Performance, Operation and Maintenance Guidelines for Fishways and Fish Passage Works

Justin O'Connor, Martin Mallen-Cooper and Ivor Stuart

June 2015

Arthur Rylah Institute for Environmental Research,
Department of Environment, Land, Water and Planning

Technical Report Series No. 262 for the Water and Catchments Group,
Department of Environment, Land, Water and Planning

Arthur Rylah Institute for environmental research

Department of Environment, Land, Water & Planning

State Government Victoria

Performance, operation and maintenance guidelines for fishways and fish passage works

J. O'Connor, M. Mallen-Cooper and I. Stuart

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
123 Brown Street, Heidelberg, Victoria 3084

June 2015

Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
Heidelberg, Victoria

Report produced by: Arthur Rylah Institute for Environmental Research
Department of Environment, Land, Water and Planning
PO Box 137
Heidelberg, Victoria 3084
Phone (03) 9450 8600
Website: www.delwp.vic.gov.au

Citation: O'Connor, J., Mallen-Cooper, M. and Stuart, I. (2015). Performance, operation and maintenance guidelines for fishways and fish passage works. Arthur Rylah Institute for Environmental Research Technical Report No. 262 for the Water and Catchments Group, Department of Environment, Land, Water and Planning. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Front cover photo: Casey's Weir and vertical-slot fishway, Broken Creek, Victoria (photo: Justin O'Connor).

Printed by Snap Printing

Edited by Organic Editing

ISBN 978-1-74146-561-7 (Print)

ISBN 978-1-74146-562-4 (pdf)

Accessibility

If you would like to receive this publication in an alternative format, please telephone the DELWP Customer Service Centre on 136 186, email customer.service@delwp.vic.gov.au or contact us via the National Relay Service on 133 677 or www.relayservice.com.au. This document is also available on the internet at www.delwp.vic.gov.au

Contents

Acknowledgements....1

Summary....2

1 Introduction....6

1.1 Stream barriers....6

2 Part 1. Fishway Performance Guidelines....10

2.1 Introduction....10

2.2 Setting ecological and fish passage objectives....10

2.2.1 Fish distribution and abundance....12

2.2.2 Migration ecology....12

2.2.3 Migration flows and season....12

2.2.4 Migratory population and biomass....12

2.3 Fishway Performance Standards....15

2.3.1 Biological Performance Standards....16

2.3.2 Hydraulic and Physical Performance Standards....22

2.3.3 Hydraulic Performance Standards....27

2.3.4 Physical Performance Standards....30

3 Part 2: Fishway Operational Guidelines....35

3.1 Introduction....35

3.2 Operational Performance Standards for attraction....35

3.2.1 Very low flows (no spill over weir or regulator)....35

3.2.2 Low flows (with minor spill)....36

3.2.3 Moderate flows (with medium spill)....36

3.2.4 High flows (with major spill)....36

3.3 Operational Performance Standards for passage in fishways....38

3.3.1 Maintaining minimum depth in fishways....38

3.3.2 Operating gates on fishways....38

3.3.3 Periods of operations....38

3.4 Operational Performance Standards for exit of fishways....39

4 Part 3. Fishway Maintenance Guidelines....40

4.1 Introduction....40

4.2 Fishway diagnostics....40

4.2.1 Visible blockages....40

4.2.2 Head loss....41

4.2.3 Turbulence....42

4.3 Fishway inspection checklist....43

4.3.1 Vertical-slot fishways....43
4.3.2 Rock-ramp fishways....43

5 Supporting Material 45

5.1 Supporting Material 1: Fish ecology 45
5.1.1 Victorian fish species 45
5.1.2 A conceptual model of fish movement....48
5.1.3 A model of fish movement 48
5.2 Supporting Material 2: Fishways 49
5.2.1 Background 49
5.2.2 Common Victorian fishway designs....49
5.2.3 Eel passage....56
5.2.4 Culverts and fish passage....58
5.3 Supporting Material 3: Fishway case studies 61
5.3.1 Categorising Victorian fishways 61
5.3.2 Ecological data for fish using vertical-slot fishways....61
5.3.3 Recommended specifications for a vertical-slot fishway located in inland Victorian waters 62
5.3.4 Vertical-slot fishways – coastal rivers....64
5.3.5 Recommended specifications for a vertical-slot fishway located in coastal Victorian waters....65
5.3.6 Rock ramp fishways – coastal 66
5.3.7 Recommended specifications for rock-ramp fishways in coastal Victorian waters....67
5.3.8 Rock ramp fishways – inland....70
5.3.9 Fish locks – inland....71
5.3.10 Fish locks – coastal 73
5.3.11 Fish lifts – inland and coastal 73
5.3.12 Denil fishways 74
5.3.13 Case study synthesis....74

6 Glossary of technical terms 76

7 References 78

Boxes

Box 1. Examples of ecological and fish passage objectives in Victoria 14
Box 2. Proportional passage of a life stage 17
Box 3. Application of Biological Performance Standards to achieve ecological and fish passage objectives..20
Box 4. Flows and fish migration....25
Box 5. Application of Hydraulic and Physical Performance Standards in order to achieve ecological and fish passage objectives 33
Box 6. Summary of Operating Standards for fishway attraction....38

Box 7. Summary of Operating Standards for passage in fishways 39
Box 8. Summary of Operating Standards for fishway exit 39
Box 9. Summary of maintenance rules for a vertical-slot fishway 43
Box 10. Summary of maintenance rules for a rock-ramp fishway 44

Appendices

Appendix 1: Pool hydraulics 83

Appendix 2: Current Victorian fishways 85

Appendix 3: Timing of Victorian fish movements 97

Tables

Table 1. Biological Performance Standards and proposed standards of fish passage with potential methods of evaluation 22
Table 2. Performance criteria and hydraulic standards for fish attraction and exit at fishways 28
Table 3. Hydraulic Performance Standards for passage within fishways 29
Table 4. Physical Performance Standards for passage within fishways 31
Table 5. Performance indicators and standards for fishway maintenance 40
Table S1. Victorian fish species 46
Table S2. Head loss, water velocity and minimum sizes of negotiating fish for a given culvert 58
Table S3. Specifications of some vertical-slot fishways in inland Victoria 63
Table S4. The relationships between fishway hydraulic parameters and fish size for coastal and inland vertical-slot fishways 64
Table S5. Specifications of some coastal vertical-slot fishways 66
Table S6. Specifications of some coastal rock-ramp fishways 69
Table S7. The relationships between fishway hydraulic parameters and fish size for coastal and inland rock fishways 69
Table S8. Specifications of some inland rock-ramp fishways 70
Table S9. Generic parameters for Victorian fish locks 73
Table S10. Summary of learnings from fishway case studies 75

Figures

Figure 1. Conceptual role of the fish passage Actions from the VWMS with likely biological response 9
Figure 2. Relationships between ecological objectives, fish passage objectives, performance standards and fishway design and monitoring. 11
Figure 3. Biogeographic regions of Victoria and common migration patterns 13

Figure 4. Biological Performance Standards for fishways and their application 18
Figure B3.1. Vertical-slot fishway under construction at Lock 9 in 2005 21
Figure B3.2. Carp Gudgeon and other small-bodied fish aggregating below Lock 9 fishway 21
Figure 5. Common Galaxias utilising the boundary layer to move upstream 23
Figure 6. Examples of head loss measurements 24
Figure B4.1 A generic model of flow and fish migration for the lowlands of the Murray–Darling river system 25
Figure 7. Turbulence (white water) is a function of high head loss (high water velocity) and a small shallow area for dissipating water energy 26
Figure 8. Concept of a vertical-slot fishway with middle sill block-outs, which reduce pool discharge and turbulence for optimal ascent of abundant numbers of small-bodied fish. 32
Figure 9. Application of Hydraulic and Physical Performance Standards 34
Figure 10. Optimising fish attraction to a fishway entrance. 37
Figure 11. Build-up of *Azolla* at fishway exit can cause a behavioural barrier. 41
Figure 12. An example of head loss in a rock-ridge fishway 41
Figure 13. Head loss in a rock fishway 42
Figure 14. Turbulence (white water) is a function of high head loss (high water velocity) and a small shallow area for dissipation of water energy 42
Figure 15. Regular clearing of trash racks is required for maintaining attraction flows into fishways and to maintain appropriate head loss (and therefore velocities) at the exit 43
Figure S1. Conceptual layout of a vertical-slot fishway 49
Figure S2. A vertical-slot fishway on Broken Creek in northern Victoria 50
Figure S3. Conceptual layout of a full-river-width rock fishway 51
Figure S4. Conceptual layout of a lock fishway 52
Figure S5. Conceptual layout of a Denil fishway 53
Figure S6. Close-up of internal baffles in a Denil fishway on the Murray River at Mildura Weir. 53
Figure S7. Conceptual layout of a bypass fishway 54
Figure S8. (Left) Pre-cast plastic cones and (right) concrete cones, which break up laminar flow and provide roughness for fish to ascend culverts in Qld 55
Figure S9. A trapezoidal fishway on the coastal Wyong River in central NSW 56
Figure S10. (Top) A prototype elver pass, with nylon brushes that give juvenile eels a rough surface for climbing. (Bottom) A mussel spat rope in New Zealand for climbing galaxias. 57
Figure S11. Some options for improving fish passage at existing culverts 60
Figure S12. Torrumbarry Weir vertical-slot fishway 62
Figure S13. The full-river-width lateral rock-ridge fishway on the coastal Tarwin River in Gippsland, Victoria,

in 2010 ... 67
Figure S14. The full-river-width random-rock fishway on the coastal Yarra River at Dights Falls, Melbourne, in 2012 ... 67
Figure S15. The upper leg of the Wangaratta rock-ramp fishway on the Ovens River in 2010. Note the raised rocks on the bank margins that increase the headwater range of the fishway ... 71
Figure S16. The Hipwell Offtake regulator on Gunbower Creek nears completion in November 2013 ... 72
Figure S17. The four functional phases of a fish lock similar to that at Hipwell Road fish lock on Gunbower Creek ... 72
Figure S18. Fish lift constructed at Tallowa Dam on the coastal Shoalhaven River in south-eastern New South Wales ... 74

Acknowledgements

The Water and Catchments Group (DELWP) funded this project. The authors would like to thank Greg Woodward from the Water and Catchments Group for managing this project and participating in many useful discussions. Thanks to Dennis Lovric and Mark Turner, who were members of the steering committee, and to Tim O'Brien and Matt Jones for providing access to reference material and for helpful discussions. Thanks also to Bec Hemming and Rex Candy (EGCMA), Stephen Ryan (GHCMA), Peter Kelly (Mallee CMA), Dan Borg (Melbourne Water), Anna Chatfield (NCCMA), Anthony Wilson (NECMA), Greg Fletcher (WCMA) and Matt Bowler and David Stork (WGCMA) for providing details on the latest fishway developments in their respective areas.

Summary

Recognising the importance of fishways in restoring native fish populations, a review of the status of fishways within Victoria was undertaken in 2010 (O'Brien et al. 2010) to inform the development of the Victorian Waterway Management Strategy (VWMS) (DEPI 2013). The objectives of the review document were to:

- Review approaches to providing fish passage for new structures
- Review approaches to providing fish passage at existing structures
- Review the management, maintenance and operation of existing fishways
- Develop recommendations for improving fish passage in Victoria.

The review identified a number of strategic issues and provided key recommendations. These recommendations informed the development of fishway policy in the VWMS (DEPI 2013), which contained clear actions including:

- Action 11.9: Develop Performance, Operation and Maintenance Guidelines for fishways and fish passage works.

The objective of the present report is to address Action 11.9. The report is organised into three sections focussed on the development of:

1. Fishway Performance Guidelines
2. Fishway Operation Guidelines
3. Fishway Maintenance Guidelines.

Specific recommendations are unique for particular sites, and this report is intended to provide a framework for developing site-specific guidelines. Supporting documentation is included in order to provide a broader context for the recommendations; this includes a brief review of fish ecology and fishways, and a review of case studies highlighting successful fishways. This has been used to capture key learnings from fishway installations around Victoria and in other states of Australia.

Fishway Performance Guidelines

An important component of fishway design is defining the level at which the fishway is required to perform. Performance can be defined as the reduction in the delay at a structure and the proportion of the migrating population that successfully pass through the fishway. Performance standards for fishways need to be developed on the basis of clear ecological objectives.

Determining the ecological and fish passage objectives

Ecological objectives are generally broad-level ones for the ecosystem or, in some cases, relate to particular species (e.g. species that are threatened or recorded as having declined).

Performance standards

Once the ecological and fish passage objectives have been established for a site, the next step is to establish performance standards. Performance standards are developed in accordance with the fishway's intended function. They fall into two groups:

- Biological Performance Standards
- Physical and Hydraulic Performance Standards.

Biological Performance Standards can be divided into three categories that can also be used to assess if the fishway is meeting its ecological objectives:

1. Fish distribution and abundance
2. Proportional (percentage) passage of life stages of species for various flows
3. Delay in passage of life stages of species for various flows.

These categories can be further subdivided into the phases of attraction, passage and exit. When defining the performance standards for a particular site, it is then necessary to set specific targets for these in order to assess whether the ecological objectives have been met.

Hydraulic and Physical Performance Standards are determined by the ecological and fish passage objectives. They are derived from information on the swimming ability, size and behaviour of fishes. Hydraulic and physical performance criteria can be classified into a number of categories relevant in particular situations, and they include:

- Water velocity
- Turbulence
- Hydraulic gradient
- Roughness
- Depth
- Space
- Length of fishway
- Vectors or flow direction
- Light.

Physical Performance Standards apply to passage within fishways. Examples of physical characteristics of fishways are space and light. Most of the physical characteristics are fixed in design (e.g. pool size), but it is useful to be aware of them because they reflect the ecological and fish passage objectives, and they can be reassessed if these objectives change.

Hydraulic Performance Standards include velocity, turbulence, head loss, hydraulic gradient, and direction of flow (vectors). Hydraulic standards are grouped into the phases of attraction, exit and passage. Conditions for the attraction and exit of fishways are independent of fishway design, and the standards are mostly generic for all sites. Unlike hydraulic standards for the attraction and exit of fishways, which are generic, the standards for passage within fishways are specific to biogeographic regions and the species and size range of the fishes present.

Fishway Operational Guidelines

For a fishway to perform to its design criteria and fulfil the ecological objectives, it is important that it is operated to specifications. Like the Biological, Hydraulic and Physical Performance Standards, operating standards can also be grouped into attraction, passage and exit.

Operating standards for fishway attraction:

1. Low flows through fishway. Flow to the fishway is the highest priority at low streamflows, and flow should pass through the fishway until cease-to-flow occurs i.e. ‘the fishway is first on and last off’.
2. Maintain integrity of fishway flow. Spill over the weir or regulator should not mask fishway flow. Flow over the weir should be adjusted so that turbulence and white water is ~0.5–1.0 m from the fishway entrance.
3. Low flow spill adjacent to fishway entrance.
4. Moderate spill spread evenly across the weir, tapering to the fishway entrance.
5. High flow spill spread evenly across the weir, tapering to the fishway entrance.

6. It is still essential to continue operating the fishway at low volumes of water – small fish are still able to migrate.

Operating standards for passage in fishways:

1. Maintain minimum depth in fishway. This is achieved through weirpool management.
2. Operation of fishway gates for attraction: one gate fully open; follow settings in operations manual.
3. Operation of fishway de-watering gate: either fully open, or fully closed (when zero flow required downstream or when maintenance required).
4. Periods of operation: all year, with maintenance scheduled for brief periods in autumn and winter for coastal fishways, and in early winter for Murray–Darling fishways.

Operating standards for fishway exit:

1. Flow vectors in weirpool do not vary more than 90° from centreline of stream i.e. no recirculation or eddies.
2. Minimum depth leading from exit:

   0.3 m for small-bodied fish (20–100 mm)

   1.0 m for medium- and large-bodied fish (100–1400 mm).
3. Maximum water velocity at exit in weirpool/impoundment:

   0.05 m/s for small-bodied fish (20–100 mm)

   0.30 m/s for medium- and large-bodied fish (100–1400 mm).
4. Trash racks should have <20 mm head loss in order to maintain suitable exit velocities.

Fishway Maintenance Guidelines

For a well-designed and well-operated fishway to perform consistently, it requires regular maintenance. Build-up of debris, movement of the structure over time, weed encroachment, and sedimentation will impact upon the performance of the fishway. Fishway maintenance should include:

- Annual de-watering
- Measurement of internal fishway hydraulics
- Regular fishway inspection
- Debris management
- Fishway diagnostics
- Checking for visible blockages.

The frequency of site visits to inspect the operational fishway should be based on the seasonal fish migrations, with the most frequent inspections being undertaken before and during peak migration season.

Maintenance rules for a rock-ramp fishway:

1. Visually inspect the fishway at the entrance and exit for blockages and ensure it is trash free
2. Visually inspect head loss at each rock ridge to ensure it meets the design specifications
3. Inspect fishway for weed encroachment
4. Inspect fishway for sediment deposition
5. After major flooding, check for any damage to the fishway (movement of rocks) and also to the bank armour.

Maintenance rules for a vertical-slot fishway:

1. Visually inspect the debris load on the trash rack (Fig. 15) and in the vertical slots
2. Visually check head loss and turbulence throughout the fishway
3. Remove the grid deck, de-water, and inspect the internal fishway structure.

1 Introduction

European settlement of Australia has resulted in many changes to the natural environment, including that of aquatic ecosystems. Aquatic habitats have been transformed through the construction of dams, weirs and culverts to provide hydropower, irrigation, navigation, storage, and flood control, with important benefits to the communities they support (Bowman 2002). However, these structures have also modified flow regimes, disrupted sediment transport, altered water quality, and reduced river connectivity (Poff and Hart 2002), to the detriment of the species that live within them (Jungwirth 1998; Lucas and Baras 2001).

All fish species move among habitats, and movement is a key life-history trait that ensures high survival of young, dispersal, and re-colonisation (McDowall 1996). In Victorian inland and coastal rivers, there are longitudinal fish migrations upstream and downstream, and also lateral migrations into and out of wetlands and floodplains (Mallen-Cooper 2000a; O'Connor et al. 2005; O'Brien et al. 2010). Connectivity is a key characteristic of healthy aquatic ecosystems, and fish need to move within their environment for:

- Adult access to spawning habitats
- Dispersal of juveniles to new habitats
- Access to feeding habitats for all age classes
- Re-colonisation of habitats (e.g. post drought)
- Undertaking exploratory movements and habitat selection
- Accessing refuge areas during droughts, floods or blackwater (poor water quality) events.

1.1 Stream barriers

Stream barriers have had severe impacts on many native fish migrations, with fragmented fish populations leading to loss of upstream biodiversity and fish population declines (see reviews in McDowall 1996; Pusey et al. 2004; Lintermans 2007; Humphries and Walker 2013). Dams, weirs and culverts are a particular threat to migratory fish because they act as physical, hydraulic (e.g. fast-flowing water) and behavioural barriers (e.g. long dark tunnels) to fish movements.

Fishways are a major tool in the restoration of fish populations, contributing to stream continuity and connectivity of fish communities worldwide (Jungwirth 1998; Northcote 1998; Mallen-Cooper 1999). In Australia, fishways are becoming increasingly important for restoring migratory pathways for native fish (Stuart and Mallen-Cooper 1999; MDBC 2003; Barrett and Mallen-Cooper 2006; Naughton et al. 2007). In Victoria, there are ~150 fishways on coastal and inland rivers, and there are over 400 fishways in Australia (Mallen-Cooper 1999; Barrett and Mallen-Cooper 2006; O'Brien et al. 2010). There are, however, many thousands of weirs and barriers without fish passage (McGuckin and Bennett 1999; Hardwick 2005; O'Brien et al. 2006; Ryan et al. 2010), so fishways will continue to be an ongoing and powerful tool in river rehabilitation.

Fishways in Australia are largely a success story. Targeted research has led to innovative and cost-effective designs, and monitoring has enabled designs to be refined and further developed. New fishways have passed large numbers of fish, encompassing a diverse range of species and size classes. Recognising the importance of fishways in restoring native fish populations, a review of fishways in Victoria was undertaken (O'Brien et al. 2010). The objectives of the review document were to:

- Review approaches to providing fish passage for new structures
- Review approaches to providing fish passage at existing structures
- Review the management, maintenance and operation of existing fishways
- Develop recommendations for the improvement of fish passage in Victoria.

A major finding of the review was that many of the fishways that had been built in Victoria had not been assessed, so it was not known if they worked or not. Some fishways were no longer functional, and <30%

were considered to be working efficiently. Reasons for this included: limited fishway design criteria, inadequate guidelines outlining optimal performance of fishways, limited maintenance and operation plans, no clear ownership and responsibility for fishways in Victoria, and insufficient specialist input into planning and construction of fishways. It was apparent that despite the extraordinary commitment and enthusiasm shared by stakeholders during the design and initial construction of fishways, the longer-term issues of evaluating performance (to ensure fishways meet the objectives for which they were designed), continuing operation, and ensuring maintenance are hampered by a lack of clear guidelines having statewide standards and coordination.

The review identified these and other strategic issues and provided six key recommendations:

1. Define responsibilities for the provision, performance and maintenance of fish passage
2. Develop procedures and standards for designs, approvals and construction
3. Develop design guidelines for use at small structures
4. Develop Performance, Operation and Maintenance Guidelines for all Victorian fishways
5. Establish a Technical Review Committee
6. Maintain a database of fishways and new instream structures.

These recommendations informed the development of fishway policy in the Victorian Waterway Management Strategy (VWMS) (DEPI 2013), which was designed to provide the framework for government, in partnership with the community, in order to maintain or improve the condition of rivers, estuaries and wetlands so that they can continue to provide environmental, social, cultural and economic values for all Victorians. The strategy outlines the Victorian Government's policy on regional decision-making, investment, management activities and specific management issues for waterways and provides clear policy directions around fishways including:

- Policy 11.6: Waterway managers will identify priority structures for removal in the regional Waterway Strategies.
- Policy 11.7: Passage for native fish in waterways will be maintained or improved by:
  - Minimising further loss of connectivity
  - Improving fish passage at priority sites.
- Policy 11.10: Programs will be put in place to ensure the operation, performance and maintenance of fishways and other fish passage works are monitored and continue to meet best practice standards.

The VWMS also included the following actions specific to fishways:

- Action 11.6: Develop best practice guidelines for the appropriate design, approval and construction of fishways and other fish passage works.
- Action 11.7: Develop a suite of fish passage design guidelines for use at small-scale structures.
- Action 11.8: Develop and implement a statewide program for monitoring the performance of fishways and fish passage works.
- Action 11.9: Develop Performance, Operation and Maintenance Guidelines for fishways and fish passage works.

The objective of the present report is to address Action 11.9 (Figure 1). The report is organised into three sections and is focussed on the development of:

1. Fishway Performance Guidelines
2. Fishway Operation Guidelines
3. Fishway Maintenance Guidelines.

Specific recommendations are unique for particular sites, and this report is intended to provide the framework for developing site-specific guidelines. Supporting documentation is included in order to provide a broader context for the recommendations; this includes a brief review of fish ecology and fishways, and a review of case studies highlighting successful fishways. This has been used to capture key learnings from fishway installations around Victoria and in other states of Australia.

