maintenance budget, and therefore it should apart of the original design.



Sediment collection ponds (Qld)



Access ramp (Qld)

Recently installed ramp (1997)

Same access ramp shown left in 2003

Same access ramp shown above in 2007

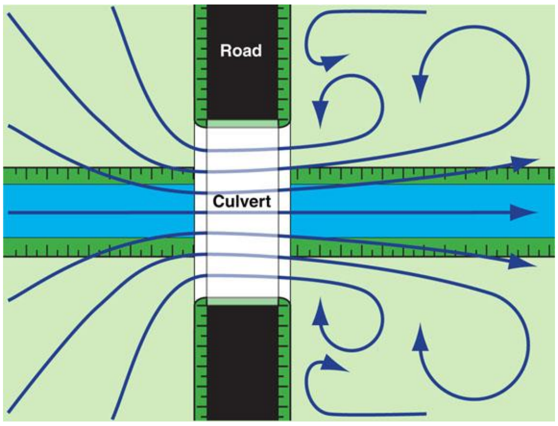
Same access ramp in 2014

Culvert maintenance and its interaction with fish passage

De-silting a long culvert

Introduction

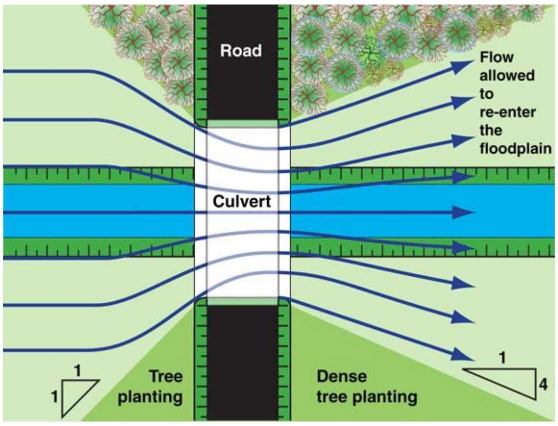
- The deposition of natural bed sediments (substrate) on the floor of a culvert can benefit fish passage; however, excess sediment deposits can become a barrier to fish passage.
- Riparian vegetation can aid fish movement during floods, but excess vegetation can interfere with the culvert's hydraulics, and can add to debris blockages.



Typical flow conditions through a culvert

Clearing flow the path through a culvert

- Significant energy loss can occur as floodwaters pass under bridges and through culverts.
- If strong woody vegetation establishes near a culvert it can increase the energy loss of flood flows and contribute to localised erosion around the structure.
- The selective removal of certain plants can be an essential component of floodplain management.



Ideal flow conditions through a culvert

Using plants to improve flow conditions upstream and downstream of a culvert

- There are some circumstances where dense vegetation planted in specific locations adjacent to a culvert can actually **improve** the hydraulics of the waterway crossing by allowing the gradual contraction and expansion of the flow.
- Floodplain vegetation located inside a 45-degree angle adjacent to the inlet embankment, or a 1:4 expansion adjacent to the outlet of a culvert, could actually benefit the structure's hydraulics.

Permanent maintenance access (Qld)

Access ramps

- The idea of a 'cleared' area of a waterway bank being used as a permanent access ramp would likely meet with objections from Fisheries officers.
- The fact is that access will be needed at some stage, and it is not a sensible use of public money to have equipment craned into a waterway after each flood event.
- If riparian vegetation is maintained each side of the access ramp, then good fish passage is possible across these narrow gaps in the riparian vegetation.

References:

Argue, J R 1960, ‘New structure for roadway pipe culverts’, Journal of the Institution of Engineers, Australia, Sydney, NSW.

ASCE 1992, ‘Design and construction of urban stormwater management systems’, Water Environment Federation, American Society of Civil Engineers, ASCE Manuals and Reports of Engineering Practice No. 77, New York.

Brisbane City Council 2003, ‘Stormwater outlets in parks and waterways’, Version 2, Brisbane City Council, Brisbane.

IPCC 2007, ‘4th Assessment report on climate change’, International Panel on Climate Change, Paris, France.

Keim, S R 1962, ‘The Contra Costa energy dissipater’, Journal of the Hydraulic Division, Proceedings of the American Society of Civil Engineers, Vol.88, No.HY2, March, 1962, ASCE, New York.

Korom, S F, Sarikelle, S and Simon, A L 1990, ‘Design of hydraulic jump chamber’, Journal of the Hydraulic Division, Proceedings of the American Society of Civil Engineers, Vol.116, No.HY2, March/April 1990, ASCE, New York.

Meredith, D D 1975, ‘Model study of culvert energy dissipater’, Journal of the Hydraulic Division, Proceedings of the American Society of Civil Engineers, Vol.101, No.HY3, March 1975, ASCE, New York.

O'Loughlin, E M 1960, ‘Culvert investigations by hydraulic models’, Harbours and Rivers Branch Hydraulics Laboratory, Department of Public Works, Sydney, NSW.

Peterka, A J 1984, ‘Hydraulic design of stilling basins and energy dissipators’, U.S. Department of the Interior Bureau of Reclamation Engineering Nomograph No. 25, Washington, USA.

Queensland Transport 1975, ‘Urban road design manual – Volume 2’, Transport Technology Division, Queensland Transport, Brisbane.

Rice, C E and Kadavy, K C 1991, ‘HGL elevation at pipe exit of USBR Type VI Impact Basin’. Journal of the Hydraulic Division, Proceedings of the American Society of Civil Engineers, Vol. 117, No. HY7, July, 1991, ASCE, New York.

Smith, C D and Yu, J U G 1966, ‘Use of baffles in open channel expansions’, Journal of the Hydraulic Division, Proceedings of the American Society of Civil Engineers, Vol. 92, No. HY2, March 1966, plus various discussions: G V Skogerboe, M Leon Hyatt and M M Soliman ASCE HY5 September 1966 pp255-261; B V Rao, V J Galay and W H R Nimmo ASCE HY6 November 1966 pp 212-215; J M K Dake, S Kar & S Raghunathan, and V C Kulandaiswamy & M Narayanan ASCE Hy1 January 1967 pp 78-85; C D Smith & J N G Yu ASCE Hy4 July 1967 pp 273-275.

Standing Committee on Rivers and Catchments, Victoria 1991, ‘Guidelines for stabilising waterways’, prepared by The Working Group on Waterway Management, Armadale, Victoria.

US Department of Transport 2009, ‘Urban Drainage Design Manual – Hydraulic Engineering Circular No. 22’, Third Edition, Federal Highway Administration, US Department of Transport

US Department of Transport 1983, ‘Hydraulic design of energy dissipaters for culvert and channels’, Hydraulic Engineering Circular No. 14

US Soil Conservation Service (—) ‘Criteria for the hydraulic design of impact basins associated with full flow in pipe conduits’, Water Resources Publication, Technical Release No. 49, National Engineering Publications, Colorado.

Vallentine, H R, Hattersley, R T and Cornish, B A 1961, ‘Low cost scour control at culvert outlets’, Reports 48 and 62, October, 1961, University of NSW, Water Research Laboratory, Sydney.