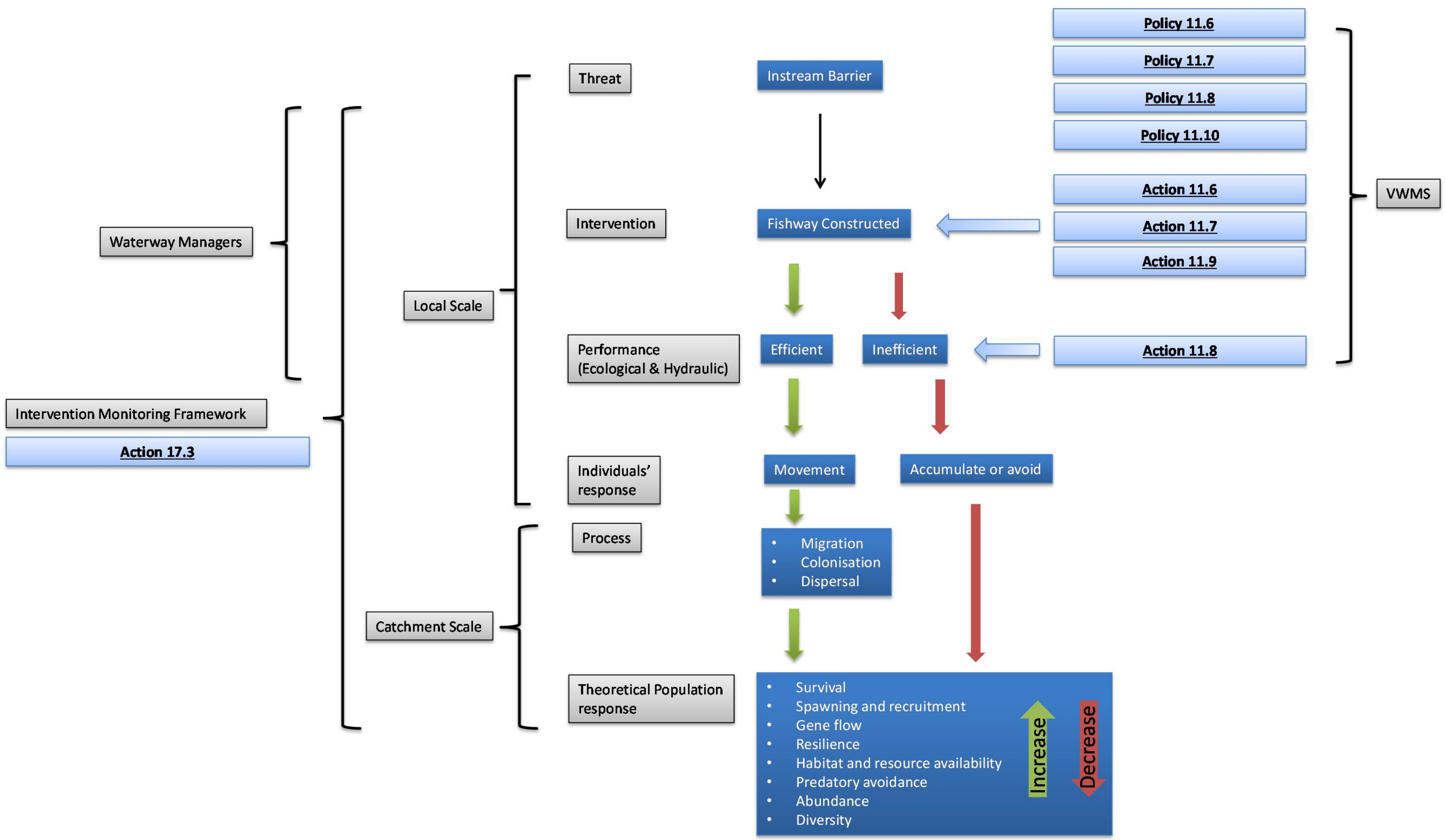

Figure 1. Conceptual role of the fish passage Actions from the VWMS with likely biological response (modified from Jones and O'Connor 2014)

2 Part 1. Fishway Performance Guidelines

2.1 Introduction

An important component of fishway design is defining the level at which the fishway is required to perform. Performance can be defined as the reduction in the delay at a structure and the proportion of the migrating population that successfully pass through the fishway (Kroes et al. 2006). The effectiveness of the fishway is a qualitative description of performance. Effectiveness depends on the ability to attract fish to the fishway entrance, the passability for each target species, and the ecological outcomes of the level of passage achieved (Kroes et al. 2006). This section of the report describes the criteria around which fishway performance can be measured, including generic performance standards that can be applied to all barriers. Case studies are provided to illustrate the development of specific performance standards. This is not a prescriptive set of standards for all Victorian barriers, as the number and type of fish species differ between river systems and along each river. Hence, performance standards for fishways need to be developed for each biogeographic region (e.g. tidal coastal or Murray–Darling lowlands); in practice, however, this generally occurs on a site-by-site basis as fishways are proposed, designed and performance standards applied. The objective of the present document is to clarify the process of developing specific performance standards on a site, river reach or catchment scale, and to provide a basis or starting point for managers, asset owners and scientists.

2.2 Setting ecological and fish passage objectives

Performance standards of fishways need to be developed on the basis of clear ecological objectives. Ecological objectives are generally broad-level objectives for the ecosystem or, in some cases, relate to particular species (e.g. species that are threatened or recorded as having declined). Ecological objectives are mostly generic, such as 'restore fish distribution and abundance', and apply to almost all fishway projects, but they can also be specific if a particular ecological issue has been identified. Examples include: access for adult Macquarie Perch to specific spawning grounds (e.g. Cotter River, ACT (Broadhurst et al. 2012)), restoration of Short-finned Eel populations (e.g. Lake Condah in Western Victoria (Crook et al. 2008)), or preventing fish deaths from poor water quality in wetlands (e.g. Murray River forest floodplains (Jones and Stuart 2008)). (Please note: for the scientific names of species not provided in the text, please refer to Table 1.) See Box 1 for examples of ecological and fish passage objectives from Victoria.

Ecological objectives form the basis of site-specific fish passage objectives. For example, if the ecological objective is to restore fish distribution and abundance at a coastal Victorian stream, the fish passage objectives for a barrier located just upstream from the estuary may be to pass:

- Juvenile Australian Grayling between October and December (entering fresh water following their mandatory marine phase), and
- Adult Australian Grayling between April and June (returning upstream following their downstream spawning migration).

Figure 2 shows the relationships between ecological objectives, fish passage objectives, performance standards and fishway design and lists five information needs required for the development of ecological and fish passage objectives and for designing effective fishways. (Design of fishways is not discussed in this document but is reviewed in detail in another document currently in preparation (Action 11.6 VWMS).) Initially these information needs are to be undertaken as a desktop study by a fish scientist. Quantitative data are preferable, but this should not be a barrier to rapid collation and assessment of the available data. In assembling the information required for informing the ecological objectives, some assumptions will need to be made (e.g. the likely behaviour of a species in a concrete, tunnel-like vertical-slot fishway or a shallow rock-ramp fishway), and these should be stated. In addition to setting ecological and fish passage objectives, the process identifies knowledge gaps requiring further investigation. It is worth noting that a decision on every criterion is included in every fishway, either as an active part of the design process, or by default.

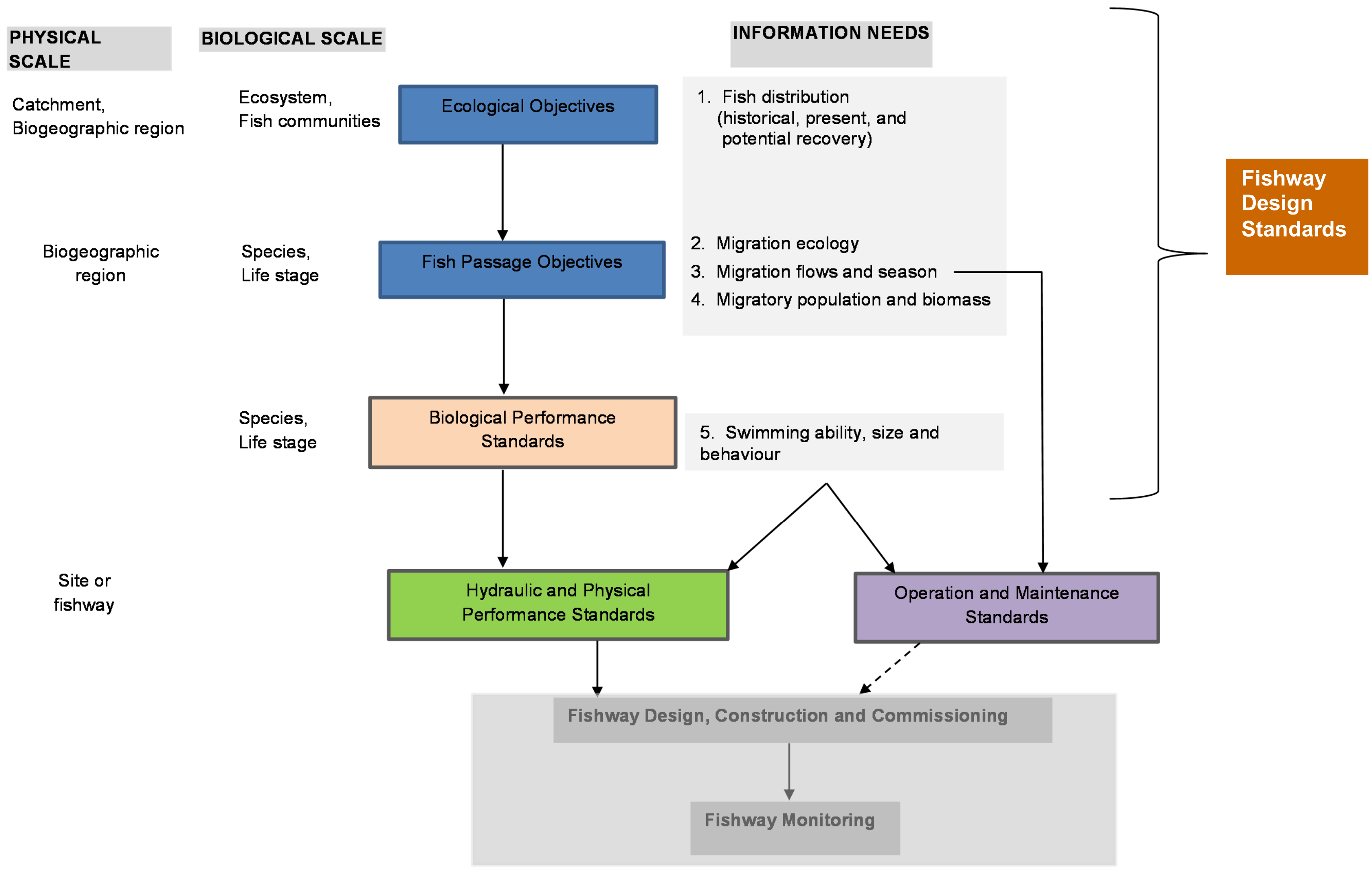

Figure 2. Relationships between ecological objectives, fish passage objectives, performance standards and fishway design and monitoring. (Note that fishway design and monitoring (grey) are reviewed in detail in two separate documents (Jones and O'Connor 2014; O'Connor et al. 2016 in prep.).)

The following describes the first four information needs (identified in Fig. 2) in more detail.

2.2.1 Fish distribution and abundance

The first step in setting ecological objectives is establishing a model of fish distribution and abundance along the river for: (i) historical, (ii) present and (iii) expected recovery post fishway. This is initially a rapid desktop study by a fish scientist and establishes achievable goals for the river and fishway.

Fish distribution identifies the expected species composition in each biogeographic (e.g. coastal or inland) region (Fig. 3). Abundance estimates usually need to be relative or qualitative, coarse categorical measures (e.g. ‘abundant’, ‘common’, ‘rare’, ‘absent’) that provide sufficient detail for identifying key species for fish passage and ecological priorities. At a site scale, this could apply to changes in localised abundance or accumulations near a weir; at a river reach scale, this might apply to changes in abundance upstream and downstream of a barrier; at a catchment scale, this could apply to population recovery.

2.2.2 Migration ecology

The second step in determining ecological and fish passage objectives is to describe the migration ecology of the species listed in Step 1. These are broadly known for all freshwater fish species in Victoria, but research constantly refines and changes knowledge of migration. Migration ecology identifies the direction of movement (e.g. upstream or downstream for spawning), the timing of movement, and the life stages (e.g. adult or juvenile) that are expected in a biogeographic region (Fig. 3); it might include spawning (e.g. downstream migration of adult Australian Grayling to spawning grounds located close to the estuary) or dispersal (e.g. upstream migrations of juvenile diadromous species into freshwater habitats).

2.2.3 Migration flows and season

Many freshwater fish migrate in response to changes in flow and/or water temperature, and different species and life stages have different responses. The range of migration flows can vary between biogeographic regions due to varying fish species (e.g. upland vs lowland species) and life stages (e.g. juveniles near the tidal limit vs subadults in the lowlands). Knowledge of migration flows and season are required for determining the range of flows the fishway is required to operate over and are important when defining fish passage objectives.

2.2.4 Migratory population and biomass

Migratory population and biomass (including the number of fish migrating, the size of the fish migrating, and the spread of the timing of the migration) are factors that influence fish passage design and can be used in developing fish passage objectives. However, at present in Australia the knowledge of migratory populations is poorly quantified and so this has only been used at a coarse, qualitative level (high or low biomass).

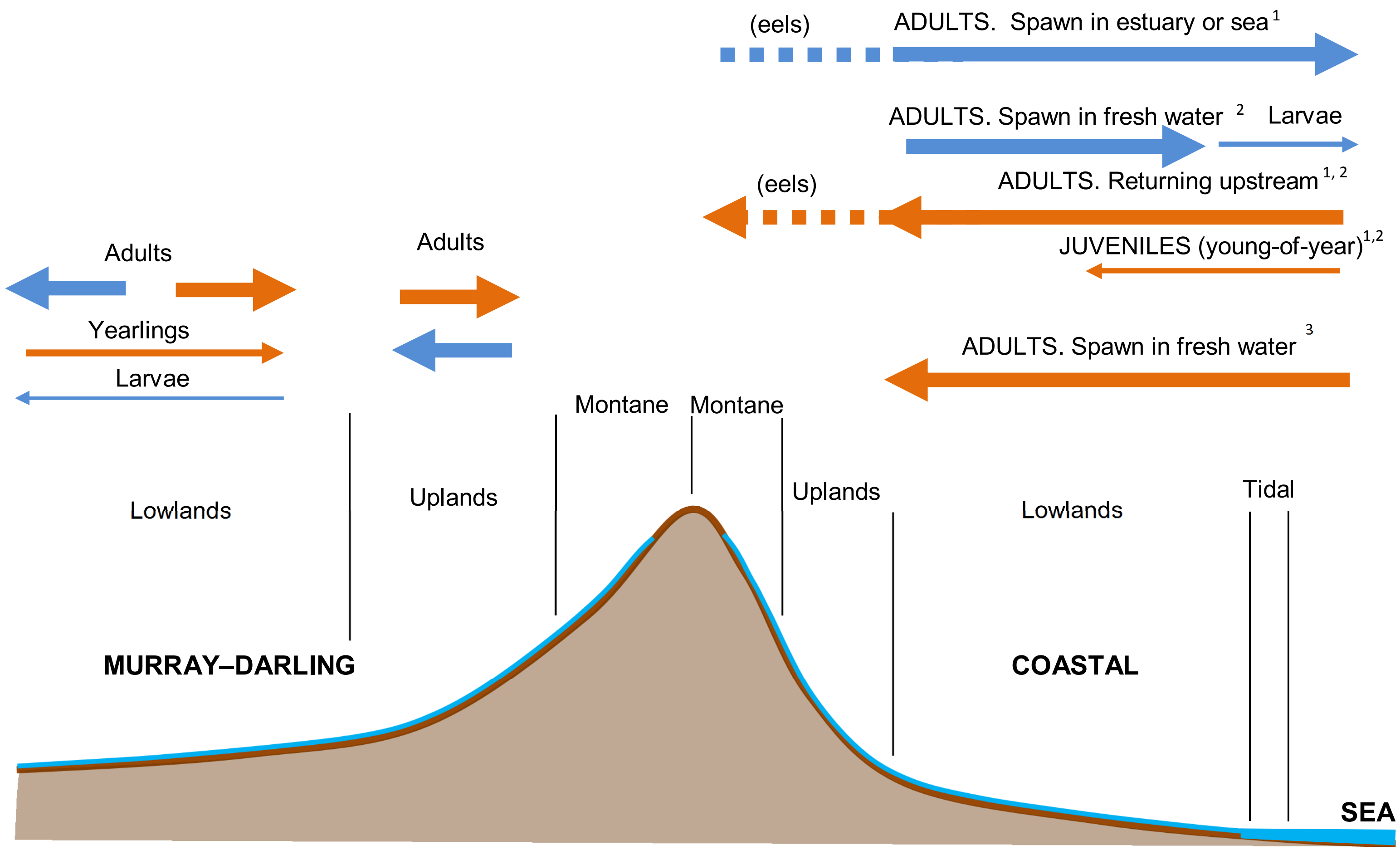

Figure 3. Biogeographic regions of Victoria and common migration patterns. Blue arrows represent downstream migration and orange arrows represent upstream migration. See *Supporting Material 1* for details.

[1] Catadromous (e.g. Australian Bass, Common Galaxias, eels)
[2] Amphidromous (e.g. Australian Grayling)
[3] Anadromous (lampreys are the only example in Australia)

Box 1. Examples of ecological and fish passage objectives in Victoria

The following are examples of ecological and fish passage objectives that have been developed in Victoria for individual fishways. These have generally been at sites of high conservation value. Site-based objectives are influenced by a combination of biological (e.g. species, size class, etc.) and hydrological (e.g. range of flows that the fish migrate over) characteristics, and collectively these sites have common standards within biogeographic regions and provide general guidance regarding the provision of fish passage in similar biogeographical regions.

Coastal Lowlands – Dights Falls vertical-slot fishway

The ecological objective of the Dights Falls fishway was to restore connectivity to upstream habitats for the whole fish community. This included small- and medium-bodied fishes (25–400 mm long). The small fishes (25–150 mm long) were mostly Common Galaxias, Climbing Galaxias, Flat-headed Gudgeon, Australian Smelt, juvenile Short-finned Eels, juvenile Tupong and juvenile Australian Grayling. The medium-bodied fishes (150–400 mm long) were mostly subadult/adult Short-finned Eels, lampreys, Tupong and adult Australian Grayling, with the occasional occurrence of displaced freshwater fish (e.g. Golden Perch and Macquarie Perch). Consideration regarding the passage of the larger adult Short-finned Eels (>400 mm) was also made through the placement of rocks on the bottom of the fishway.

Coastal Tidal – Lower Barwon River tidal barrage vertical-slot fishway

The ecological objectives of the Barwon River barrage fishway were to restore connectivity to upstream habitats for the whole Barwon River fish community. This included a target size range of fishes of 20–400 mm long to cater for largely diadromous species such as the galaxiids, Tupong, Lamprey and Australian Grayling, with consideration being given to some larger fish present such as Bream, Estuary Perch, Short-finned Eel and Mulloway; however, these were not the main passage targets, although the design arrangement catered for their passage at higher flows. To achieve this, the fish passage objectives required that the fishway operates for the full tidal range to enable the movement of fish at all times when there is sufficient flow in the river.

Coastal Uplands – Muddy Creek rock-ramp fishway

This fishway had specific objectives around restoring connectivity to upstream habitats for three *Environment Protection and Biodiversity Conservation Act* (EPBC)-listed species: Yarra Pygmy Perch, Variegated Pygmy Perch and Dwarf Galaxias. All of these species are small bodied (<100 mm Total Length), and none have particularly good swimming ability.

To allow for the passage of these species, the fish passage objective required that the fishway be conservative in velocity and turbulence levels. The rock-ramp fishway was designed with a 70-mm head loss between each pool and a grade of 1:40. The fishway design also incorporated more rock on either side of the low-flow channel to create more of a pool-and-riffle effect that would ensure the fishway is able to operate during a wide range of flows.

Box 1 (cont.). Examples of ecological and fish passage objectives in Victoria

Murray–Darling lowlands – Locks 7, 9 and 10, located on the Murray River

The ecological objective of the Murray–Darling lowlands fishways was to restore connectivity for the whole fish community. Three major size classes of native fishes dominated the community in the Murray River: 30–70 mm long (e.g. Australian Smelt, Unspecked Hardyhead and Carp Gudgeon); 90–600 mm long (juvenile Murray Cod, immature and mature Silver Perch, Golden Perch and Bony Herring; and 600–1400 mm long (primarily adult Murray Cod). The vertical-slot fishways were designed to pass all fish species and most size classes (30–1000 mm long).

Murray–Darling – large floodplains connected to the river – Hipwell Road fishway

The ecological objective of the Hipwell Road fishway was to pass larval, juvenile and adult fish on and off the floodplain. The fish passage objectives for larval and juvenile fish were to provide for the:

- passage of larvae into the forest, and
- passage of juvenile fish (30–100 mm) out of the forest.

The fish passage objectives for adult fishes were to provide passage in and out of the forest for:

- adult small-bodied fish (30–100 mm, e.g. gudgeons),
- adult medium-bodied fish (100–500 mm, e.g. Golden Perch), and
- adult large-bodied fish (500–1000 mm, e.g. Murray Cod.)

The ecological requirements of off-channel specialists also required that the design of the regulators needed:

- to provide fish passage out of the forest for small-bodied fish (30–100 mm) during high and low inflows, and
- to accommodate operations more frequently than only in managed inundations, and to provide flows to replenish forest refuges; ecological windows to be for optimum operation, rather than a continuous range based on percentage.

2.3 Fishway Performance Standards

Following the development of ecological and fish passage objectives, performance standards are developed in accordance with the fishway's intended function. They fall into two groups:

1. Biological Performance Standards. This is the actual measure of fishway function, and may include the movement of a particular species and size class of fish through the fishway, or changes to the upstream fish community (e.g. the fishway is required to pass Australian Grayling with >40-mm fork length).
2. Physical and Hydraulic Performance Standards. These include specific measures of depth, velocity, turbulence, etc. designed to pass a particular species and size class of fish (e.g. the fishway should have minimum cell dimensions of 2 x 3 m to minimise turbulence levels, and maximum velocities of <1 m/s to pass juvenile Australian Grayling).

The development of Biological, Hydraulic and Physical Performance Standards is determined by the fishway's ecological and fish passage objectives (Fig. 2). Biological, Hydraulic and Physical Performance Standards differ from design standards and have a wider range of criteria, including more detail for commissioning new fishways; however, the steps around defining these performance standards are also part of the 'design process' and the need to define 'design standards' for a site. However, this formal process has been carried out to varying degrees and has only recently been undertaken more often in an attempt to get more consistent outcomes. In the context of the present document, it is often necessary to revisit or establish ecological objectives and fish passage objectives so as to define performance standards for existing fishways, as this has often not been formally undertaken.

2.3.1 Biological Performance Standards

The ecological objectives identify: the likely target species; their approximate abundance, distribution and biomass; the recovery potential of species that have declined; and the life stages that are migrating in response to season, temperature and flow. These can be categorised into three categories of Biological Performance Standards, which can also be used to assess whether the fishway is meeting its objectives (Fig. 4).

1. Changes in fish distribution and abundance

   At the site, river reach or catchment scale, fish distribution and abundance can be used to develop specific Biological Performance Standards (Fig. 4). These can apply to a single species, a specific fish assemblage (e.g. fish that migrate between the sea and fresh water), or the whole fish community.

2. Proportional (percentage) passage of life stage of species, in differing flows

   This Biological Performance Standard applies at the site scale. The proportional passage of a life stage determines what proportion of the migrating population needs to be successful in order to achieve the ecological objectives at the site. (Ideally, this should be as close to natural (i.e. 100%) as possible, but realistically it will be less and determined by the ecological objectives (see Box 2).) This can also be used to directly quantify fishway function (Fig. 4). It can be used to assess the three elements of fish passage at a site: attraction, passage (through the fishway) and exit. Quantifying proportional passage through a fishway by comparing species diversity, abundance, or size class between entrance and exits is one of the most common methods of assessment (e.g. Mallen-Cooper 1999; Stuart et al. 2008a). Although attraction and exit are arguably just as important, they are often more difficult to assess and are performed less often.

Box 2. Proportional passage of a life stage

A proportion of the population needs to pass the barrier in order to maintain sustainable populations. Using the proportional passage of a life stage of a species has more sensitivity than using all life stages of a species in one group, because the ecological priorities of adult and juvenile fish can be different, and large numbers of one life stage (juveniles are usually more numerous) can numerically dominate the data. For example, to maintain sustainable populations of Australian Grayling, it may be necessary to pass 95% of adults returning upstream following their downstream spawning migration, whereas the more abundant juveniles moving into freshwater habitats may only require the passage of 90% of fish to achieve this. Proportional passage as a standard can vary, depending on conservation status, distribution and ecological objectives for the target species. For example, a species that has a dispersal migration each summer and is abundant upstream and downstream would have a lower standard of passage than a threatened species with a small population undergoing a spawning migration. Typically, measuring proportional passage success is performed by comparing species composition, abundance and size range at exits and entrances. Determining the proportion of fish that are required to pass to maintain a sustainable population is more difficult to ascertain and will depend on the ecology of the species (e.g. number of eggs in a fecund female or number of dispersing juveniles), the ecology of the migration (e.g. adult spawning or juvenile dispersal migration) and the status of the species (e.g. common or threatened). Significantly, establishing migration patterns identifies the proportional passage of a life stage (e.g. passage of 90% of juvenile Golden Perch) required to achieve the ecological objective.

3. Delay in passage of life stage of species, in differing flows

   Delay in passage is a Biological Performance Standard that applies at the site scale. Migration delay has particular relevance in fish passage, as increased delay at a barrier has three major impacts: reduced or failed spawning, increased predation (from birds and larger fish) and increased legal and illegal fishing. Increased competition for food is another impact, but is much less critical than direct mortality or spawning failure. The consequences of migration delay are determined by the ecological significance of the movement (e.g. typically a delay to a spawning migration may be more detrimental to a fish community than a delay to a dispersal migration of juvenile diadromous fish). Understanding migration ecology enables parameters around migration delay to be set as performance standards that vary between species, life stages and biogeographic regions. For example, small juvenile fish migrating upstream at a tidal barrier have high predation pressure from estuarine fish and need to get into freshwater habitats quickly, probably within two tidal cycles, whereas adult Australian Grayling undertaking downstream spawning migrations should be delayed less than one day. Delay in passage is also used to measure the same three aspects of fish passage: attraction, passage and exit (Fig. 4). This has not been measured in Australia, but it can have a high ecological significance.

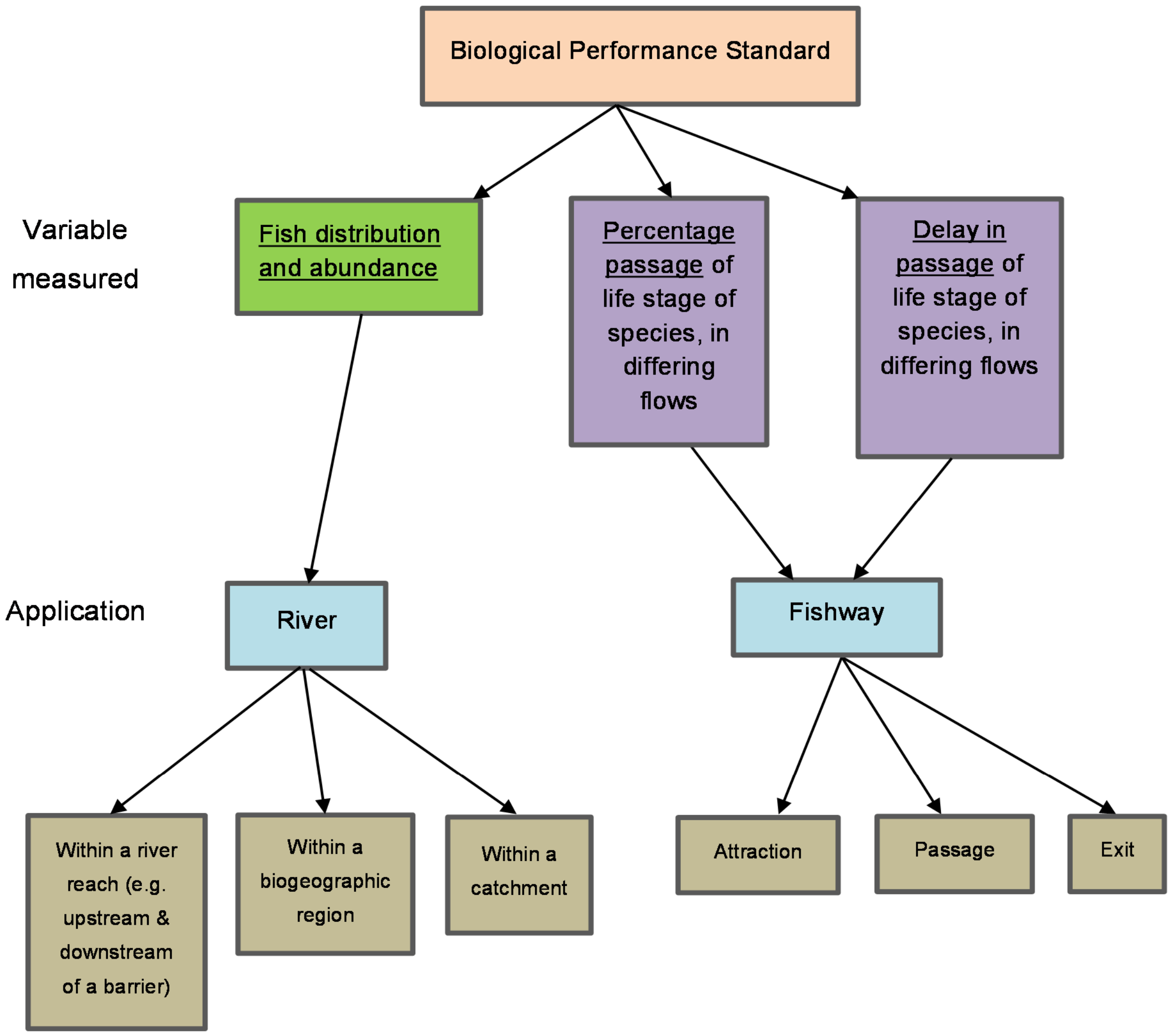

Figure 4. Biological Performance Standards for fishways and their application.

2.3.1.1 Setting values around Biological Performance Standards

When developing performance standards for a particular site, you need to set specific values around them in order to meet your ecological objectives, and these are measurable. Biological Performance Standards at a site are subdivided into 'attraction', 'passage' and 'exit'. Ecological and fish passage objectives, along with performance standards, relate to different physical scales (catchment, biogeographic region, or site) and biological scales (ecosystem, species, or life stage) (Fig. 2).

The four information needs described in Fig. 2 (fish distribution and abundance, migration ecology, migration flows and season, and migratory population and biomass) also contribute to the defining of parameters around Biological Performance Standards. For example, understanding migration ecology and flows identifies two key criteria that are used to define the parameters around the performance standards required to achieve the ecological objective: the 'proportional passage of a life stage' (e.g. passage of 90% of juvenile Golden Perch) and 'migration delay' (e.g. spawning adult Golden Perch delayed by less than 2 days). These have direct ecological relevance relating to the impacts of restricting migration.

Migration flows leads to two criteria for design and for determining performance standards: the 'minimum streamflow' (or level for tidal and floodplain sites) and the 'maximum streamflow' (see Box 4 and *Supporting Material 1: Fish ecology* for details) over which the fishway operates. These are criteria that are always used in fishway design, and although fixed once the fishway is built, they can be used to evaluate the design of an existing fishway with respect to migrating fish, and any new information gathered can be used to refine future fishway designs.

The migration flows at which the target species are migrating are also used to determine the specific design criteria of the upstream and downstream water levels over which a fishway operates – frequently referred to as the ‘operational range’. These levels can differ between adjacent fishways (although the flow range is the same) because of variation in river channel shape. Biological Performance Standards (including the diversity, abundance and size range of fish successfully utilising the fishway) need to be assessed at varying upstream and downstream water levels to ensure the fishway is operating to specification.

Once the Biological Performance Standards of the fishway have been determined (e.g. 95% upstream passage of Australian Grayling adults following their downstream spawning migration), the migration season of the target species of fish can be used to identify the period when the fishway is required to function. Generally, there is some migration all year, but there are some seasons that are critical for spawning or dispersal and that involve a high proportion of the population. These seasons are prioritised. The migration season of the target species of fish is also used for determining the timing and prioritisation of Operation and Maintenance Procedures. See Box 3 for an example of an application of Biological Performance Standards to achieve ecological and fish passage objectives.

Box 3. Application of Biological Performance Standards to achieve ecological and fish passage objectives

Case study from the Murray River Sea to Hume Fishway Program
The following is a case study from the Murray River Sea to Hume Fishway Program as an example of how ecological and fish passage objectives are applied. Other case studies are presented in *5.3 Supporting Material: Fishway case studies*.

The Murray River Sea to Hume Fishway Program was initiated to restore fish passage at 14 weirs along 2000 km of the Murray River between Lake Hume and the sea (Barrett and Mallen-Cooper 2006). The initial objective of the fishways program was to pass whole fish communities ranging from 40–1000 mm long over a wide range of flows, including >99% of flows for large fish (e.g. Murray Cod, Golden Perch) and >95% of flows for small fish (Australian Smelt, Murray–Darling Rainbowfish). Passing such a diverse size range of fishes over this range of flows required specific fishway design criteria. Initially, data on the swimming ability of small-bodied coastal fish species provided accurate criteria for water velocity (maximum 1.4 m/s) and turbulence (45 W/m^3) (Stuart and Mallen-Cooper 1999; Barrett and Mallen-Cooper 2006), and these were combined with large pools (3 m long × 2 m wide × 1.5 m deep) for the passage of large-bodied fish (Baumgartner et al. 2014). The fishways were intensively monitored and passed Murray Cod to 1000 mm long and small-bodied fish >40 mm long, including Murray–Darling Rainbowfish, Unspecked Hardyhead and Australian Smelt (Stuart et al. 2008a; Baumgartner *et al*. 2010). For the first time, the 1v:32h fishway (Fig. 10) with low turbulence passed whole fish communities (40–1000 mm long) and achieved their original ecological objectives. However, an unexpected finding was that Carp Gudgeon, previously considered non-migratory, were also collected at the fishway entrance in their thousands (Fig. 11). These small fish (15–50 mm long) have very poor swimming ability and could not ascend even these low-gradient (1v:32h) vertical-slot fishways. In a great example of adaptive management, the fishway was experimentally operated as a lock, and this demonstrated that small fish passage was possible using this method (Stuart et al. 2008b). Following this, fish locks were introduced as a standard component of Murray River fishways, and dual fishway designs were utilised on the remaining weirs, with a high-flow vertical-slot fishway catering for the passage of large-bodied fish and a fish lock designed to pass small-bodied fish. The objective of the new vertical-slot/lock combination fishways was to enable the passage of fish varying from 12 to 1000 mm long (Baumgartner et al. 2014). Other innovations to be successfully trialled in the Sea to Hume Fishway Program included the use of middle sills, which reduced pool discharge and turbulence and increased the passage of small-bodied fish between 6 and 13 times (Mallen-Cooper et al. 2008; Stuart et al. 2008b) and the use of Denil fishways to pass large-bodied fish. Importantly, this is an example of where monitoring of new fishways has identified what has worked well and what has not worked so well and has led to new innovative fishway designs that have improved the movement of whole fish communities.

Box 3 (cont.). Application of Biological Performance Standards to achieve ecological and fish passage objectives

Figure B3.1. Vertical-slot fishway under construction at Lock 9 in 2005 (photo: A. Richter).

Figure B3.2. Carp Gudgeon and other small-bodied fish aggregating below Lock 9 fishway.

Biological Performance Standards are likely to be refined as ongoing research contributes to a greater understanding of fish ecology. For example, two specific areas of research that would aid in refining standards are: (i) the effect of delays on spawning migrations, and (ii) the extent of predation of small fish at tidal and other barriers.

Using these standards from Fig. 4, some preliminary performance standards are suggested in Table 1. These would need to be developed for the species expected at each site and would likely vary for each biogeographic region in Victoria (Fig. 3). These standards could be generic for all species at a site or they could vary between species at a site, depending on the ecological priority or the conservation value and distribution of individual species. For example, at a site with a threatened species, such as Australian Grayling, there might be a heightened standard of passage (e.g. 98% of juveniles ascend the fishway).

Table 1. Biological Performance Standards and proposed standards of fish passage (modified from Mallen-Cooper 2000b), with potential methods of evaluation.

Biological Performance Criteria	Biological Performance Standard	Evaluation Methods
1. Attraction • Fish locate fishway entrance over operational flow range • Fish enter fishway	(i) Period of delay <1 day (ii) No significant accumulation of fish below weir (for upstream migrants), or above the weir (for downstream migrants) (iii) Passage of 95% of each migratory life stage of each species	Radio-tracking or sonar imaging (e.g. DIDSON sonar), electrofishing PIT tags Trapping
2. Passage • Fish ascend/descend fishway	(i) Passage of 95% of each migratory life stage of each species (ii) No accumulation of fish in fishway	Trapping PIT tags Sonar imaging (e.g. DIDSON sonar)
3. Exit • Fish leave fishway and continue migrating upstream/downstream	(i) Safe passage of 95% of each migratory life stage of each species (ii) No post-passage mortality	Trapping Passive tags/marking and radio-tags

2.3.2 Hydraulic and Physical Performance Standards

The development of Hydraulic and Physical Performance Standards is determined by the ecological and fish passage objectives. They are derived from information on the swimming ability, size and behaviour of fish (Fig. 2). They form site-specific design standards and can also be used to evaluate existing fishways. Hydraulic and Physical Performance Standards are an important surrogate – the logic is that if the correct hydraulic and physical conditions are provided (e.g. water velocity, depth, turbulence and space), then the target species of fish can use the fishway. Hydraulic and physical measurements provide a rapid assessment of performance and are also useful for determining when maintenance is required. Figure 2 shows the relationships between biological, hydraulic and physical, operation and maintenance, and design performance standards, together with the information needs for each group that are required to finalise these on a site basis. All of the information needs are used in fishway design; hence, for an existing fishway the data are usually available for clarifying the ecological and fish passage objectives for the site.

The distribution and migration patterns of the fish population at specific sites will determine the species and size of fish expected at the site, which determines the swimming ability that needs to be accommodated in the fishway design. A knowledge of migration ecology is used to determine two key related criteria: the 'maximum size of fish', which determines the amount of space and depth needed in the fishway, and the 'minimum size of fish', which relates to fish with the weakest swimming ability and determines the maximum water velocity and turbulence. Swimming ability is directly related to body size, and smaller fish are generally weaker swimmers. Smaller fish, however, require less depth, and some species are adept at using boundary layers to move upstream (Fig. 5) (edges of flowing water where water velocity slows adjacent to rough surfaces).

Data on swimming ability lead to specific water velocities and turbulence criteria that are used not only for Hydraulic Performance Standards but also for fishway operation (see *Section 3: Operational Performance Standards*) and maintenance (see *Section 4: Maintenance Performance Standards*).

For swimming ability, an important context is that this varies greatly over distance. For example, over a short distance (such as 5–10 cm), 'burst swimming speed' is used, which can be up to ten times greater than the 'prolonged' and 'cruising swimming speed' that fish use over a longer distance (such as 0.5–10 m). Therefore, for fishways, the burst swimming speed should only be used for short distances (<0.1 m), and not transferred to other hydraulic situations such as culverts and entrance/exit channels, where distances would be >0.5 m.

Swimming ability also includes other aspects such as climbing ability (e.g. of juvenile eels (elvers) or other climbing species such as Broad-finned Galaxias) and the use of boundary layers. These are useful characteristics for attempting to pass upstream, and vary between species and life stages. The following sections expand on these information needs and how they are applied.

Figure 5. Common Galaxias utilising the boundary layer to move upstream.

Hydraulic and physical performance criteria can be categorised into a number of types that can be applied to different situations.

2.3.2.1 Water velocity and head loss

Water velocity is a fundamental performance standard of fish passage and is determined by the swimming ability of the target fish species. Within fishways, maximum water velocity is a common measure. It can be measured using a current meter, but a more rapid field measurement for pool-type fishways that is commonly used is the difference in adjacent water levels, or 'head loss' (Fig. 6). Head loss is a key parameter used directly in fishway design and, through a simple calculation (Appendix 1), can be used to calculate maximum water velocity; hence, it is a very useful hydraulic performance standard.

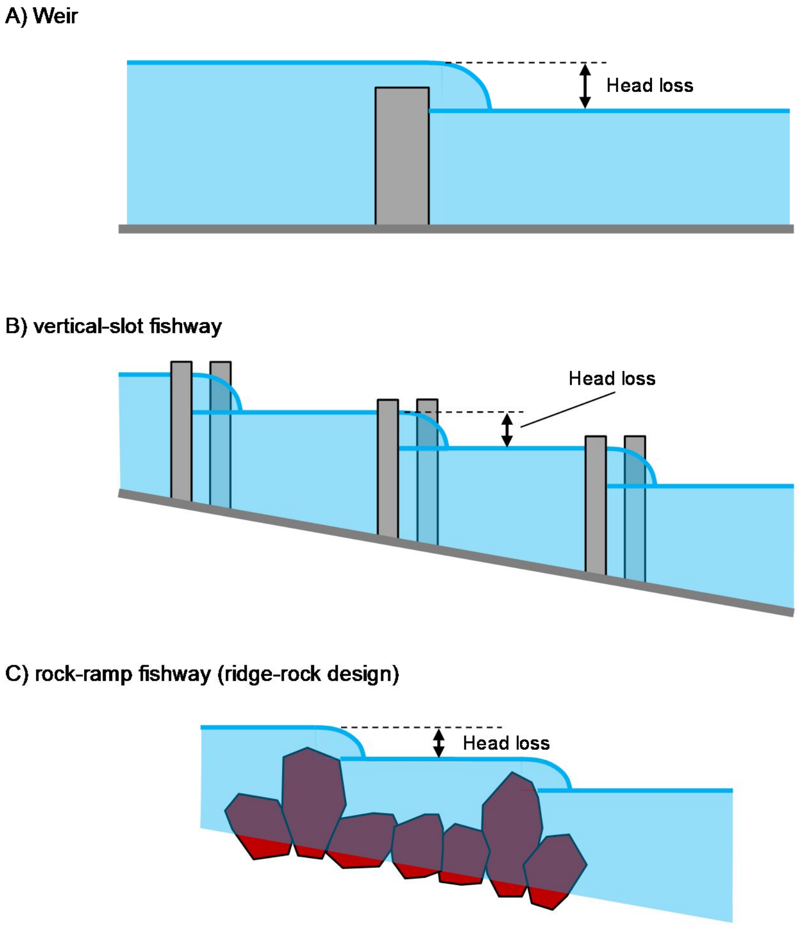

Figure 6. Examples of head loss measurements.

Head loss applies to fishways that have a discreet difference in water level, such as vertical-slot fishways or rock-ramp fishways with ridges that divide the rock ramp into pools. It does not apply to Denil fishways or rock-ramp fishways with random-rock placement.

In long channels and culverts, water velocity reflects the 'prolonged' and 'cruising swimming speeds' required by fish to negotiate upstream. These are measured in the field with a current meter. Water velocity in channels is also modelled on computers with a variety of software; these models generally provide a mean velocity and are poor at evaluating the response of fish to roughness. Significantly, these models need to be linked to the migratory response to flow (see Box 4).

Box 4. Flows and fish migration

Freshwater fish migrate at different times of the year in response to changing flow and temperature. Fish scientists and engineers use this information to design fishways that suit specific river systems and the fish species present. For example, in the Murray–Darling system, some large-bodied fish migrate on peak flows that occur once a year or less frequently, while some small-bodied fish and juveniles migrate on low flows (Fig. B4.1). In coastal rivers at the tidal limit, the recession of flows (i.e. the outgoing tide) and low flows appear to be key periods of migration.

When evaluating fishway design and performance, the maximum streamflows over which the fishway operates need to be viewed in conjunction with the drownout flows of the weir, because if the weir drowns out frequently then the maximum streamflows required for the fishway to operate are lower and therefore less expensive.

It is worth noting that the previously accepted design standard – that fishways are required to operate over 95% of flows – is no longer used, as it eliminates the peak flows, or the low flows in some cases, which are increasingly being regarded as key periods of fish migration. The approach is now to establish the ecological objectives and set 'ecological windows' of optimum operation, rather than a continuous range based on percentage.

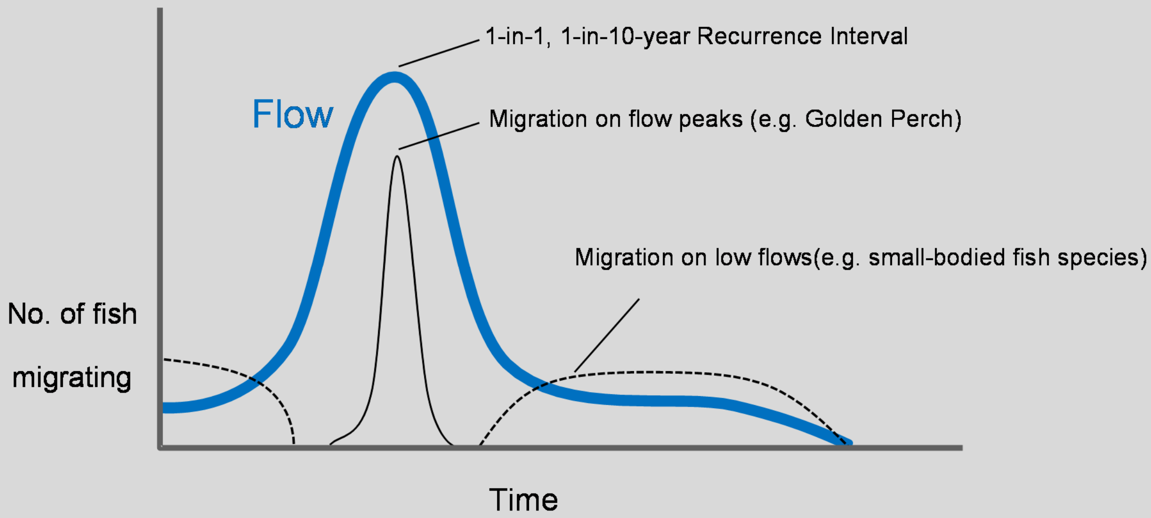

Figure B4.1. A generic model of flow and fish migration for the lowlands of the Murray–Darling river system.

2.3.2.2 Turbulence within fishways

In fishways, fish negotiate water velocity and turbulence (Fig. 7). Turbulence is not measured on site but is calculated from the pool volume (which is a fixed characteristic) and a measurement of depth and velocity, primarily using head loss (see Appendix 1 for example of calculation). In fishways, water velocity and turbulence interact; fish can negotiate a higher water velocity with less turbulence, and vice versa. Turbulence criteria (also called EDF (Energy Dissipation Factor) or Power) are used for: pools in pool-type fishways (e.g. vertical-slot designs); rock-ramp fishways with ridges and pools; resting pools in Denil fishways; and fish lock chambers. Turbulence is measured in units of energy (Watts) per volume of water.

Figure 7. Turbulence (white water) is a function of high head loss (high water velocity) and a small shallow area for dissipating water energy. Here a head loss of 350 mm creates a local area of high turbulence that fish find difficult to navigate.

1. *Turbulence in the river near weirs.* While fish are attracted to turbulence, such as falling water over weirs, they will avoid intense zones of turbulence, seeking adjacent areas of low velocities and low turbulence. Combined with 'flow vectors' (see below), it is also used to assess fish attraction.
2. *Hydraulic gradient.* In fishways that do not have discrete steps or pools, the hydraulic gradient or slope of the water is a measureable hydraulic feature that determines the performance of a fishway. It applies to Denil fishways and rock-ramp fishways that have a random-rock design.
3. *Roughness.* Roughness provides a measure of the variety of water velocities within the channel being used by fish. High roughness, such as is provided by a continuous rocky layer in a stream, provides low water velocities between rocks, thus enabling fish to rest. Roughness is measurable using the wetted perimeter of a cross-section combined with the cross-sectional area of the stream or channel. Fish passage and roughness has not been well quantified as yet, but it still provides a useful qualitative measure of hydraulic performance and fish passage.
4. *Minimum depths.* Fish can be inhibited from swimming through shallow water, as this makes them more vulnerable to predators; hence, minimum depths are needed for the approach, passage and exit from fishways. Depth criteria for approach and exit that are in the river are different from depth within a fishway. In a river, fish will negotiate a shallower depth because it is much wider, whereas in the restricted space of a fishway, fish require more depth.
5. *Depth preference.* Fish can have specific depth preferences that can affect the performance of fishways. Some species are surface species, like Mullet, while others are bottom-species (benthic), like Tupong. The design of a fishway can favour particular species, and this needs to be guided by the biological objectives.
6. *Vectors or flow direction.* Fish are highly responsive to vectors or flow direction, with upstream-migrating fish orienting against the current and downstream-migrating fish orienting with the current. This characteristic is used in the design and assessment of fish attraction and exit to measure the extent to which fish are guided to the fishway entrance.

7. *Response to regulator gates and weirs.* Downstream-migrating fish respond to regulator gates and weirs. Undershot gates cause mortalities of larvae and small fish (Baumgartner et al. 2006), while overshot gates have minimal mortalities but may cause delayed migration (O'Connor et al. 2006). Plunge pools below overshot gates improve survival.

   Sudden accelerations of water velocity, such as at sharp-crested weirs, provide some inhibition for fish passing downstream. If downstream fish passage is an objective, then a gradual acceleration of water velocity towards the crest provides optimal conditions; this is provided by overshot tilt gates or rounded ('ogee') weir crests.
8. *Light.* Lack of light in fishways and sudden transitions of light have varying effects on fish. For some fish, the lack of light is a complete behavioural barrier, whereas for others it provides no barrier. For many native fish, their response to light is well known, although more data are needed on specific minimum light levels (measured in lux).
9. *Noise.* Changes in the acoustics at a fishway compared with those of the natural river may have varying impacts on fish movement. Further research is required in order to elucidate this.
10. *Space.* Fish behaviour is strongly influenced by space in fishways. If there is insufficient space, fish may not enter, or upon entering they may leave. The depth of the cell/pool will be determined by the size of the target species of fish and will need to be deep enough to allow for the target species of fish to swim through the pool, particularly at low headwater or tailwater, when the fishway operating depth is low. The dimensions of the cell/pool of the fishway will also be determined by the size of the target fish species and will need to be large enough for the species to physically fit within the pool and still be capable of swimming and resting.
11. *Length of fishway.* The length of the fishway and the number of pools is determined by the head loss between pools, the length of each pool, and the weir height (differential head). There is no definitive study on the maximum length of a fishway for Australian fish, but studies have shown that, in long fishways, fish may not complete their ascent during daylight (i.e. juvenile galaxias and Bony Herring), and fish descend back down the fishway when light fades (Mallen-Cooper 1999). Large resting pools may facilitate fish overnighting in a long fishway, but more data are required to confirm this behaviour.

2.3.3 Hydraulic Performance Standards

2.3.3.1 Hydraulic Performance Standards for attraction and exit at fishways

Attraction and exit of fishways are grouped together under Hydraulic Performance Standards because they are independent of fishway design, and the standards are mostly generic for all sites. Table 2 lists performance criteria and hydraulic standards presently applied at fishways. Research and fishway assessment is constantly refining these standards.

Table 2. Performance criteria and hydraulic standards for fish attraction and exit at fishway.

Performance Criteria	Hydraulic Performance Standard
Attraction (for both upstream- and downstream-migrating fish) • Fish locate fishway entrance over operational flow range • Fish enter fishway	For upstream- and downstream-migrating fish: (i) Vectors do not vary more than 90° from centreline of stream, i.e. no recirculation or eddies (see Fig. 10c in *Section 3: Operational Performance Standards*). (ii) Entrance is at the 'upstream limit of migration' for upstream migrants or 'downstream limit of migration' for downstream migrants; confirmed by flow vectors, water velocity and observations of zones of intense turbulence. (iii) Minimum depth leading to entrance: 0.3 m depth for small-bodied fish (20–100 mm) 1.0 m depth for medium- and large-bodied fish (100–1400 mm). For upstream-migrating fish: (iv) Entrance discharge is not masked by other flows i.e. 'integrity of fishway flow' is maintained. (v) Minimum head loss at entrance maintained: 20 mm for small-bodied fishes (20–100 mm) 80 mm for medium- and large-bodied fishes (100–1400 mm). (vi) Maximum head loss at entrance not exceeded: 100 mm for small-bodied fishes (20–100 mm) 150 mm for medium- and large-bodied fishes (100–1400 mm).
Exit • Fish leave fishway and continue migrating upstream or downstream	For upstream- and downstream-migrating fish: (i) Flow vectors do not vary more than 90° from centreline of stream, i.e. no recirculation or eddies. (ii) Minimum depth leading from exit: 0.3 m for small-bodied fish (20–100 mm) 1.0 m depth for medium- and large-bodied fish (100–1400 mm). For upstream-migrating fish: (iii) Maximum water velocity at exit in weirpool/impoundment: 0.05 m/s for small-bodied fish (20–100 mm) 0.30 m/s for medium- and large-bodied fish (100–1400 mm). (iv) Less than 20 mm head loss across trash racks.

2.3.3.2 Hydraulic Performance Standards for passage within fishways

Unlike hydraulic standards for attraction and exit of fishways, which are generic, the standards for passage within fishways are specific to biogeographic regions and the species and size range of fish present. Fishways in this context include any structure designed to pass fish upstream or downstream, and hence include weirs and regulators with gates that can be fully opened to re-establish connectivity.

Table 3 lists the Hydraulic Performance Standards for passage within fishways that are presently used in eastern Australia (after Mallen-Cooper 2000b). These relate to depth, velocity, turbulence, hydraulic gradient, and specific criteria for downstream passage. Of these, the maximum velocity (measured using head loss) is a particularly useful standard. The internal hydraulics of vertical-slot fishways are usually consistent and are predictable at a range of flows. By contrast, rock-ramp fishways are more variable, and each rock ramp is hydraulically unique and varies according to river flow. Therefore, Hydraulic Performance Standards, including velocities and turbulence, need to be assessed at varying upstream and downstream water levels in order to ensure the fishway is operating to specification.

In New South Wales (NSW), rock-ramp fishways have a specified maximum head loss of 100 mm, and the theoretical maximum water velocity is 1.4 m/s (Mallen-Cooper 2000b). Within Victoria, many new rock-ramp fishways also use the 100-mm head loss standard. In one respect, this velocity standard is a simplistic performance measure because it is a point source measure and does not account for turbulence or the diversity of hydraulic pathways in a rock fishway. For example, in the shallow marginal areas at the sides of rock-ramp fishways, head loss is not a good indicator of water velocity because roughness has a much greater effect in shallow water (Mallen-Cooper 2000b). Nevertheless, a maximum head loss standard is useful for rock-ramp fishways.

Table 3. Hydraulic Performance Standards for passage within fishways (modified from Mallen-Cooper 2000b).

Hydraulic Performance Criteria	**Hydraulic Performance Standard**
1. Minimum depth in fishway	<u>Vertical-slot fishways, fish locks</u>: • 0.40 m minimum depth (0.5 m desirable) for small-bodied fish (20–100 mm) • 0.75 m minimum depth (1.0 m desirable) for medium-bodied fish (100–650 mm) • 1.0 m minimum depth (1.5 m desirable) for large-bodied fish (650–1400 mm). <u>Rock-ramp fishways</u>: Criteria presently being refined for rock-ramp fishways. Preliminary standards for the 'ridge design', which is a series of pools and ridges, include: • Minimum depth of 0.3 m for 50% of pool surface area, for small- to medium-bodied fish (20–150 mm) • Minimum depth of 0.5 m for 50% of pool surface area, for medium-bodied fish (150–400 mm) • Same minimum depths above and below 50% of gaps in ridge rocks • Same minimum depth providing a continuous path between ridges • Minimum depth of 0.15 m for 50% of ridge-rock gaps for small-bodied fish (20–100 mm) • Minimum depth of 0.3 m for 50% of ridge-rock gaps for medium-bodied fish (20–400 mm). Preliminary standards for the 'random-rock design', which is more like a roughened channel without discrete pools, include a minimum depth: • Of 0.3 m for a minimum 2 m of channel width for small-bodied fish (20–100 mm) • Of 0.4 m for a minimum 3 m of channel width for medium-bodied fish (100–400 mm) • Providing a continuous path of minimum depth from top to bottom of the ramp. Note: there are few data concerning minimum depth in rock fishways for large-bodied fish (>400 mm).

2. Maximum water velocity	Measured using head loss between baffles or pools and needs to be interpreted together with turbulence. Vertical-slot fishways, fish lock entrance or exit. Head loss: • 0.075 ± 0.015 m for small-bodied fish (30–50 mm) • 0.100 ± 0.020 m for small-bodied fish (40–100 mm) • 0.165 ± 0.035 m for medium- and large-bodied fish. (100–1400 mm). Rock-ramp fishways – ridge design • 0.075 ± 0.015 m for very small-bodied fish (15–40 mm) • 0.100 ± 0.02 m for small-bodied fish (40–100 mm). Connecting channels Head loss is not applicable and direct measurement of velocity is used. • <0.03 m/s for small-bodied fish >20 mm • <0.10 m/s for medium-bodied fish >100 mm • <0.30 m/s for medium-bodied fish >300 mm.
3. Turbulence	Not directly measured on site but calculated from head loss and pool volume (see Appendix 1): Vertical-slot fishways • <30 Watts per cubic metre (W/m^3) (calculated using a Cd of 0.7) for small-bodied fish >25 mm • <60 W/m^3 for medium-bodied fish >90 mm • <90 W/m^3 for medium-bodied fish >150 mm. Rock-ramp fishways (ridge-rock design) • <30 W/m^3 in pools. Denil fishways • <10 W/m^3 in resting pools. Fish locks • <20 W/m^3 in lock chamber.
4. Hydraulic gradient	Denil fishways, rock-ramp fishways – random-rock design Headwater depth entering fishway channel ≤ tailwater depth leaving fishway channel, within specified operating range of fishway.
5. Downstream passage	Regulator gates overshot, not undershot, as the latter causes mortality of larvae and juveniles. For weirs, plunge pool downstream of crest provides a depth that is >40% of the difference in upstream and downstream water level (i.e. head differential). For large dams, spilling water at the base of the dam has a gradual deceleration of 1.5 $m\ s^{-2}$ per metre distance. No dissipators or structures on the downstream apron that could impact fish. (Note: these are recent criteria developed in the last 5 years, and many weirs may not comply).

2.3.4 Physical Performance Standards

Physical Performance Standards apply to passage within fishways. Physical characteristics of fishways include space and light. Most of these characteristics are fixed in design (e.g. pool size), but they are useful as they reflect the ecological and fish passage objectives, and they can be reassessed if these objectives change. Table 4 lists standards for pool size, length, slot width or gaps in ridge-rocks of rock-ramp fishways, Denil channel width, and light. All of the parameters (except light) relate to the maximum size of fish; a larger space enables passage of larger fish. In rock-ramp fishways, the minimum gap-widths in the ridges are often greater to avoid blockage by debris. Rocks can also move in these fishways during high flows; hence, the gap widths need to be checked, which is discussed in *Section 4: Maintenance*.

Table 4. Physical Performance Standards for passage within fishways (modified from Mallen-Cooper 2000b).

Performance Criteria	Physical Performance Standard
1. Minimum space	Pool size (internal measurements) • 1.5 m long × 1.1 m wide, maximum fish length of 150 mm • 2.0 m long × 1.5 m wide, maximum fish length of 500 mm • 3.0 m long × 2.0 m wide, maximum fish length of 1200 mm • 3.5 m long × 2.0 m wide, maximum fish length of 1400 mm. Slot width of baffle, or gap in ridge rocks of rock-ramp fishways • 0.10 m, maximum fish length of 150 mm • 0.15 m, maximum fish length of 450 mm • 0.25 m, maximum fish length of 650 mm • 0.30 m, maximum fish length of 1000 mm • 0.35–0.40 m, maximum fish length of 1400 mm. Denil channel width (internal) • 0.325 m, maximum fish length of 600 mm • 0.400 m, maximum fish length of 1200 mm. Length – will vary depending on the species
2. Light	>200 lux

In vertical-slot fishways, the slot width specifically determines the maximum size of fish that can use the fishway, and the slot needs to be large enough for the largest species to physically fit. For example, a 1.4-m-long Murray Cod might have a head width >0.3 m and will therefore require a slot width greater than this. The dimensions of fishways also need to allow for other more specific factors associated with swimming, such as the larger the fish then the greater the amplitude of the fish's tail beat; thus, a 1000-mm long fish requires a minimum tail beat amplitude of 0.3 m, and these fish also produce a strong propulsion wave. The physical size of a fishway may sometimes be determined by the number and size of fish that need to utilise it in a given day (if the migratory population is large enough to warrant this).

The width of the vertical slot or gaps between rocks in a rock fishway or the Denil channel width also influence hydraulics and fish passage. Slot width, combined with head loss and depth, determine the overall discharge of water from the fishway, and hence the turbulence within each pool. Where there is a need to pass large fish (e.g. Murray Cod >1 m long), there is also a need to widen the slots; e.g. at Mullaroo Creek (north-western Victoria) the slot widths of a new vertical-slot fishway are 0.35 m. The issue with wider slot widths is that they require larger pools to dissipate the energy, especially if small fish are also migrating through the fishway, and this usually results in an increase to capital cost. The solution is to use 'keyhole' slots (Fig. 8) (variable slot width and shape), so that the same fishway can pass small and large fish without increasing turbulence and the required pool size (Mallen-Cooper et al. 2008).

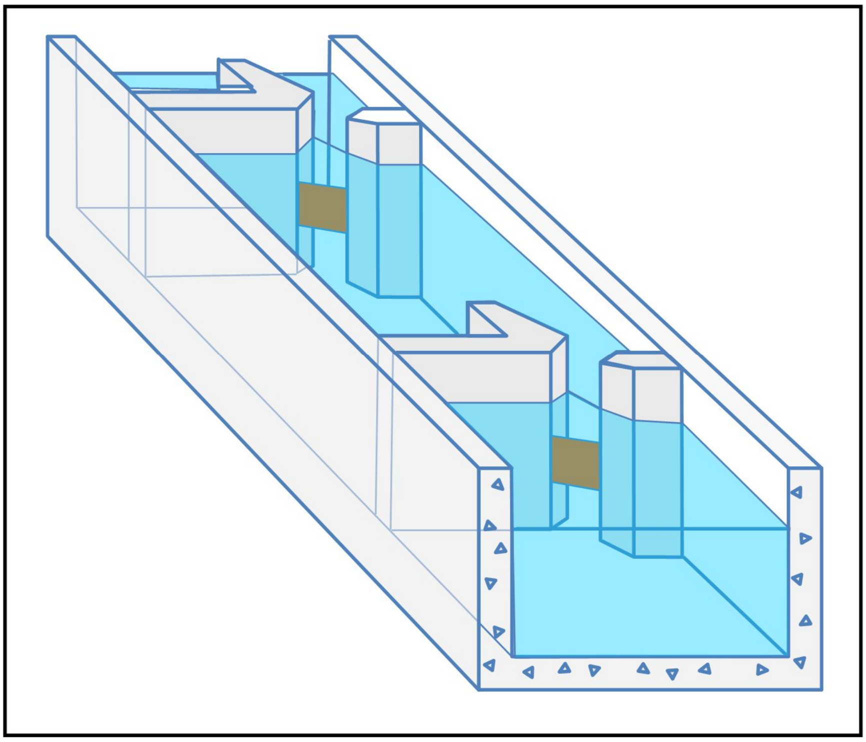

Figure 8. Concept of a vertical-slot fishway with middle sill block-outs, which reduce pool discharge and turbulence for optimal ascent of abundant numbers of small-bodied fish (e.g. 15+ mm long; drawing: M. Mallen-Cooper).

Keyhole slots and variations on this theme, such as bottom or middle sills (slot block-outs) (Fig. 8) are a major innovation and have been successfully incorporated into many new coastal and Murray–Darling Basin fishways. Middle sills or changing slot shape also have great potential to be retrofitted to existing fishways in order to pass much smaller fish, which can be highly abundant (Baumgartner et al. 2014). See Box 5 for an example of an application of Hydraulic and Physical Performance Standards set in order to achieve ecological and fish passage objectives.

Box 5. Application of Hydraulic and Physical Performance Standards in order to achieve ecological and fish passage objectives

Case study from Dights Falls vertical-slot fishway

The following is a case study from the Yarra River as an example of how Hydraulic and Physical Performance Standards are applied. Other case studies are presented in Appendix 3 as *Supporting Material*.

Maximum head loss from pool to pool

Head loss per internal fishway slot at the maximum overall head difference is 76 mm in order to allow the passage of smaller fish. This provides a slot velocity of 0.85 m/s, with a discharge coefficient of 0.7. The flow velocity at the fishway entrance shall be 1.0 m/s to improve fish attraction.

Slot width

150 mm. Fishway flow 11.1 ML/d. Upper part of slot (above depth of 1.0 m) to be widened to 200 mm, provided that it does not increase turbulence.

Turbulence in the pools is to be limited to allow 30-mm fish to pass

A maximum of 25 W/m^3.

Pool size required in order to conform to these turbulence limits

1.8 m wide × 2.1 m long. May be varied to maintain cell turbulence at 25 W/m^3. Turning pools to have a volume of 2.5 times the normal cell volume. Resting pools to be provided every 1-m rise, with a volume of four times the normal cell volume.

The slope and pool dimensions of the fish passage to maintain a constant water depth within the fish passage

Will be 1:30.3 to maintain a constant depth with a 76-mm head loss between pools, given a pool length of 2.1 m and a baffle thickness of 200 mm. May vary if cell dimensions or baffle thickness change.

Absolute minimum design water depth throughout fish passage

Minimum 1.0 m.

Depth of rock layer on floor to create low velocities between the rocks in order to aid a range of migratory biota as well as small fish

A 150–200-mm deep continuous rock layer at the bottom of each fishway, either loose or embedded in floor.

Wall finish

Walls to be finished with a rough surface (a minimum of sand roughness).

2.3.4.1 Utilisation of Hydraulic and Physical Performance Standards in evaluating fishway performance

Hydraulic and Physical Performance Standards are used in two types of fishway evaluation (Fig. 9), where:

1. The design background is known – including ecological and fish passage objectives – and hydraulics are used to assess function as per the design specifications.

This applies to: (i) wet commissioning of fishways, (ii) operation and maintenance, and (iii) biological assessment.

2. The design background is unknown – and hydraulics are used to assess function.

This can apply to any fishway, but generally applies to older fishways, and can be used to assess potential function and the need for modifications or replacement.

The second type of evaluation requires the design process to be revisited, with an evaluation of the ecological objectives, fish passage objectives and a detailed analysis of the hydrology (Fig. 9); from this process, specific hydraulic standards are developed. This process will be described in more detail in the Design Guidelines (O'Connor et al. 2016 in prep.); the present report covers the first type of fishway evaluation, in which the hydraulic standards are known (Fig. 9).

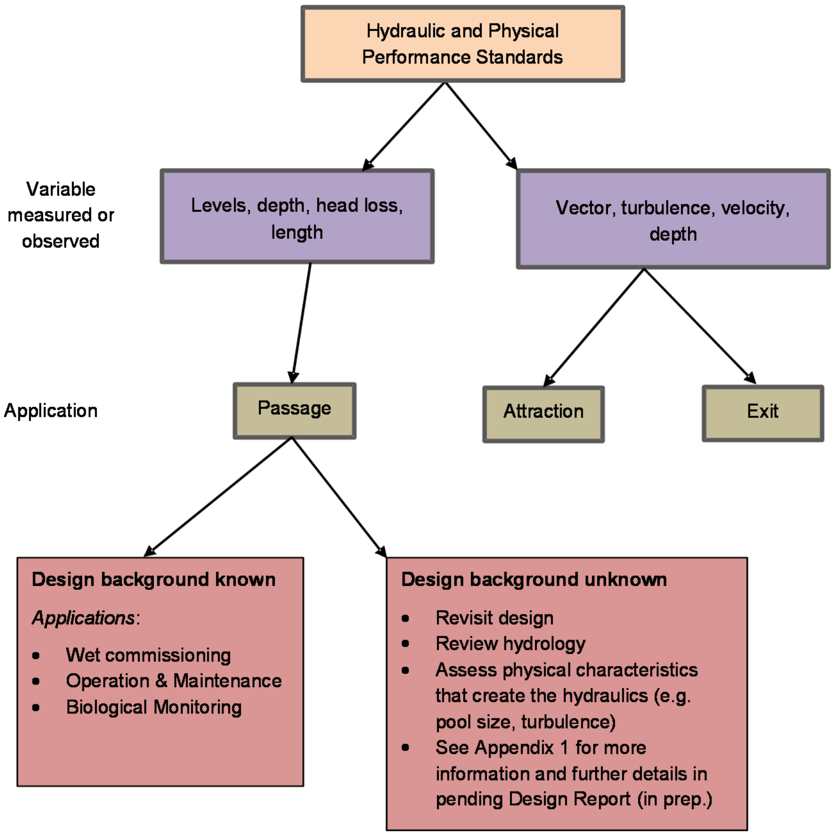

Figure 9. Application of Hydraulic and Physical Performance Standards.

3 Part 2: Fishway Operational Guidelines

3.1 Introduction

For a fishway to perform to its design criteria and fulfil the ecological objectives, it is important that it is operated to specification. This section of the report outlines the key features in operating fishways. It provides solutions for more effective fishway operation, with a series of practical rules to help operations staff manage fishways in order to protect and conserve native fish populations.

Optimal operation of a fishway facility is best achieved when personnel have an appreciation for the importance of providing fish passage and a clear understanding of correct fishway operation. The more complicated the operation requirements (e.g. multiple exit gates), the more likely the fishway will not be operated as intended.

Often, the most critical fish passage timing coincides with the worst conditions of rain, rapidly changing stream flow, and debris. Staff responsible for the operation of fish passage facilities are also often responsible for other infrastructures that are stressed and require attention at the same time. The intent of these guidelines and standards is to enable staff to proactively manage fishways so as to reduce workloads in peak periods.

An operations manual should be an outcome of the design process; if not, this can easily be developed retrospectively. Development of an operations manual needs to include the asset owner and operator of the facility to ensure the manual is practical and realistic.

Like the Biological, Hydraulic and Physical Performance Standards in the previous section, Operation Standards can be grouped into 'attraction', 'passage' and 'exit'. They only apply to weirs, regulators or fishways that are adjustable in some way or have moving parts, such as gates. They do not apply to fixed structures and fixed weirs; these can be assessed for performance using the criteria in the previous section and modified if necessary, or they may require maintenance, but as they are fixed they do not have any operation requirements.

3.2 Operational Performance Standards for attraction

All of the principles outlined for Hydraulic Performance Standards in Table 2 are applied to set operational standards for attraction. In summary, the principles are:

(i) No recirculation or eddies (i.e. flow vectors do not vary more than 90° from centreline of stream)

(ii) The entrance is at the 'upstream limit of migration' for upstream migrants

(iii) The entrance discharge is not masked by other flows (i.e. 'integrity of fishway flow' is maintained).

When applying these principles to operational standards, they need to be considered at a range of streamflows (Fig. 10).

3.2.1 Very low flows (no spill over weir or regulator)

In streams with very low flow, the priority is to direct these flows through the fishway and keep the fishway fully open until zero flow is going downstream, at which time the de-watering gate is fully closed. In streams with cease-to-flow periods, this results in a 'first on – last off' protocol, whereby the fishway receives the first and last flows.

If the upstream water level drops to the point at which only very shallow flows are passing through the fishway, it is still essential to continue operating the fishway. Low volumes of water passing through a fishway, although limiting the movements of larger-bodied individuals, can still allow small fishes to migrate past a structure. Fishways should be allowed to operate at any water levels in the channel. In some cases, low water volumes can even provide better opportunities for movement, as water velocities are reduced due to friction. Low flows such as these can be important in providing fish passage for some smaller species.

Although outside direct operational standards, it is desirable in streams with allocated environmental flows that these are not less than the minimum fishway flow requirement.

3.2.2 Low flows (with minor spill)

Attract fish to the fishway entrance by manipulating weir gates so that flow is adjacent to the entrance but not masking fishway flow (Fig. 10a). In general, the gate closest to the fishway should allow only a small amount of water through. The next gate should allow a large amount of water, and subsequent gates should allow a decreasing amount of water to pass. In this way, fish are attracted to the fully opened gate(s) and would have a high probability of locating the fishway entrance, due to the low flow coming from the gate directly next to the fishway.

3.2.3 Moderate flows (with medium spill)

Adjust weir gates so that flow is spread evenly along the weir and tapered toward the fishway entrance so as to not mask fishway flow. The flow coming over the weir should not create recirculation or create alternate zones where fish aggregate (Fig. 10c and d).

3.2.4 High flows (with major spill)

Adjust weir gates to spread flow evenly across the weir/regulator, ensuring that 'integrity of fishway flow' is maintained and not masked by other flows and turbulence. Taper flow to the fishway entrance (Fig. 10e). More protection of fishway entrance flow may be required. Gates should be adjusted so that turbulence and white water is ~0.5–1.0 m from the fishway entrance; fish will swim along the edge of fast-flowing water directly into the fishway.

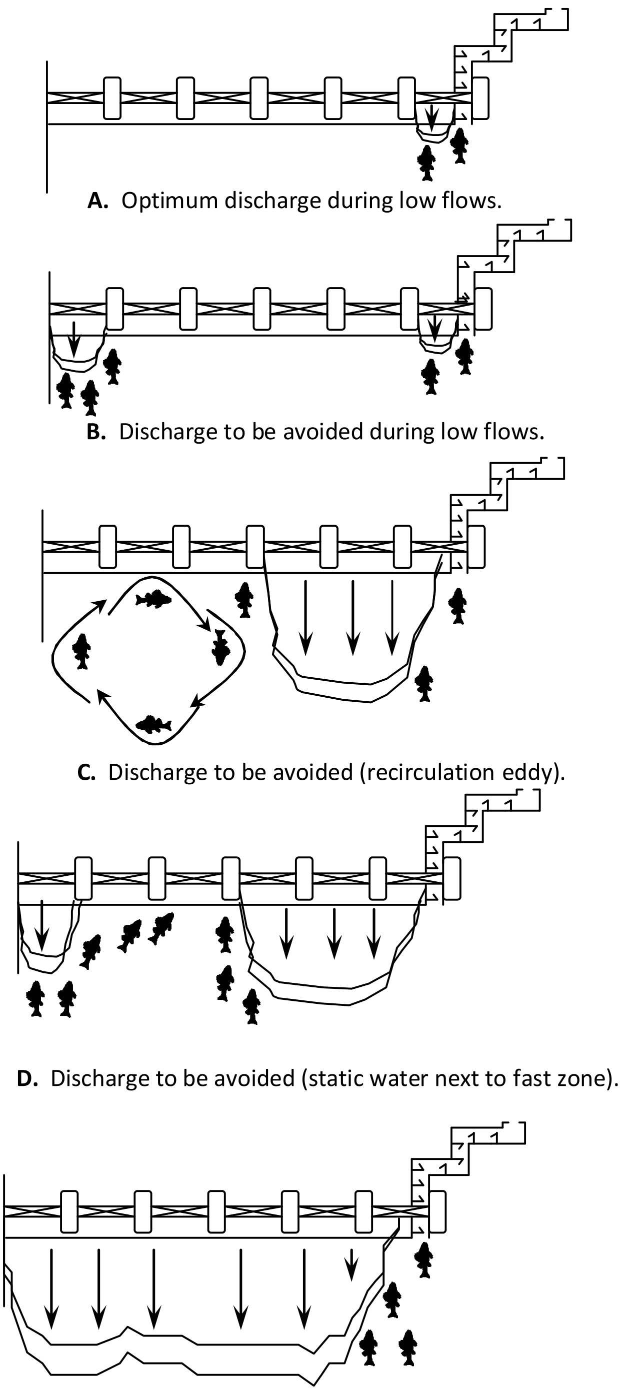

Figure 10. Optimising fish attraction to a fishway entrance (modified from Larinier 2002).

Box 6. Summary of Operating Standards for fishway attraction

1. Low flows through fishway. Flow to the fishway is the highest priority at low streamflows, and flow should pass through the fishway until cease-to-flow occurs i.e. 'fishway is first on and last off'.
2. Maintain integrity of fishway flow. Spill over the weir or regulator should not mask fishway flow. Flow over the weir should be adjusted so that turbulence and white water is ~0.5–1.0 m from the fishway entrance.
3. Low flow spill adjacent to fishway entrance.
4. Moderate spill spread evenly across the weir, tapering to the fishway entrance.
5. High flow spill spread evenly across the weir, tapering to the fishway entrance.
6. It is still essential to continue operating the fishway at low volumes of water – small fish are still able to migrate.

3.3 Operational Performance Standards for passage in fishways

There are three components to operating standards for passage in fishways:

3.3.1 Maintaining minimum depth in fishways

Maintaining minimum depth in fishways is done by maintaining headwater levels upstream. This relates to weirpool management and should be considered in detail in the design phase; if the information is not available, then the minimum depths in Table 2 can be used.

3.3.2 Operating gates on fishways

Gates are used on fish locks, vertical-slot fishways and Denil fishways (the only Denil fishway in Victoria is located at Lock 10 on the Murray River). The gates on fish locks are automated and hence are not part of regular operation, although they require regular maintenance. Gates are not used on rock-ramp fishways in Australia as yet, although they are used overseas to protect bypass channels from flood flows.

There are two types of operating gates that are used: (i) those that provide more attraction through the fishway (e.g. Murray fishways at Torrumbarry, Locks 7, 8, 9 and 10) and (ii) those for de-watering, which applies to most vertical-slot and Denil fishways. Importantly, in both cases the gates are on/off gates that are never used partially open. Gates should be fully open when the fishway is operating. Operating the fishway with the gate only half or three-quarters open does not save water. Water usage is not determined by the amount of water entering the fishway, but by the design of the slots. By not opening the gate fully, greater underwelling velocities can be created that are faster than the maximum swimming speed of some fish species, making this final section of the fishway impassable.

Gates for attraction have unique settings for each site but, uniformly, only one gate is open at a time. Gates for de-watering are either fully open if there is any downstream flow requirement or fully closed if zero flow is required downstream. This overlaps with fish attraction and a 'first on – last off' protocol for flow in the fishway.

3.3.3 Periods of operations

As a general rule, fishways should be operated all year, as there are low levels of fish movement at all times. There are, however, periods of intense migration (when the fishways should be fully operational) and periods when there is less movement (which are suitable for maintenance).

In coastal streams, active movement occurs all year, but there are peaks in upstream migration in spring and summer and downstream migration in autumn and winter. In streams with significant flow over the weir crest, downstream migration is likely to be directly over the weir; hence, fishway operation is less critical at these times and the fishway can be shut off briefly for maintenance.

In Murray–Darling streams, upstream movement occurs mainly from late winter to autumn, whereas downstream movement occurs from spring to late summer. Hence, early winter is an appropriate time for maintenance.

Box 7. Summary of Operating Standards for passage in fishways

1. Maintain minimum depth in fishway. This is achieved through weirpool management.
2. Operation of fishway gates for attraction: one gate fully open; follow settings in operations manual.
3. Operation of fishway de-watering gate: either fully open, or fully closed (when zero flow required downstream or when maintenance is required).
4. Periods of operation: all year, with maintenance scheduled for brief periods in autumn and winter for coastal fishways, and in early winter for Murray–Darling fishways.

3.4 Operational Performance Standards for exit of fishways

Standards to be considered for the operation of the exit of fishways are for depth, velocity and flow direction (vector). Depth is required in the weirpool for fish to exit, and this directly overlaps with maintaining minimum depth in the fishway. Low velocities are required at the fishway exit, and this includes ensuring that head loss and therefore velocities at trash racks are low. The flow direction also needs to ensure that fish do not swim back over the weir crest but continue migrating upstream. Standards for these criteria are detailed in Table 2 and are repeated here:

Box 8. Summary of Operating Standards for fishway exit

1. Flow vectors in weirpool do not vary more than 90° from centreline of stream i.e. no recirculation or eddies.
2. Minimum depth leading from exit:
   - 0.3 m for small-bodied fish (20–100 mm)
   - 1.0 m depth for medium- and large-bodied fish (100–1400 mm).
3. Maximum water velocity at exit in weirpool/impoundment:
   - 0.05 m/s for small-bodied fish (20–100 mm)
   - 0.30 m/s for medium- and large-bodied fish (100–1400 mm).
4. Trash racks should have <20 mm head loss in order to maintain suitable exit velocities.

4 Part 3. Fishway Maintenance Guidelines

4.1 Introduction

A well-designed and operated fishway requires regular maintenance. Build-up of debris, movement of the structure over time, weed encroachment, or sedimentation will impact upon the performance of fishway by changing hydraulic conditions or creating behavioural or physical barriers. Regular maintenance and inspection is required to ensure optimal operation, and a clear maintenance plan is required. Maintenance is best done as part of a structured inspection program or protocol that defines the times when the maintenance is required. There may also be a need for a formal reporting procedure concerning operational days per month, and maintenance reports and actions. Table 5 lists performance indicators and standards for fishway maintenance.

Table 5. Performance indicators and standards for fishway maintenance.

Performance indicator	Performance standard	Rock ramp; full width	Rock ramp; partial width	Vertical slot
1. Annual de-watering	Fishway de-watered on an annual basis for inspection, particularly at the crest and toe, and maintenance performed.	✓	✓	✓
2. Internal fishway hydraulics	Any increase in head loss above design (e.g. 70 mm) is rectified.	✓	✓	✓
3. Fishway inspection	Fishway visually inspected and operational reporting arrangements conducted regularly (e.g. monthly).	✓	✓	✓
4. Debris management	Debris removed from fishway and trash racks at the start of spring and regularly (e.g. monthly or as required) for systems with high debris loads thereafter.	✓	✓	✓

4.2 Fishway diagnostics

4.2.1 Visible blockages

A visual inspection of blockages caused by debris build-up should be regularly undertaken. There are two main types of blockages, the first being physical, in which wood, other debris or sedimentation builds up within vital areas of the fishway (this includes weed infestation for rock-ramp fishways). Areas most commonly subject to blockages include trash racks, vertical slots or between rocks in rock ramps. Physical blockages can change the hydraulics of a fishway, making it impassable to fish, as well as creating smaller widths in slots, preventing larger fish from physically being able to pass. The second type of blockage is behavioural. Behavioural blockages occur primarily when an object (usually a bed of aquatic flora, such as *Azolla* spp. (Fig. 11)) becomes lodged upstream of the exit to the fishway. Although this may not interfere greatly with flow rates, it can create a darkened area under which fish will be hesitant to continue moving upstream. For this reason, the exit (upstream) end of the fishway needs to be kept clear of accumulations.

Figure 11. Build-up of *Azolla* at fishway exit can cause a behavioural barrier.

4.2.2 Head loss

A major component of fishway maintenance is understanding and observing head loss. Head loss refers to the difference in water level, or step height, between two adjacent pools of a fishway (Figs 12 and 13). Head loss is important because it determines the maximum water velocity that occurs and the amount of turbulence (white water). Head loss is a useful design standard for fishways because it can be measured in the field, and it indicates the highest water velocity that fish must swim against to negotiate the barrier. It is most useful to set a maximum head loss standard. Head loss should be checked at the entrance and in all pools, as it will be noticeably higher (and louder) if there is a blockage below the surface. Critical times would be during and after rises in the stream levels, when more debris will be transported down the stream, and when fish migration is at its peak. If head loss varies from design, this indicates that there are problems with the fishway's structural integrity or that there is a blockage.

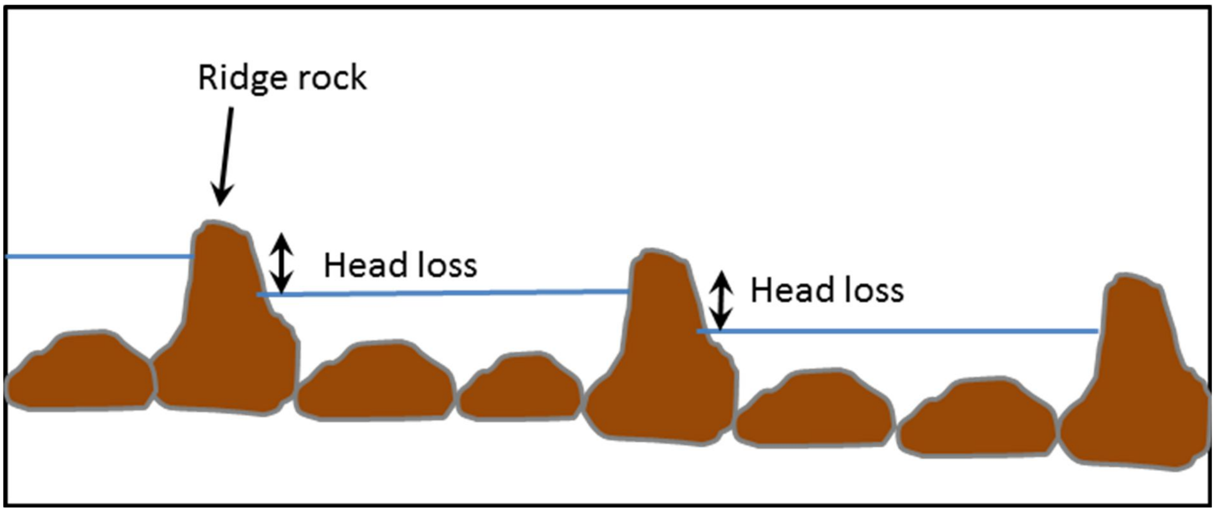

Figure 12. An example of head loss in a rock-ridge fishway. Inspection of head loss can be made visually or measured with a tape measure or laser level (modified from a drawing by M. Mallen-Cooper).

Figure 13. Head loss in a rock fishway.

4.2.3 Turbulence

Turbulence refers to energy dissipated in the pools of the fishway. Average turbulence is a function of the water velocity (governed by head loss) and the size of the pool. In general, white water indicates high turbulence (Fig. 14), and this can become a complete barrier to fish movement, particularly for small size classes (e.g. <100 mm long). If turbulence levels vary from design, this indicates that there are problems with the fishway's structural integrity or that there is a blockage.

Figure 14. Turbulence (white water) is a function of high head loss (high water velocity) and a small shallow area for dissipation of water energy.

4.3 Fishway inspection checklist

The frequency of site visits to inspect the operational fishway should be based on the seasonal fish migrations, with most frequent inspections undertaken before and during the peak migration season.

4.3.1 **Vertical-slot** fishway

The maintenance requirements of a vertical-slot fishway, and particularly the trash rack, can be minimised with a floating shear boom mounted in the weirpool. A shear boom is manufactured from strong durable material (e.g. polyethylene pipe) and should be designed to carry floating debris past the fishway exit and then over the weir crest. A number of designs have been used in Victoria and Australia, but those that are angled at 45^{o} to the flow will more efficiently deflect debris away from the fishway exit.

Box 9. Summary of maintenance rules for a vertical-slot fishway

1. Visual inspection of the debris load on the trash rack (Fig. 15) and in the vertical slots.
2. Visual check of head loss and turbulence throughout the fishway.
3. Removal of the grid deck, de-watering, and inspection of the internal fishway structure.

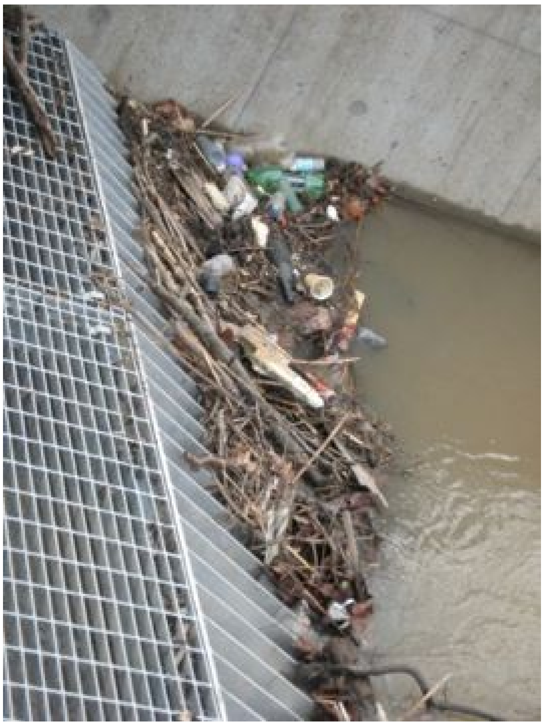

Figure 15. Regular clearing of trash racks is required to maintain attraction flows into fishways and to maintain appropriate head loss (and therefore velocities) at the exit.

4.3.2 Rock-ramp fishway

Rock fishways require maintenance; in the absence of maintenance, they may have a functional life span of 10 years or less. With regular maintenance, particularly following a flood event, rock fishways can meet their functional requirements indefinitely. Rock fishways tend to require little human intervention at an operations level. Nevertheless, optimal hydraulic operation and regular maintenance is crucial for the long-term passage of migratory fish. Rocks that move during high flows can eventually cause the hydraulics to become suboptimal and lead to functional failure of the fishway. A regular inspection schedule will ensure the fishway functions effectively in the long term. However, it is often hard to determine when maintenance is needed, and this aspect requires some training for local operators. The irregular nature of rock ramps makes it very difficult to produce consistent head losses throughout the ramp. It is most useful to set a maximum head loss standard, and at the weir crest there should be little, if any, head drop at all. At the edge of the rock ramp, in the shallow water, some small fish utilise the low velocities generated by the roughness of the rocks for ascending.

Box 10. Summary of maintenance rules for a rock-ramp fishway

1. Visually inspect the fishway at the entrance and exit for blockages and ensure it is trash free.
2. Visually inspect head loss at each rock ridge to ensure it is at design specification.
3. Inspect fishway for weed encroachment.
4. Inspect fishway for sediment deposition.
5. After major flooding, check for any damage to the fishway (movement of rocks) and also to the bank armour.

5 Supporting material

5.1 Supporting Material 1: Fish ecology

5.1.1 Victorian fish species

There are 42 species of native freshwater fish listed in Victoria (Table S1), and the rivers that these fish inhabit and the fish themselves can be broadly separated into two geographic drainage groups: Murray–Darling Basin (MDB) and coastal. Within both MDB and coastal rivers, fish follow a number of movement strategies, depending on their life history. Here we define the accepted fish migration terminology that we will use consistently throughout this section of the report:

- **Potamodromous**: fish that migrate wholly within fresh water (e.g. Golden Perch, Murray Cod)
- **Diadromous**: fish that migrate between fresh water and the sea or estuary (e.g. Tupong).

Within the diadromous fishes, there are a number of subcategories:

- **Anadromous** – diadromous fish that spend most of their life in the sea or estuary and migrate to fresh water to breed (e.g. the Lampreys)
- **Catadromous** – diadromous fish that spend most of their life in fresh water and migrate to the sea or estuary to breed (e.g. eels, Australian Bass, Tupong, Australian Grayling)
- **Amphidromous** – diadromous fish that migrate between the sea or estuary and fresh water, but not for the purpose of breeding, with movement occurring regularly within the life cycle (e.g. Yellow-eyed Mullet).

Fish movements can vary in distance, from small, localised movements (<1 km) to >1000 km, depending on the species and the ecological purpose of the movement. Environmental cues are important to fish, and these can stimulate movement. Important cues include: seasonal or diurnal cycles, rises or falls in river flow, and water temperature. Fish movement can be short distance (e.g. for foraging, feeding) or long distance (e.g. for spawning, colonisation), obligatory to complete a life-history stage (e.g. diadromous migrations between the sea and fresh water) or non-obligatory (feeding movements). In one sense, all movements are obligatory for maintaining healthy native fish populations over their entire natural geographic distribution. Consequently, the impact of reduced connectivity on fish populations will vary depending on the fish species concerned and the reasons for movement.

Table S1. Victorian fish species.

Scientific name	Common name	Migratory strategy	Conservation status	Distribution (1 = MDB, 2 = coastal)
Bidyanus bidyanus	Silver Perch	Potamodromous	EPBC[4], FFG[5]	1
Craterocephalus fluviatilis	Murray Hardyhead		EPBC, FFG	1
Craterocephalus stercusmuscarum fulvus	Unspecked Hardyhead	Potamodromous	FFG	1
Gadopsis bispinosus	Two-spined Blackfish	Local		1
Galaxias fuscus	Barred Galaxias	Local	EPBC, FFG	1
Galaxias sp. 2	Riffle Galaxias	Local		1
Hypseleotris klunzingeri	Western Carp Gudgeon	Potamodromous		1
Maccullochella macquariensis	Trout Cod	Potamodromous	EPBC, FFG	1
Maccullochella peelii peelii	Murray Cod	Potamodromous	EPBC, FFG	1
Macquaria ambigua ambigua	Golden Perch	Potamodromous		1
Macquaria australasica	Macquarie Perch	Potamodromous	EPBC, FFG	1
Melanotaenia fluviatilis	Murray–Darling Rainbowfish	Potamodromous	FFG	1
Mogurnda adspersa	Southern Purple-spotted Gudgeon			1
Nematalosa erebi	Bony Herring	Potamodromous		1
Tandanus tandanus	Freshwater Catfish	Local	FFG	1
Anguilla australis	Short-finned Eel	Diadromous		2
Anguilla reinhardtii	Long-finned Eel	Diadromous		2
Galaxias maculatus	Common Galaxias	Diadromous		2
Galaxias truttaceus	Spotted Galaxias	Diadromous		2
Galaxiella pusilla	Dwarf Galaxias	Local	EPBC, FFG	2
Geotria australis	Pouched Lamprey	Diadromous		2
Gobiomorphus australis	Striped Gudgeon			2
Gobiomorphus coxii	Cox's Gudgeon		FFG	2
Hypseleotris compressa	Empire Gudgeon		FFG	2
Lovettia sealii	Australian Whitebait		FFG	2
Macquaria novemaculeata	Australian Bass	Diadromous		2
Mordacia mordax	Short-headed Lamprey	Diadromous		2
Nannoperca sp.1	Flinders Pygmy Perch			2
Nannoperca variegata	Variegated Pygmy Perch	Local	EPBC, FFG	2
Neochanna cleaveri	Australian Mudfish	Local	FFG	2
Potamalosa richmondia	Freshwater Herring		FFG	2
Prototroctes maraena	Australian Grayling	Diadromous	EPBC, FFG	2
Pseudaphritis urvillii	Tupong	Diadromous		2
Galaxias brevipinnis	Broad-finned Galaxias	Diadromous		1, 2
Galaxias sp.1	Obscure Galaxias	Local		1, 2
Nannoperca australis	Southern Pygmy Perch	Local		1, 2
Nannoperca obscura	Yarra Pygmy Perch	Local	EPBC, FFG	1, 2
Philypnodon grandiceps	Flat-headed Gudgeon	Migratory		1, 2
Philypnodon macrostomus	Dwarf Flat-headed Gudgeon	Local		1, 2
Retropinna semoni	Australian Smelt	Migratory, diadromous, local		1, 2
Gadopsis marmoratus	River Blackfish	Local		2, 1
Galaxias olidus	Mountain Galaxias	Local		2, 1

5.1.1.1 Murray–Darling fish species

[4] EPBC refers to *Environment Protection and Biodiversity Conservation Act* listing.
[5] FFG refers to *Flora and Fauna Guarantee Act* listing.

The migratory species that inhabit inland Victorian freshwater habitats in the MDB largely exhibit a potamodromous life cycle. Potamodromous fish species can undertake either small- or large-scale movements, but all require connectivity to allow movement of fish between different habitats (often associated with spawning and dispersal).

In cases where freshwater species are abundant upstream and downstream of the barrier, or if the migration is mainly for dispersal of a small proportion of the population and not an obligatory seasonal movement, then the fish passage objectives of a fishway may be less critical than those for obligatory migrations (e.g. in diadromous fish). For example, populations of Murray Cod persist upstream and downstream of barriers within the MDB, and while not obvious, the health of these populations may be compromised by these barriers through reduced spawning, dispersal and population mixing. Impacts on other species can be more obvious. Golden Perch can be completely extirpated from areas as a result of decreased connectivity; for example, following the construction of the Yarrawonga Weir (Lake Mulwala) in the late 1930s, there were no Golden Perch found upstream of this structure for many decades (Cadwallader 1977). An intensive stocking program has seen the return of this species to the area since the 1970s. This example demonstrates how the impact of barriers on fish populations can be masked by stocking with fish.

Golden Perch migrate in spring and summer and can move many hundreds of kilometres upstream and downstream (Reynolds 1983; Mallen-Cooper 1999; O'Connor et al. 2005). Some studies have suggested that adult Murray Cod and Golden Perch undergo upstream migrations specifically to access favourable spawning locations (O'Connor et al. 2005; Koehn et al. 2009). There is also some evidence for home site fidelity (Crook 2004; O'Connor et al. 2005), but the numbers of Golden Perch moving through fishways as both adults and juveniles suggest that movement is a key component of their life history (Mallen-Cooper 1999; Stuart et al. 2008a).

5.1.1.2 Coastal fish species

Seventy per cent of native fish species in Victoria's coastal drainages need to migrate at some stage of their life cycle. In south-eastern coastal drainages, ~50% of the available aquatic habitat has been obstructed by barriers. This has had dramatic effects on many native coastal species, particularly those species that require access to both fresh water and the sea or estuary to complete their life cycle. For fish that migrate between separate habitats, restricted fish passage can lead to localised extinctions above the barrier, particularly if it is a large structure.

Large barriers such as dams usually cause extinction of diadromous species upstream, while smaller barriers such as weirs, tidal barrages and culverts reduce the diversity and age classes of fish upstream, depending on the frequency and timing of drownout events and whether these happen to coincide with diadromous fish migrations.

A case in point is for Australian Grayling, a shoaling, amphidromous species in which the young recruits migrate upstream from the sea to complete their life cycle. Spawning occurs near the estuary, downstream of adult freshwater habitats, during autumn, and the hatched larvae drift downstream into the sea (Schmidt et al. 2011; Koster et al. 2013). Around six months later, the juvenile fish return upstream to freshwater habitats. Australian Grayling have undergone severe decline throughout most of their former range and are now listed as vulnerable at a State and National level. The main cause of the decline of Australian Grayling is stream barriers that prevent downstream spawning migrations and return upstream, and the movement of juveniles into freshwater habitats following their mandatory marine larval phase.

5.1.1.3 Semelparous species

There is a further level of subtlety within the obligatory movement patterns of a small number of diadromous fish species. Some obligatory migrations are classified as semelparous, when the fish die after their one-off lifetime spawning event. For example, eels migrate from freshwater to spawn and die in marine environments, while lampreys migrate from marine waters well upstream into fresh water (i.e. from the Murray River mouth to Yarrawonga) to spawn and die. Before their spawning migration, these semelparous species cease to feed and divert much of their energy toward the gonads for the production of eggs and sperm. Another species, Tupong, are also thought to migrate from fresh water to the sea, where it is thought they spawn and die (Crook et al. 2010). For this reason, it is especially important that semelparous fishes (e.g. Tupong) can complete their migration without delay.

5.1.1.4 Migration and gender separation

Barriers on coastal rivers, particularly tidal barriers, can also separate males and females of the same species, and this can lead to dramatic declines in fish abundance. Males and females of at least two species of Victorian fish, Australian Bass and Tupong, are likely to inhabit different habitats; females migrate further upstream into fresh water (catadromy), while males are more likely to stay closer to estuarine spawning areas (Harris 1986; Crook et al. 2010). Females of both species spend several years in fresh water before migrating downstream for spawning (O'Connor et al. 2012; Schmidt et al. 2014). Where tidal barriers disrupt fish movement, there can be severe population declines because females cannot reach the estuary to spawn with the waiting males unless management actions facilitate fish passage (Zampatti et al. 2011).

5.1.2 A conceptual model of fish movement

Conceptual models are representations of complex systems that use available data and current understanding – in this case of fish migration and its relationship to river flow. The model and the process of constructing the model can summarise biological data, highlight knowledge gaps, identify research and monitoring priorities, enable strategic resource allocation, and clarify and synthesise thinking. A fish migration model is important because the two generic variables that most influence the design (and cost) of a fishway are (i) the target range of flows and (ii) the fish community. It is useful to provide here the biological basis upon which a fishway's performance can be evaluated.

5.1.3 A model of fish movement

The majority of native fish species in Victoria could be expected to use a fishway, and a general movement model is:

1. Upstream movement by small-, medium- and large-bodied fish during low and rising flows in spring and summer
2. Upstream movement by some medium- and large-bodied fish with increasing discharge and during floods
3. Small-, medium- and large-bodied fish moving downstream over a wide range of seasons and flows.

Small-bodied fish are defined here as those 20–120 mm long (MDB and coastal species), medium-bodied fish as those 120–350 mm long (coastal species) or 120–500 mm long (MDB species), and large fish as those exceeding this size and up to 1000 mm long (MDB and coastal species). It is likely that at low flows and small-to-moderate river rises, there will be large numbers of small- and medium-bodied fish moving upstream. Large-bodied fish will continue to migrate during medium and high flows. Hence, the fishway design should be based on fish biology and hydraulically cater for a variety of fish behaviours.

5.2 Supporting Material 2: Fishways

5.2.1 Background

There are a suite of engineering solutions for enabling fish passage at stream barriers, and these are collectively known as fishways. The best fishway does not provide 100% fish passage transparency at a weir, and hence weir removal is nearly always the best option for fish passage. However, when removal or modification is not a feasible option, there are numerous designs of fishways engineered to overcome different barrier types, designs and heights, thus catering for the various sizes, swimming capabilities and behaviours of the target fish species. The type of fishway will be partially determined by the target fish species and the size classes that are moving, with their known capabilities for ascending fishways. Here we provide a brief review of the major types of fishways.

5.2.2 Common Victorian fishway designs

5.2.2.1 Vertical-slot fishways

Vertical-slot fishways are generally used on medium-sized weirs up to 6 m high, and there are probably 100 of these in Australia. Vertical-slot fishways consist of a concrete channel structure divided into individual pools, each connected by a vertical slot. The vertical slot runs the full depth of the baffle and angles the jet of water across the pool to the opposite side, dissipating the energy of the water in each pool. The vertical drop between each pool, the size (volume) of the pool, and the width of the slot connecting each pool determines the turbulence and velocity parameters of the fishway, which in turn determine the size and species of fish that are capable of utilising the fishway (Fig. S1).

Vertical-slot fishways are particularly useful in that they are self-adjusting and maintain constant velocity and turbulence levels throughout the fishway at varying flows; thus, they are able to operate over a fairly wide range of head- and tailwater levels. Vertical-slot fishways are currently installed at sites throughout Victoria, including in northern Victoria at Torrumbarry Weir on the Murray River, at Caseys Weir on the Broken River, at numerous weirs on Broken Creek (Fig. S2), and on Gunbower Creek and Kerang Weir on the lower Loddon River. There are also vertical-slot fishways on coastal streams, including at Dights Falls on the Yarra River and at the lower Barwon Breakwater tidal barrage on the Barwon River near Geelong.

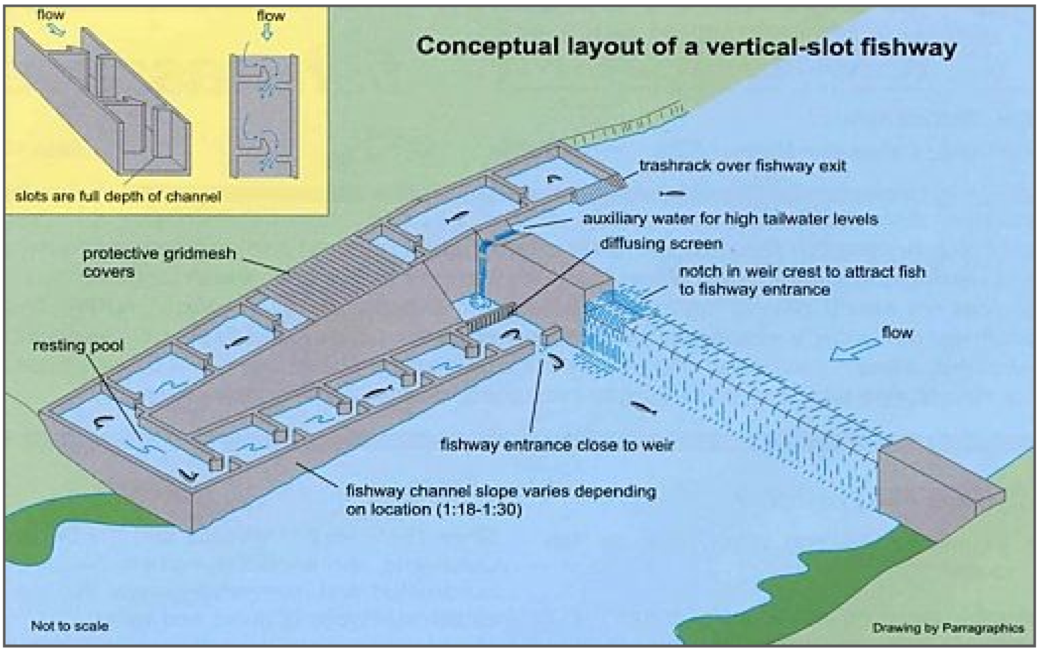

Figure S1. Conceptual layout of a vertical-slot fishway (from Thorncraft and Harris 2000).

Figure S2. A vertical-slot fishway on Broken Creek in northern Victoria. Note the low pool turbulence and water velocities (photo: I. Stuart).

5.2.2.2 Rock-ramp fishways

Rock-ramp fishways are most commonly used for barriers <2 m in height. A low gradient is essential for successful rock-ramp fishways, and 1v:25h or 1v:30h are common slopes used when constructing these structures for Australian fishes. There are a number of variations on the design of rock-ramp fishways; however, the general concept consist of a series of pools created by rock ridges or a ramp of rocks placed below the barrier that are connected through continuous water flow from one pool to the next (Fig. S3). The size of the pool and head loss between adjacent pools determines the water velocities and turbulence through which the target species of fish have to pass to move upstream. In Victoria, rock ramps are useful for passing small fish upstream and in particular for returning juvenile diadromous species upstream into freshwater habitats following their mandatory marine phase. They pass small fish by providing a range of water velocity profiles and interstitial spaces, and also pass other aquatic fauna (e.g. turtles and invertebrates).

There are many variations in the design of rock fishways; full-width fishways (which occupy the full stream width) tend to provide considerably more functionality, particularly if the headwater varies. However, partial-width designs (a rocky channel that occupies a portion of the stream width) can also be effective. Rock fishways can be built entirely in the tailwater or less commonly be entirely recessed in the headwater. They can also have a straight profile or reverse back toward the weir for optimal entrance placement. Rock fishways can have a random-rock type design or consist of carefully placed ridges, depending on the site conditions and objectives.

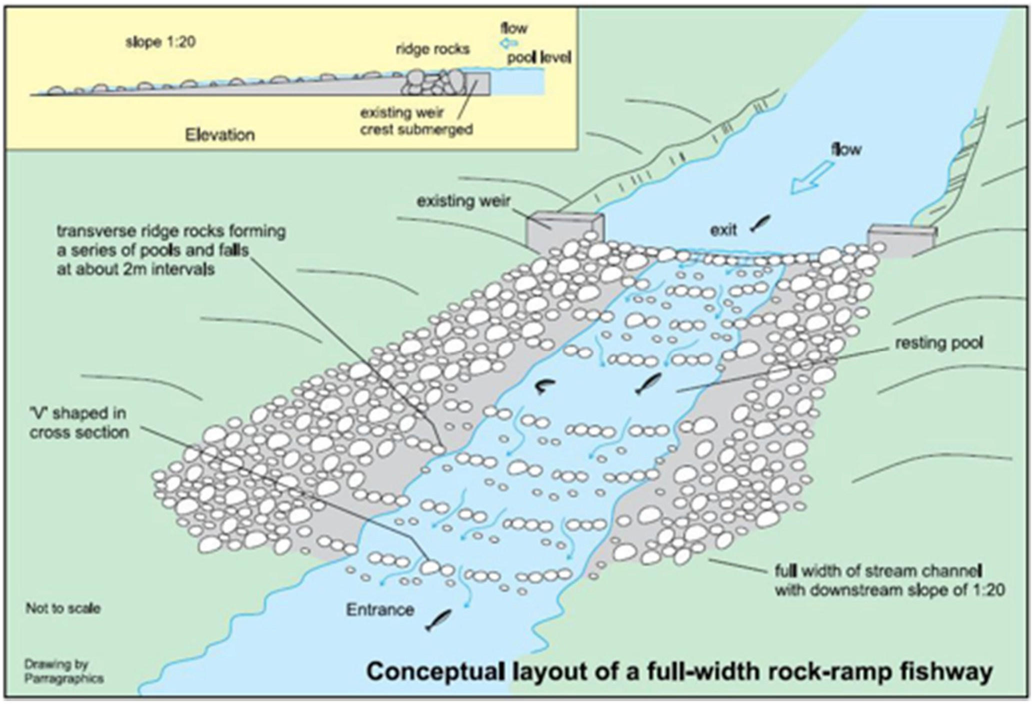

Figure S3. Conceptual layout of a full-river width rock fishway (from Thorncraft and Harris 2000).

5.2.2.3 Fish lock

Fish locks are used to transport fish over high structures, typically 6–8 m high, where a conventional vertical-slot fishway would be too long. Fish locks function similarly to a navigation lock system designed to move ships and boats over weirs and dams and are able to pass a wide diversity and size range of fish. Fish locks have a chamber located on the downstream side of the barrier. Fish are drawn into the chamber using attraction flows. The chamber is periodically closed (the duration of lock cycle will be dependent on the target species of fish), and the chamber is filled with water until it reaches the same level as the upstream weir pool. An exit flow then encourages fish to move out of the fish lock into the waters upstream (Fig. S4). There is a fish lock at Yarrawonga Weir, and another was recently commissioned in early 2014 on Gunbower Creek at Hipwell Road. A fish lock is also planned for the Kow Swamp regulator on the Pyramid Creek. All these fish locks are located in the MDB in northern Victoria. There are several fish locks on the lower Murray River and in NSW and Queensland (Qld), and these can be broadly categorised as bottom fill (‘Ardnacrusha’ design) or top fill (Borland or open design).

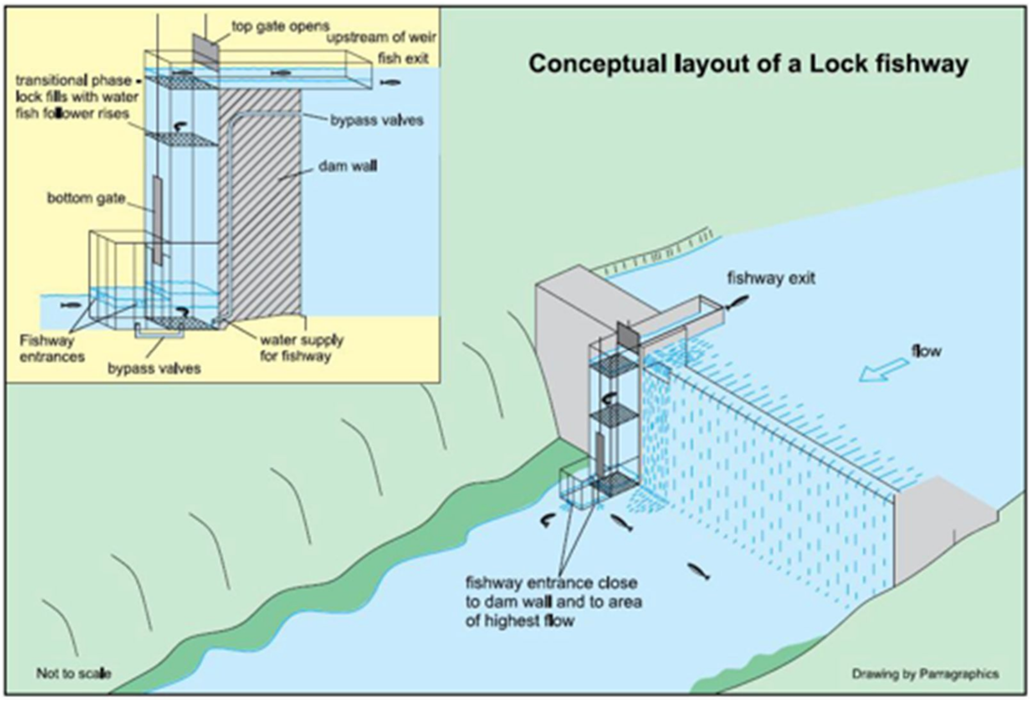

Figure S4. Conceptual layout of a lock fishway (from Thorncraft and Harris 2000).

5.2.2.4 Fish lift

Fish lifts function in a similar manner to fish locks, except that the downstream chamber (known as 'the hopper') is mechanically lifted up to the level of the head water, rather than raising the level of the water. These operations are usually automated. Fish can be attracted into the hopper via an entrance channel or a short section of vertical-slot fishway. Generally, fish lifts are used to transport fish over high dams >10 m in height, and there are several of these in NSW and Qld. There are currently no fish lifts located in Victoria, but this would be the type of option necessary for overcoming barriers such as Goulburn Weir or Lake Hume.

5.2.2.5 Denil fishways

The Denil fishway (Fig. S5) consists of a rectangular chute with closely spaced triangular baffles or vanes located along the sides and bottom and set at 45°, causing part of the flow to turn back on itself, resulting in reduced velocity against which fish are able to ascend (Clay 1995). The large flow associated with the Denil designs reduces the deposition of sediment within the fishway and also provides good attraction capability, assisting the fish in finding the fishway. There is a Denil fishway on Lock 11 (Mildura Weir) on the Murray River (Fig. S6).

Denil fishways are common in southern NSW (e.g. the Koondrook–Pericoota channel and Gulpa Creek), where they can pass large- and medium-bodied fish, but small-bodied fish passage is more limited (Mallen-Cooper and Stuart 2007). Denil fishways discharge relatively high volumes of water and can be fitted on a relatively steep slope (e.g. 1v:12h), and for this reason they can often be used in combination with a vertical-slot fishway.

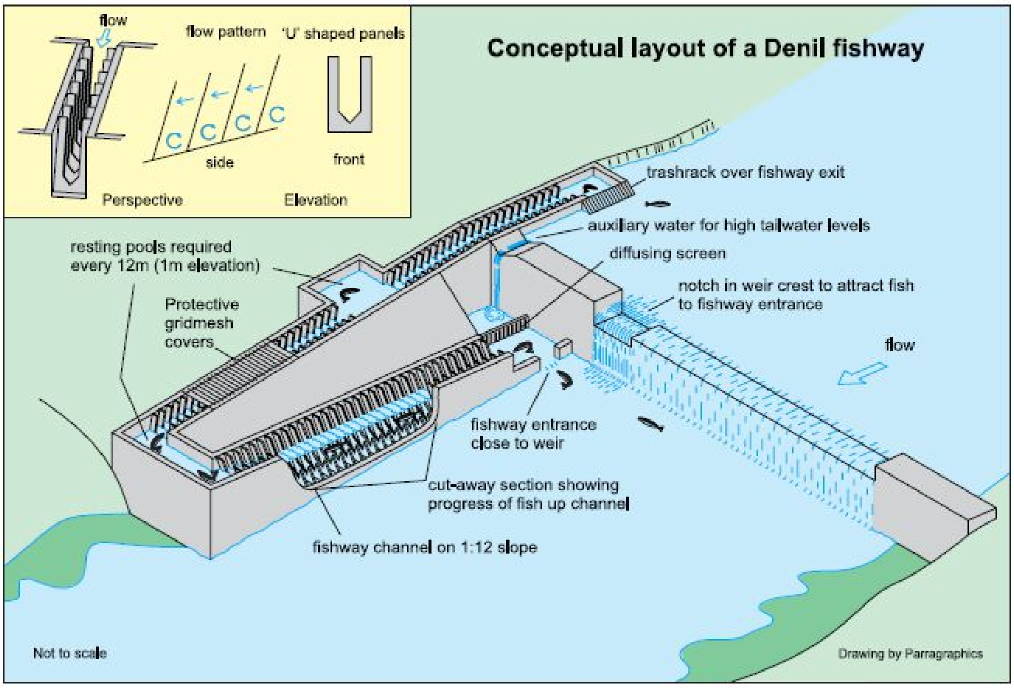

Figure S5. Conceptual layout of a Denil fishway (from Thorncraft and Harris 2000).

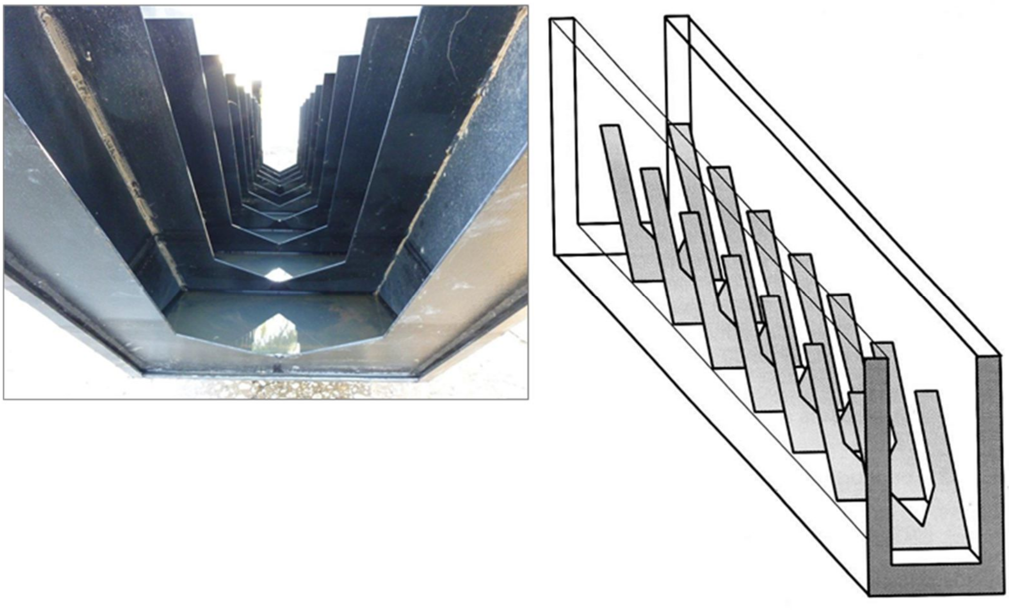

Figure S6. Close-up of internal baffles in a Denil fishway on the Murray River at Mildura Weir (diagram and photo: M. Mallen-Cooper).

5.2.2.6 Bypass fishways

Bypass fishways (Fig. S7) are low-gradient earthen or rocky channels that mimic the structure of the natural stream. Unlike rock-ramp fishways, they are built with meanders and natural habitats and often placed at a reduced slope (1v:50h) compared with rock ramps (1v:30h). These fishways are known as ‘nature-like’ and are popular in Europe, where they have, in some instances, replaced pool-type fishways. However, in Europe there is generally more flow in streams and rivers, which is a requirement of bypass fishways for optimal functionality. There are very few bypass fishways in Australia: two in Victoria (Patterson River and Coburg Lake (Merri Creek)) and one in Qld. Bypass fishways have high sensitivity to variable headwater, and this has limited the broad application of bypass fishways in Australia, mainly because of the highly variable flows in many rivers.

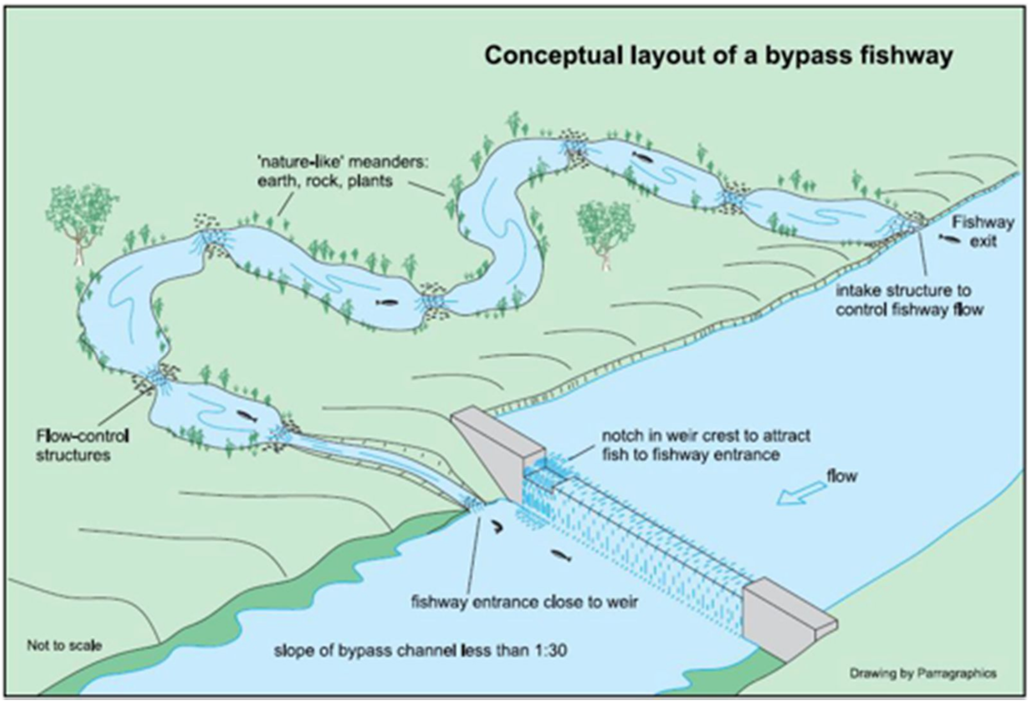

Figure S7. Conceptual layout of a bypass fishway (from Thorncraft and Harris 2000).

5.2.2.7 Cone fishways

At present there are no cone fishways in Victoria, but they have strong application as they have been successful in Qld, where they were first developed (by Qld Fisheries) (Fig. S8). Essentially, cone fishways can replace rock fishways, particularly in existing culverts or pre-cast applications for small- to medium-bodied fish. There has been some biological assessment demonstrating improvements to fish passage in relatively short culverts. These fishways are most useful where there is limited headwater variation and relatively low (<1.5 m) head differential. They have low discharge and turbulence, and the upstream invert sets the operational range, as opposed to a de-watering gate.


Figure **S**8. (Left) Pre-cast plastic cones and (right) concrete cones, which break up laminar flow and provide roughness for fish to ascend culverts in Qld (photos: A. Berghuis and T. Marsden).

5.2.2.8 The case for two fishways

For some sites, fish passage can be better facilitated and possibly have a lower capital cost by installing two fishways with separate ecological/hydrological functions. For example, on the Murray River at Lock 10 (Wentworth Weir) there is a vertical-slot fishway for the passage of small-, medium- and large-bodied fish at low to medium flows. However, at high flows there are many larger fish migrating, such as Golden Perch and Murray Cod, and so instead of incurring the high capital cost to raise the operating range of the vertical-slot fishway to include these high flows, a second fishway was constructed. This was a short Denil fishway, which has higher discharge and fish attraction and hence greater functionality for large fish at high flows.

5.2.2.9 Other fishways

Fishway technology is constantly evolving, and new designs, refinements and variations are commonly being trialled and adopted in Australia, e.g. Fig. S9: a trapezoidal fishway. It is important that new designs are documented and biological evaluations completed in order to refine future fishways, and these field studies provide new insights into fish ecology.

Figure S9. A trapezoidal fishway on the coastal Wyong River in central NSW. This type of innovative fishway is still subject to evaluation, but appears to have strong application and will also be trialled at the Murray River barrages located near the Murray River mouth from 2015 (photo: M. Mallen-Cooper). One interesting aspect is the splash zone at the edges of the trapezoidal weirs, which may facilitate the passage of climbing fishes.

5.2.3 Eel passage

Short-finned and Long-finned Eels are present in Victoria, and both species have a complex life history, with their early life stages being particularly vulnerable to tidal barriers. Larval eels change into unpigmented glass eels, and mass migrations of small eels (40+ mm long) enter fresh water during spring and early summer (McDowall 1996). Eels >150 mm long are strong swimmers, but glass eels and the larger brown eels (<130 mm long) have a very poor swimming ability (burst swimming speed 0.6–0.9 m/s); however, this is offset by a remarkably strong ability to climb waterfalls, weirs and even high dams by using the wetted perimeter, or splash zone, alongside the spillway area. Climbing is enhanced by rough surfaces or by moss and algae. The climbing ability of young eels has important implications for fishways, as young eels appear to prefer to climb over stream barriers. Where they are required to swim through a fishway, even at low gradient and water velocity, there is relatively poor success.

As almost all fishways require fish to swim faster and for longer than most juvenile eels can accomplish, there has been greater success when the ecological function of the fishway includes a specific 'elver pass' designed to facilitate juvenile eel passage by climbing. Elver passes are common in North America, Europe and New Zealand, but are only recently starting to gain momentum in Australia. The growth of the eel industry in eastern Australia is increasing the importance of providing fishways for these fish, and the most common elver passes are briefly discussed below.

5.2.3.1 Elver ramps

Elver ramps are the most common type of elver fishways, and there are considerable data to support their success in North America, Europe and New Zealand. They consist of a steep (e.g. 1v:2h) pipe or ramp installed on the face of the stream barrier, with a roughened surface (usually nylon brushes or gravel-lined channels) that (with the addition of water) gives the elvers a rough surface to climb over (Porcher 2002; Soloman and Beach 2004). These types of fishways are usually inexpensive, and an example is shown below (Fig. S10). Mussel spat ropes have recently been used in New Zealand for passing climbing galaxias, and these also have potential for elvers (David and Hamer 2012). There are also trap-and-truck fish passage systems for eels, which use fishways and elver passes to collect young eels before transporting them to upstream release areas.

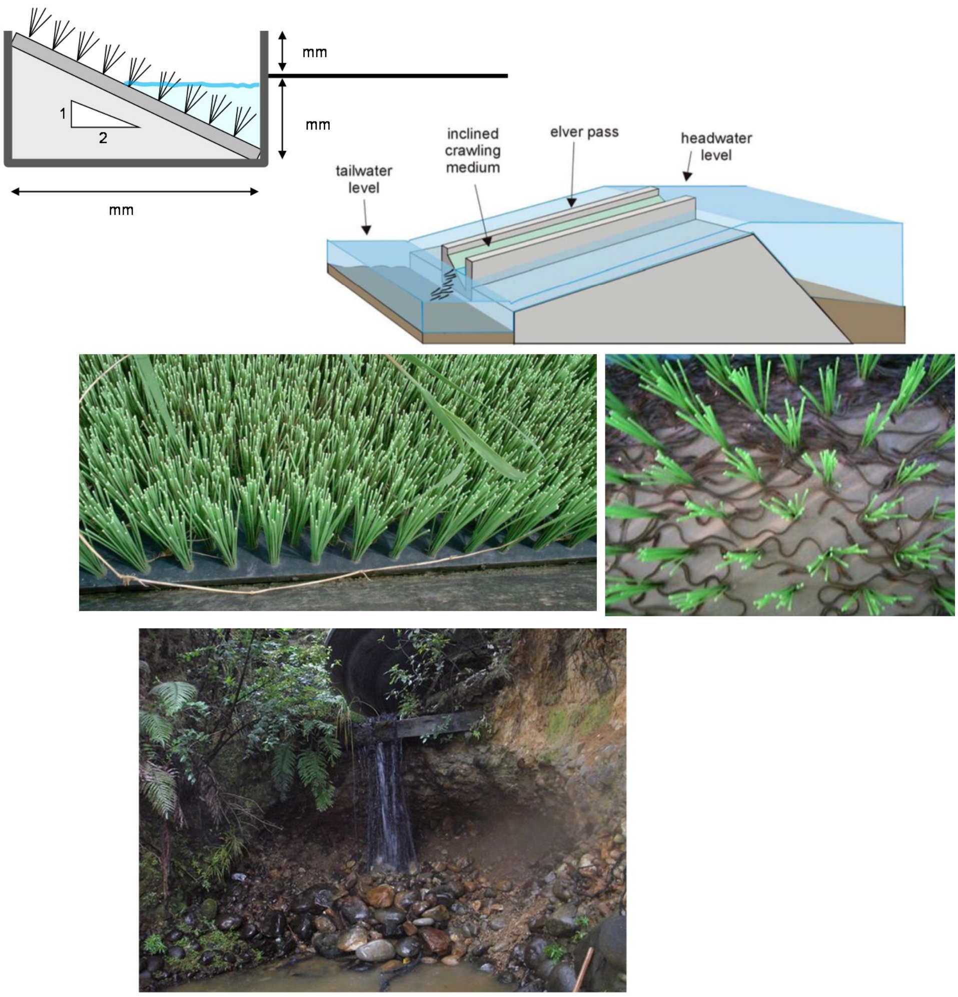

Figure S10. (Top) A prototype elver pass with nylon brushes that give juvenile eels a rough surface for climbing (modified from Soloman and Beach 2004). (Bottom) A mussel spat rope in New Zealand for climbing galaxias (photo: Bruno David).

5.2.4 Culverts and fish passage

Culverts present a special fish passage problem in which the main fish passage issue is the laminar flow of water. Laminar flow occurs when water is flowing uninterrupted and parallel to the culvert surface so there is a smooth flow with no eddies or turbulence. In this type of flow there is no space for fish to rest and they must swim constantly.

In recent years, there has been a lot of work in North America (and most recently in New Zealand) examining the hydraulics of culverts and the swimming speed of fish. The characteristics of culverts that are important in determining the hydraulics and water velocities are the shape, cross-sectional area, slope, length and roughness of the culvert material (e.g. rough concrete will slow the water velocity more than, for example, a smooth stainless steel pipe).

A head loss >100 mm in a culvert produces a water velocity of >1.5 m/s, and this can be considered impassable for most native fish (Table S2). When negotiating culverts, the swimming ability of fish is very important because of the greater distance the fish is required to swim through maximum velocities (compared with the shorter distance of maximum velocities through which the fish is required to negotiate in a vertical-slot or rock-ramp fishway). Fish must utilise their sustained swimming speed, a speed they can maintain for long periods (e.g. up to 200 min), rather than their burst speed. A general rule of thumb is that fish can swim at three times their body length (3BL) during sustained efforts. For Common Galaxias, a common Victorian migratory species, there is a need for very conservative water velocities (e.g. <0.3 m/s) in order for these fish to pass through a long culvert.

Table S2. Head loss, water velocity and minimum sizes of negotiating fish for a given culvert.

Head loss (mm)	Max. water velocity (m s^{-1})	Fish length
2	0.15	<80 mm
10	0.3	>100 mm
20	0.45	>150 mm
50	0.75	>250 mm
80	0.93	Impassable except to large fish (>400 mm)
100	1.50	Impassable except to largest fish (>500 mm)

While each culvert is unique, there are several simple generic ways to design a culvert to facilitate fish passage, and these should be tailored specifically to optimise fish passage at individual culverts.

5.2.4.1 Culvert design features

1. Generally box or arched culverts provide greater fish passage opportunities than pipes.
2. Culverts that enable good light penetration and have water ‘freeboard’ are preferred.
3. Often larger culverts (e.g. minimum culvert size of 1.5 m^2) provide a greater cross-sectional area than smaller culverts, and thus reduced flow velocity for improved fish passage.
4. Culverts should be installed with *no* slope (i.e. match natural geology).
5. Maintain natural stream depth, width and cross-sectional area.
6. Avoid water constrictions at the culvert and high water velocities.
7. The invert of the culvert entrance and exit should be counter-sunk (c. 30 cm) into the streambed.
8. Generally culvert length should not exceed 6 m.
9. Scouring and perching at the entrance or exit of the culvert should be avoided.
10. A 0.5-m-high downstream-sloped (30°) water retention end-sill (usually concrete) can be considered – which raises tailwater, thereby reducing turbulence and providing a refuge/plunge pool.

5.2.4.2 Adding roughness to culverts

Over the last decade there has been increasing interest in adding roughness elements inside the culvert barrel, which break up laminar flow and create turbulence, hydraulic complexity and edge effects that facilitate fish passage. A variety of materials and configurations have been trialled, including: (i) rocks or timber blocks, (ii) side baffles, (iii) chains or ropes, (iv) pre-cast cones and (v) spoiler baffles e.g. (bio-baffles). The aim of these roughness elements is to break up the laminar flow, producing locally turbulent flow, and to thereby pass small- and medium-bodied fish.

In the main, the addition of roughness elements is limited to sites with long periods of steady-state headwater, or where the total head differential is relatively small. There are several options to retrofit roughness units to culverts, and these depend on the fish species and the range of flows over which the culvert operates. A field example for Cardinia Creek is shown in Fig. S11, whereby a rock fishway below the culverts reduced the differential head, and side baffles were placed near the exit of the pipe culvert to further enhance fish passage. Biological evaluation of the Cardinia Creek fishway and culvert baffle installation is currently underway (2013–2014).

Figure S11. Some options for improving fish passage at existing culverts. (Top left) Pipe, (top right) spoiler baffles and (bottom) box culverts with retrofitted one-side baffles. Baffles help to slow water velocity and create eddies for fish to rest in during their upstream migration. The pipe culvert baffles (top left) are newly installed on Cardinia Creek in eastern Melbourne, along with a rock fishway. Photos: courtesy T. Marsden and Melbourne Water.

5.3 Supporting Material 3: Fishway case studies

The setting of each fishway is unique, and hence each evaluation adds to knowledge of fish ecology and design refinement. In this section of the report we provide several fishway case studies, from which the key learnings are summarised. The case study approach is valuable (especially where there has been fishways monitoring) for identifying how the fishways performed and how subsequent fishway design, operation and maintenance has been influenced.

5.3.1 Categorising Victorian fishways

For the purposes of this document, Victorian fishways were broadly separated into (i) inland (MDB) and (ii) coastal river systems, which reflects the fishes with potamodromous and diadromous life histories, respectively.

Fishway types were determined by those most relevant to improving fish passage at Victorian barriers; these were rock ramps, vertical slots, fish locks, fish lifts, Denil fishways, elver passes, cone fishways, culvert fishways, and emerging innovative designs, such as trapezoidal fishways.

5.3.2 Ecological data for fish using vertical-slot fishways

5.3.2.1 Torrumbarry Weir

The original Torrumbarry Weir fishway, completed in 1990, was the first vertical-slot fishway installed in Australia and was designed to pass medium- and large-bodied fish (150–1000 mm long), which were considered to be the major migratory fish. Performance evaluation of the fishway found that it was efficiently passing native fish >100 mm long. A new finding was that some small-bodied fish (Australian Smelt) and juveniles of medium-bodied fish (e.g. Golden Perch and Silver Perch <120 mm long) were also migratory, but that they did not efficiently ascend the fishway (Mallen-Cooper 1999) because they could not negotiate the fishway hydraulics and possibly the relatively extensive length of the fishway (131 m). The Torrumbarry Weir and fishway were rebuilt in 1996–1997 (Fig. S12), and the new fishway was designed to have greater functionality at high flows; large-volume resting pools were also included.

5.3.2.2 Broken Creek

There are numerous vertical-slot fishways operating successfully in the Victorian section of the MDB. Among these are a series of eight vertical-slot fishways that were constructed on the lower Broken Creek between 1997 and 2003. This was an early example of restoring fish passage at multiple weirs along a whole river reach. Following the installation of these fishways, there has been a five-fold increase in Murray Cod abundances in the upstream weirpools of this system; however, other river restoration activities such as re-snagging, riparian restoration, and environmental flows have also greatly contributed to fish recovery (O'Connor et al. 2006).

Other fish species collected using the Broken Creek fishways include small-bodied Australian Smelt, Flat-headed Gudgeon (<100 mm long) and large-bodied Golden Perch, Carp and Goldfish (*Carassius auratus*). In a good example of fish passage restoration at a multi-barrier scale between September and December 2010, three Murray Cod travelled 43 km upstream during a high-flow event, negotiating five fishways along the way. These fish completed these journeys in 3, 19 and 47 days. In the same period, two Murray Cod travelled 52 km upstream, negotiating six fishways along the way; these journeys took 18 and 34 days to complete. Similarly, a Golden Perch travelled upstream through five fishways in November 2007 (a distance of >33 km). It is important to note that these fish would not have moved upstream without the installation of the fishways, and this now dynamic system would have remained sedentary.

5.3.2.3 Kerang fishway

A vertical-slot fishway at Kerang Weir on the lower Loddon River has also been monitored. In 2012, four radio-tagged Golden Perch moved between 60 and 120 km upstream, including movement through the Kerang Weir fishway. None of these fish would have been able to undertake this long-distance movement if the fishway had not been installed two years earlier (O'Connor et al. 2013). Monitoring data are lacking, but small-bodied (<100 mm long) fish appeared unable to ascend the Kerang fishway (Stuart et al. 2010).

Figure S12. Torrumbarry Weir vertical-slot fishway (photo: J. O'Connor).

5.3.3 Recommended specifications for a vertical-slot fishway located in inland Victorian waters

The recommendations below are generic in nature and tend to target small-bodied fish, as these are the weakest swimmers. The criteria provide a starting point for restoring fish passage and are based on previous successful fishway designs; however, each site and fish community is unique, and we suggest that the individual criteria are refined as part of a collaborative process for any new fishways. A summary is provided in Table S3.

5.3.3.1 Fishway operating range and differential head

The range of flows and differential head over which the fishway operates is a site-specific decision, but the standard criterion of fishway operation up to and including a 1-in-5-year flood is a generally accepted requirement.

5.3.3.2 Pool volume

It is recommended that the pool volume is 3 × 2 m to allow for large-bodied species such as Murray Cod, while maintaining acceptable turbulence levels.

5.3.3.3 Minimum depth

The minimum depth recommended is 1.0 m to allow for large-bodied species such as Murray Cod, but 1.5 m is preferred. For medium- and small-bodied fish, this can be less (see Table S4).

5.3.3.4 Fishway slope

A slope of 1v:30h is recommended for the passage of small-bodied species through the vertical-slot fishway; however, if alternative fish passage facilities are provided for this size range, i.e. a fish lock, then the slope of the inland vertical-slot fishway may be increased to 1v:18h. There is some potential for using keyhole slots to steepen the fishway (e.g. 1v:25h), but this needs to be assessed on a site-by-site basis. Keyhole slots are those where the bottom half of the slot can be wider (e.g. 0.35 m) than the top half (e.g. 0.15 m), and hence the same fishway can pass small- and large-bodied fish without increasing turbulence and pool size (Mallen-Cooper et al. 2008).

5.3.3.5 Slot width

Slot width depends on the local fish community, but the minimum for Murray Cod is 0.3 m, and a new fishway for Mullaroo Creek has 0.35-m-wide vertical slots. Narrower slots can be used for small-bodied fish (e.g. 0.12 m), or these dimensions can be used in a keyhole manner. Very narrow slots may have an increased chance of blockage by floating debris.

5.3.3.6 Head loss between pools

The maximum head loss between pools for an inland vertical-slot fishway is 0.1 m for the passage of small-bodied fish. However, a head loss of up to 0.15 m may be used where there is a need to pass medium- and large-bodied fish and where turbulence is minimised.

5.3.3.7 Hydraulics

For small-bodied fish, the recommended hydraulics of an inland vertical-slot fishway consist of maximum velocities of 1.2 m/s at the *vena contracta* and maximum turbulence levels of 20 W/m^3.

Table S3. Specifications of some vertical-slot fishways in inland Victoria.

Specifications	**Torrumbarry Weir**	**Lock 9**	**Lock 8**	**Kerang Weir**	**Broken Creek – Kennedys Weir**	**Gunbower Weir**	**Gunbower Creek – Hipwell Road**
River system	Murray River	Murray River	Murray River	Loddon River	Broken Creek	Gunbower Creek	Gunbower Creek
Construction date	1990	2005	2003	2008	1997	2009	2014
Differential head (m)	6.5	2.8	2.6	1.8	1.0	2.5	0.63
Slope	1v:18h (5.5%)	1v:32h (3.1%)	1v:32h (3.1%)	1v:20h (5%)	1v:20h	1v:20h (5%)	1v:30h (3.3%)
Pool head loss (m)	0.165	0.1	0.1	0.15	0.15	0.165	0.126
No. of pools	39	27	26	12	15		4
Dimensions of pools (m)	3 × 2	3 × 2	3 × 2	3 × 1.8	3 × 2	3 × 2	3.1 × 3
Depth of pools (m)	1.1	1.5	1.5	0.75 min	1.0	1.0	1.0
Width of slots (m)	0.3	0.3	0.3	0.3	.3	0.3	0.3
Maximum velocity (m/s)	1.8	1.4	1.4	1.72	1.72	1.7	1.57
Turbulence (W/m^3)	105	40	42	98	98	88	42
Length of fishway (m)	131	90	83	47		30	17
Discharge (ML/d)	32	38	38	32–58	32	31.1	43

Table S4. The relationships between fishway hydraulic parameters and fish size for coastal and inland vertical-slot fishways; all parameters should be reviewed on a site-by-site basis.

	Minimum depth (m)	Minimum pool size (m)	Average turbulence (W/m^3)	Maximum water velocity over 0.1 m at *vena contracta* (m/s)	Slot width (m)	Fishway slope (m)	Head loss between pools (m)
Large-bodied fish (500–1000 mm long)	1.0–1.5	3.0 × 2.0	90	1.8	0.3 to 0.35	1v:20h	0.15–0.165
Medium-bodied fish (90–500 mm long)	0.8	3.0 × 2.0	50	1.4	0.15–0.25	1v:25h	0.1
Small-bodied fish (15–90 mm long)	0.4	1.3 × 1.1	20	1.2	0.08–0.15	1v:25h to 1v:30h, depending on pool size	0.05–0.1

5.3.4 Vertical-slot fishways – coastal rivers

There are only three vertical-slot fishways operating on coastal rivers in Victoria: one built at Cowwarr Weir (Thompson River) in 2011, the second built at Dights Falls (Yarra River) in 2012, and the third at the Barwon River breakwater in 2013. All of these vertical-slot fishways replaced inefficient rock-ramp fishways and were optimised for small- to medium-bodied fish (e.g. 20–400 mm long). In addition, Dights Falls and the Barwon River breakwater fishways have a continuous layer of 150-mm diameter rocks placed on the floor of the fishway to enhance the passage of macroinvertebrates and demersal fish (e.g. Tupong). In addition to the three Victorian coastal vertical-slot fishways, we also review another coastal vertical-slot fishway in Western Australia on the Goodga River that was designed to pass Spotted Galaxias, a small-bodied native species that is also found in Victoria.

5.3.4.1 Barwon breakwater

The Barwon River breakwater is a 0.85-m-high barrier located near Geelong, ~100 km west of Melbourne, and it was built over 80 years ago to stop saltwater incursions upstream. The breakwater not only acts as a physical barrier to upstream fish movement, but it has also altered upstream habitat, making it unsuitable for obligatory estuarine species such as Luderick (*Girella tricuspidata*), Sandy Sprat (*Hyperlophus vittatus*), Black Bream (*Acanthopagrus butcheri*) and Mulloway (*Argyrosomus japonicas*), which were all once found as far upstream as Geelong (a further ~20 km upstream).

The construction of the pre-cast vertical-slot fishway was funded by the Corangamite CMA and Victorian Recreational Fishing Licence fees, and recent monitoring identified 16 species of fish (including 14 native species and two non-native species) utilising the structure. In a 4-day period between October and November 2013, ~50 young-of-the-year Australian Grayling between 40 and 55 mm long were collected in the fishway. Also during spring 2013, tens of thousands of galaxiids were collected (including >10,000 fish in 2 days in November). These mainly consisted of Common Galaxias, but also included Spotted and Broad-finned Galaxias. In autumn, hundreds of Yellow-eyed Mullet have utilised the fishway, and hundreds of juvenile Tupong have consistently been collected throughout autumn and spring. Given that during the monitoring period the barrier was not drowned out, none of these fish would have moved upstream in the absence of the fishway.

5.3.4.2 Dights Falls

Another vertical-slot fishway was completed on the Yarra River at Dights Falls weir in late 2012. This weir is over 100 years old and has major impacts on the diversity and size classes of fish found upstream in the Yarra River. This fishway operates over a differential head of ~1.9 m, with a rock-ramp fishway below facilitating upstream fish passage over ~2.3 m of head differential at a slope of 1v:36h. The fishway was funded by Melbourne Water and has successfully passed 15 fish species, including 11 native and four non-native species.

Monitoring in 2013–2014, collected tens of thousands of juvenile galaxias utilising the fishway, including the collection of over 10,000 galaxias in a single day. The catch was dominated by Common Galaxias, but also included large numbers of Spotted and Broad-finned Galaxias. Juvenile Australian Grayling 40–65 mm long have also been collected utilising the fishway (>50 fish). Tupong, which have largely been absent from the Yarra River upstream of Dights Falls for the past century, have also been collected utilising the fishway and are now appearing in upstream tributaries of the Yarra River. The fishway appears to be performing well at low river flows, but more work is required to quantify the performance at high river flows.

5.3.4.3 Goodga River gauging station

A vertical-slot fishway was built on the Goodga River at a 1.5-m-high gauging station in Western Australia in 2003 (Marsden 2002; Morgan and Beatty 2005, 2006). This low-velocity and low-turbulence fishway was primarily constructed to pass Spotted Galaxias upstream, a species also found in coastal Victorian streams. Monitoring of the fishway and changes in the upstream fish community indicated that the fishway did pass both Spotted and Common Galaxias upstream, in addition to Western Pygmy Perch (*Edelia vittata*).

5.3.5 Recommended specifications for a vertical-slot fishway located in coastal Victorian waters

The recommendations below are generic in nature and tend to target small-bodied fish, as these are the weakest swimmers. The criteria provide a starting point for restoring fish passage and are based on previous successful fishway designs. Each site and fish community is unique, and we suggest that the individual criteria are refined as part of a collaborative process for any new fishways. A summary is provided in Table S5.

5.3.5.1 Fishway operating range and differential head

The range of flows and differential head over which the fishway operates is a site-specific decision, but the standard criterion of fishway operation up to and including a 1-in-5-year flood is a baseline requirement.

5.3.5.2 Pool volume

A pool volume of at least 1.5 m^3 is recommended (pools 1.5 m long $\times$ 1 m wide) to allow for dissipation of energy so as to maintain acceptable turbulence levels; however, this is highly dependent on the slot width and head drop between pools.

5.3.5.3 Minimum depth

The minimum depth recommended for small-bodied fish is 0.4–0.5 m and for medium-bodied fish is 0.6 m.

5.3.5.4 Slope

A slope of 1v:30h is recommended for the passage of small-bodied species, but there is scope to steepen the fishway where head loss and turbulence are low (e.g. Goodga River fishway).

5.3.5.5 Slot width

A slot width of 0.15 m is appropriate in many situations, but narrower or wider slots (or keyhole slots) may be used where appropriate for the fish species and pool hydraulics.

5.3.5.6 Head differential

The head loss between pools in coastal vertical-slot fishways can be 0.05–0.1 m, depending on other hydraulic parameters such as turbulence levels.

5.3.5.7 Hydraulics

Water velocity should be <1.22 m/s at the *vena contracta* and turbulence <25 W/m^3 for the passage of small-bodied fish.

Table S5. Specifications of some coastal vertical-slot fishways.

Specifications	**Yarra River – Dights Falls fishway**	**Goodga River fishway (Western Australia)**	**Barwon River Breakwater fishway**
Construction date	2012	2003	2013
Width of weir (m)		15	
Differential head (m)	4.2	1.5	0.85
Slope	1v:30.3h (3.3%)	1v:19h (5.2%)	1v:30h (3.3%)
Pool head loss (m)	0.076	0.05	0.075
No. of pools	25	30	12
Dimensions of pools (m)	1.8 × 2.1	0.95 × 0.8	2.2 × 1.2
Depth of pools (m)	1	0.5	0.4–0.6
Width of slots (m)	Keyhole slots 0.15 and 0.20	0.05	0.18–0.14 (tapering slot)
Maximum velocity (m/s)	1.22	0.99	1.21
Turbulence (W/m^3)	25	22	18
Length of fishway (m)		24	
Discharge (ML/d)	11	1.5	6.6

5.3.6 Rock-ramp fishways – coastal

Rock ramp fishways are the most common type of fishway within Victorian coastal streams (Figs S13 and S14). Historically, these structures have had variable success in transferring fish upstream as a result of variations in design, construction and maintenance. Nevertheless, a well designed, constructed and maintained rock-ramp fishway can provide excellent connectivity of fish populations, with major positive influences on upstream fish communities.

Australia-wide, very few rock-ramp fishways have been robustly assessed; therefore, we present design elements and internal hydraulics as a surrogate for assessment. Given that rock-ramp fishways are the most common fishway type found in coastal streams of Victoria, it is disconcerting to find that there are very few robust assessments of this fishway type. However, this is largely the result of these structures being notoriously difficult to assess due to their variability in size and structure, the difficulty in applying quantitative sampling techniques, and limited access during high flows.

A lateral-ridge rock-ramp fishway constructed on the Tarwin River in 2012 (Fig. S13) by the WGCMA was monitored using a Passive Integrated Tag-reader device, and among the species utilising the fishway were Australian Grayling, Short-finned Eels, Estuary Perch, Tupong, Brown Trout (*Salmo trutta*) and Carp (*Cyprinus carpio*) during low flows, where there previously would have been no passage (O'Connor et al. 2012). Furthermore, assessment of fish accumulations directly below the barrier pre and post fishway installation indicated that a number of fish species showed significant decreases in mean abundance, including Australian Grayling, Short-finned Eel and Tupong (O'Connor et al. 2012). Differences in the catch rates of Australian Smelt and Common Galaxias below the fishway site were not detected between the two periods, and this may potentially indicate that the fishway was not efficiently passing these smaller species, but it may also be a data artefact due to small sample size.

Figure S13. The full-river-width lateral rock-ridge fishway on the coastal Tarwin River in Gippsland, Victoria, in 2010 (photo: J. O'Connor).

Figure S14. The full-river-width random-rock fishway on the coastal Yarra River at Dights Falls (Melbourne) in 2012. Note that the rocks are placed to maximise the edge effects of the bank and provide fish with a continuous path of ascent (photo: I. Stuart).

5.3.7 Recommended specifications for rock-ramp fishways in coastal Victorian waters

The recommendations below are generic in nature and tend to target small-bodied fish, as these are the weakest swimmers. The criteria provide a starting point for restoring fish passage and are based on previous successful fishway designs. Each site and fish community is unique, and we suggest that the individual criteria are refined as part of a collaborative process for any new fishways. A summary is provided in Table S6.

5.3.7.1 Fishway operating range and differential head

The range of flows over which a rock fishway operates is a site-specific decision, but the standard criterion should be up to weir drownout flows. Rock fishways that include a 'V' channel profile or a sloped lateral (bank-to-bank) channel profile tend to operate over a greater range of flows compared with fishways with a flat lateral profile.

5.3.7.2 Pool size

The recommended generic pool size for a ridge-style rock fishway is 2 m long (clear space) in order to allow dissipation of flow to maintain acceptable turbulence levels and appropriately quiet water in fish resting areas. Pool size may be reduced where head loss is also reduced.

5.3.7.3 Minimum depth

The minimum depth recommended is 0.3–0.4 m in at least 50% of the pool area in a continuous path ascending through the rock ramp. For larger-bodied fish this may need to be greater (Table S7).

5.3.7.4 Slope

A slope of 1v:30h is recommended for the passage of small-bodied fish species.

5.3.7.5 Head loss

The head differential for a coastal rock-ramp fishway is a site-specific decision, but 75–100 mm (i.e. corresponding to velocities of 1.0–1.22 m/s) is a starting point for many fishways, depending on the fish species present. Instead of trying to make each head loss exactly the same, we suggest that no head loss should exceed 120 mm.

5.3.7.6 Hydraulics

Turbulence within rock fishways is poorly understood compared with the highly predictable hydraulics of vertical-slot fishways. Rock fishways must provide ‘hydraulic diversity’ so that fish can choose their ascent path. Turbulence should be minimised, with little ‘white’ water in the fishway pools, and if there is an assumption that turbulence can be calculated in the same manner as for a vertical slot, then it should be 25 W/m^3.

Table S6. Specifications of some coastal rock-ramp fishways.

Specifications	**Tarwin River – South Gippsland Hwy**	**Pollocksford Weir – Barwon River**	**Skenes Creek – lower causeway**	**Skenes Creek – upper causeway**	**Dights Falls – Yarra River**	**Muddy Creek**
Construction date	2010	2010	2011	2011	2012	2014
Rock fishway type	Full-river-width lateral ridge	Full-river-width lateral ridge	Full-river-width lateral ridge	Full-river-width lateral ridge	Full-river-width random rock and pool	Full width
Width of weir (m)	5	15	8	6	20	8
Width of fishway						
Differential head (m)	0.5	0.9	0.4	1.0	2.3	1.0
Longitudinal slope	1v:30h	1v:30h	1v:30h	1v:30h	1v:36h	1v:40h
Lateral (bank-to-bank) slope	No	Yes	No	No	Yes	yes
Resting pool	No	No	No	No	Yes	yes
Head loss per ridge (m)	0.075	0.1	0.1	0.1	n/a	0.05
No. of pools	7	9	4	9	3	18
Dimensions of pools (m)	2 × ~5	2 m long	2 m long	1.7 m long	10 × 20	8 × 2
Depth of pools (m)	0.4	0.3	0.3	0.3	0.3–0.5	0.4
Maximum velocity (m/s)	1.21	1.4	1.4	1.4	1.4	0.75
Turbulence (W/m^3)	n/a	n/a	n/a	n/a	25 W/m^3	<20
Length of fishway (m)	15	28	8	23	50	60

Table S7. The relationships between fishway hydraulic parameters and fish size for coastal and inland rock fishways; all parameters should be reviewed on a site-by-site basis.

	Minimum depth (m)	**Minimum pool size (m)**	**Average turbulence (W/m^3)**	**Maximum water velocity over 0.1 m at *vena contracta* (m/s)**	**Slot width (m)**	**Fishway slope (m)**	**Head loss between pools (m)**
Large-bodied fish (500–1000 mm long)	0.4+	2.0 long	30 (calculated as per vertical slot)	1.22	0.3–0.35	1v:25h	0.10–0.12
Medium-bodied fish (90–500 mm long)	0.4	2.0 long	30 (calculated as per vertical slot)	1.22	0.15–0.25	1v:30h	0.075–0.10
Small-bodied fish (15–90 mm long)	0.05–0.4	1.5–2.0 m long, depending on head loss	25 (calculated as per vertical slot)	<1.22	0.12–0.15	1v:30h	0.05–0.075

5.3.8 Rock-ramp fishways – inland

Rock-ramp fishways are common within inland Victoria, and there is considerable variation in their design and ecological and hydraulic function. There are full-river-width rock-ramp fishways on major rivers at Sydney Beach Weir (Ovens River, Wangaratta) (Fig. S15) and Shepparton Weir (Goulburn River), and partial-width fishways at Sugarloaf Creek (near Puckapunyal) and at Echuca Weir (Campaspe River) (Table S8). All of these fishways are lateral-ridge fishways, and some of these (Shepparton, Sugarloaf Creek and Sydney Beach fishways) include double-width resting pools located approximately halfway up the fishway. There are no robust assessments of inland rock-ramp fishways from within Australia, and this is a major data gap in understanding the efficiency of these structures.

Table S8. Specifications of some inland rock-ramp fishways.

Specifications	**Wangaratta Weir – Ovens River**	**Shepparton Weir – Goulburn River**	**Sugarloaf Creek**	**Echuca Weir – Campaspe River**
Construction date	2010	2009	2010	2014
Rock fishway type	Full-river-width lateral ridge	Full-river-width lateral ridge	Partial-river-width lateral ridge	Full-river-width lateral ridge
Width of weir (m)	13	35	30	18
Differential head (m)	1.1	1.8	0.9	0.66
Longitudinal slope	1v:20h	1v:20h	1v:20h	1v:18h
Lateral (bank-to-bank) slope	Yes	Yes	Yes	Yes
Resting pool	Yes	Yes	Yes	No
Head loss per ridge (m)	0.1	0.1	0.1	0.11
No. of pools	10	17	8	5
Dimensions of pools (m)	2 m long	2 m long	2 m long × 6 m wide	1.8 m long
Depth of pools (m)	0.4	0.4	0.4	0.5
Maximum velocity (m/s)	1.4	1.4	1.4	1.6
Turbulence (W/m^3)	20	20	20	20
Length of fishway (m)	25	36	25	15

Figure S15. The upper leg of the Wangaratta rock-ramp fishway on the Ovens River in 2010. Note the raised rocks on the bank margins that increase the headwater range of the fishway (photo: T. Marsden).

5.3.9 Fish locks – inland

There are two fish locks in inland Victoria: one at Yarrawonga Weir (9-m high) (built in 1994) and one at Hipwell Road in the Gunbower Forest (completed in early 2014) (Figs S16 and S17). The Hipwell Road fish lock connects Gunbower Creek and Gunbower Forest to achieve a managed flood event for forest and wildlife outcomes. The recent Murray fishways program has led to the development of low-level (<3.5-m-high) fish locks that have a top-fill design, and there is ongoing evaluation of these fishways (Baumgartner et al. 2014). Other concept designs have been completed for fish locks for the National Channel (Headworks regulator) near Torrumbarry and at the Kow Swamp outlet regulator (Box Creek Weir), which discharges water into Pyramid Creek and further downstream into the Loddon River.

Assessment of fish locks in Victoria, NSW and Qld have shown that these systems can pass large numbers of fish and a diverse size range, including very small fish (Thorncraft and Harris 1997; Baumgartner and Harris 2007; Stuart et al. 2007). However, fish locks have also suffered from considerable problems relating to the operational reliability of the software control systems, the internal gate and electrical drive systems, and the highly technical and specialised nature of the maintenance requirements. A 12-month 'de-bugging' period is often required. There have been some issues with fish behaviour in locks, with some large-bodied species leaving the entrance chamber during the attraction cycle. This behaviour has also been reported overseas (Larinier 2002). In addition, there are site-specific cases where fish locks have had inappropriate exit conditions (Stuart et al. 2010).

Figure S16. The Hipwell Offtake regulator on Gunbower Creek nears completion in November 2013. This structure includes a fish lock, with the entrance slot noticeable on the right side of the picture (photo: I. Stuart).

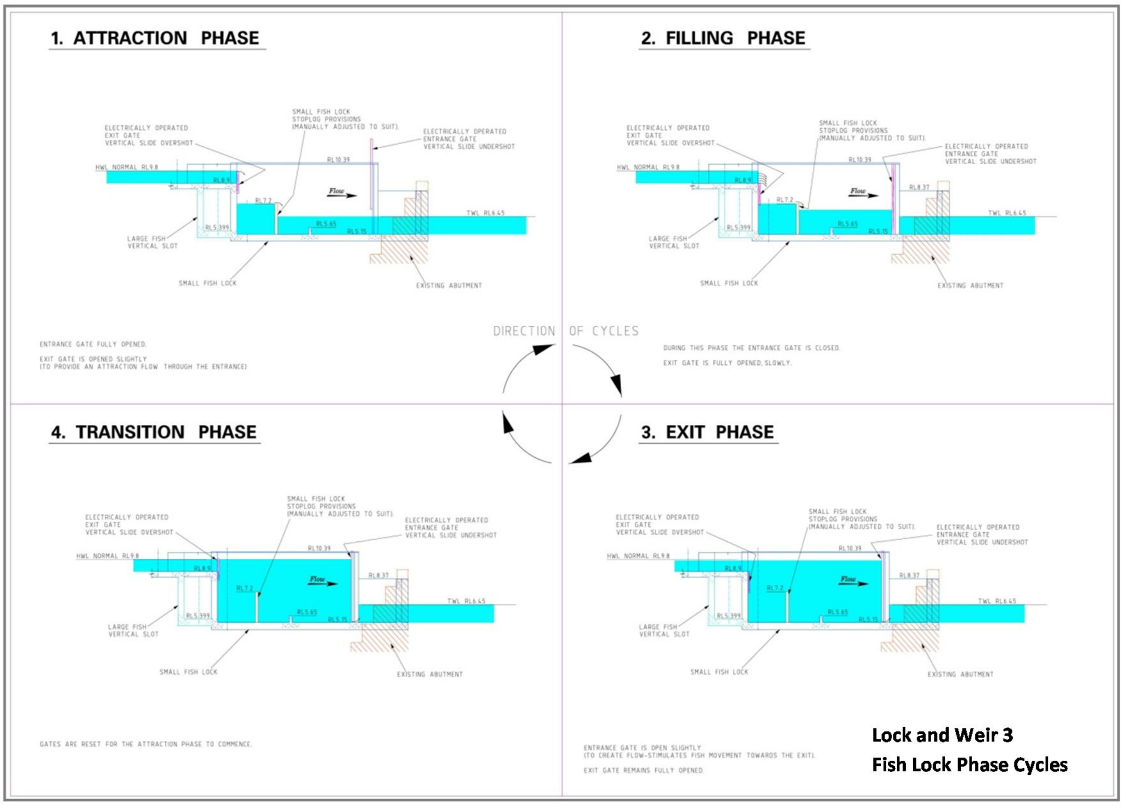

Figure S17. The four functional phases of a fish lock similar to that at Hipwell Road fish lock on Gunbower Creek (drawing: H. Robinson).

5.3.10 Fish locks – coastal

There are no fish locks on Victorian coastal systems, but there are many in Qld on the Fitzroy, Burnett, Burdekin and Pioneer rivers (McGill and Marsden 2000) and several in NSW. These locks are all bottom-fill designs, which fill through diffusers. Over the past 15 years, evaluation of their ecological efficiency has led to advancement in design and operations (Stuart et al. 2007). The design, operation, evaluation and maintenance experience for inland and coastal fish locks has been broadly similar and is summarised in Table S9 below.

Table S9. Generic parameters for Victorian fish locks. These should be individually reviewed during the design stage.

Item	Fish lock
Operating range (season)	September–April (inclusive for inland rivers) All-year-round (inclusive for coastal rivers) These criteria can be adjusted in specific circumstances
Target fish sizes	Site-specific but usually the whole fish community (20–1000 mm long)
Headwater range	Site-specific decision but maximised
Tailwater range	Site-specific decision but maximised
Entrance location	Located near weir crest. Located in quiet water so that attraction jet is clearly distinguishable.
Entrance minimum head loss	50 mm
Maximum entrance and exit head loss	70 mm
Minimum fishway depth	1.0 m, but up to 1.5 m for large fish
Entrance shape	Can be keyhole shape to take advantage of site-specific hydrology, but usually locks have relatively wide entrances (0.3–0.4 m)
Normal exit channel water velocity	0.15–0.3 m/s (preferred 0.25 m/s)
Normal entrance channel water velocity	Should be able to be varied depending on tailwater conditions in a range of 0.4 m/s (at low tailwater) to 1.0 m/s (at high tailwater)
Maximum average turbulence	20 W/m^3 (average)
Cycle time	30 min for each phase (attraction, filling, exit), but should be refined during commissioning/evaluation
Attraction water at entrance	Flow should be *continuous* with no pauses
Auxiliary water	Should be provided at entrance
Exit screens	Screened with 45–52° sloping trash rack – three times greater area than fishway channel. Vertical trash bars: 300-mm spacing.
Trash boom	High-impact floating trash boom to be placed in headwater at 45–52° above fishway to deflect floating debris over spillway.

5.3.11 Fish lifts – inland and coastal

There are currently no fish lifts (fish elevators) operating in Victoria; however, this is the type of fishway that would be required to remediate high-level barriers on large dams such as the Goulburn Weir and Hume Dam. There are only a few fish lifts operating in Australia, most notably at Paradise Dam (Burnett River, Qld) and Tallow Dam (Shoalhaven River, NSW) (Fig. S18).

A fish elevator in Qld on the Burnett River at Paradise Dam appears to function satisfactorily for some fish, but there are little data to determine its utility for larger species such as Queensland Lungfish (*Neoceratodus forsteri*) (A. Berghuis, Qld Fisheries, pers. com.). In NSW, a fish lift has been built at Tallowa Dam, where there is an ongoing assessment program (L. Baumgartner, NSW DPI, pers. comm.).

Figure S18. Fish lift constructed at Tallowa Dam on the coastal Shoalhaven River in south-eastern NSW. The ascending hopper is shown on the right (photos: Janet Pritchard).

5.3.12 Denil fishways

There are no Denil fishways in Victoria, but there are several on the Murray River and in southern NSW, including Wentworth Weir (Lock 10), Mildura Weir (Lock 11), Euston Weir (Lock 15), Gulpa Creek, Edward River offtake and Koondrook–Pericoota offtake regulators. Evaluation of these fishways has shown the passage of small-bodied fish (<120 mm long) to be poor unless the fishway is at a relatively low slope (e.g. 1v:12h or flatter) compared with the usual steep slopes of 1v:4h–1v:7h used in other countries (Baumgartner 2006; Mallen-Cooper and Stuart 2007). For this reason, Denil fishways tend to be used in combination with a vertical-slot or lock fishway for small fish where there is a clear need to service a separate ecological and hydraulic function. For example, at Wentworth Weir a vertical-slot fishway services small- to large-bodied fish at low and medium flows, but because there are large Murray Cod migrating at high flows, there is a Denil fishway with a high discharge and a wide channel width to accommodate these larger fish.

5.3.13 Case study synthesis

From the case studies, we highlight that each fishway experience is unique, and despite many fishways having the same design elements, there are always new learnings. These learnings are relevant to the central objectives of this document, which are to provide Fishway (i) Performance, (ii) Operation and (iii) Maintenance Guidelines.

The on-ground operator experience has varied between the fishway designs, as has the ecological and hydrological performance of each structure. The key learnings from the case studies are summarised in Table S10, and each of these points has been used to help develop and refine the performance criteria and Operating and Maintenance Guidelines.

Table S10. Summary of learnings from fishway case studies.

Ecological	**Performance**	**Maintenance**	**Operation**
Fishways are used by small- and large-bodied fish (15–1200 mm long)	Fishway ecological objectives need to be linked to performance criteria	All fishways need a clear Operating and Maintenance plan	Correct fishway operation can significantly enhance fish attraction
Fish migrate over a wide range of river flows	Fishways need to pass the full size range of fish	All fishways require regular maintenance; otherwise there can be functional failure of fish passage	Many fishways do not operate correctly due to basic issues (e.g. de-watering gates closed)
Fishways need clear and transparent ecological and fish passage objectives	Fishways need to operate over a wide range of flow conditions	Maintenance can be reduced with careful design and trash racks/shear booms	Simple summaries for fishway operating rules should be provided by the designers
Fishways need to be designed based on fish biology and river hydrology on a site-by-site basis	Fish should locate and ascend the fishway efficiently	Training of maintenance staff is required	The fishway owner needs to prioritise fishway operation
Fishways need collaborative design input and Quality Assurance processes	Fish communities and abundance should demonstrably benefit from fishways	Maintenance work should be documented and reported	Fish locks and lifts require considerable maintenance and a significant 'de-bugging' phase (e.g. 12 months)
Field evaluation of and experimentation with fishways helps refine designs and operation			Fishway operation is essential in spring and summer and should be documented
New fishway designs need to be considered and evaluated			

6 Glossary of technical terms

Amphidromous: fish that are born in fresh water/estuaries, then drift into the ocean as larvae, before migrating back into fresh water to grow into adults and spawn.

Anadromous: fish that migrate from the sea into fresh water to spawn.

Attraction: the ability of a fishway to efficiently attract migrating fish to the fishway entrance over a range of flow conditions.

Auxiliary water: flow added to the fishway entrance to increase fish attraction.

Burst swimming speed: fish maximum speed only able to be maintained for a short duration (e.g. 7 s).

Bypass: a type of fishway built on a low slope (e.g. 1 vertical:50 horizontal = 1v:50h), which simulates a natural river bed. Also known as 'nature-like fishways'.

Catadromous: a fish that lives in fresh water and enters salt water to spawn.

Coefficient of discharge (Cd): the ratio of the actual discharge to the theoretical discharge.

Denil: a type of fishway first developed in Belgium, which uses U-shaped baffles within a channel to reduce water velocity for fish passage.

Entrance: the downstream end of a fishway, where upstream-migrating fish leave the tailwater and enter the fishway structure.

Exit: the upstream end of a fishway, where upstream-migrating fish enter the headwater.

Diadromous: fish that migrate between fresh water and the estuary/sea.

Drownout: when the river level rises such that there is no head loss between the upstream and downstream sides of a stream barrier.

Fishway: a fishway is a water passage around or through a stream barrier, designed to provide hydraulic conditions suitable for fish to pass the barrier without undue stress, delay or injury.

Fishlift: a type of fishway for high dams where fish ascend the dam face in a hopper and are delivered to the headwater for automatic release.

Fish lock: a type of fishway consisting of three chambers (entrance, lock and exit), where the lock chamber water level can rise to the headwater level via automated pipes, valves and gates.

Fish passage: an ecological process concerning fish movement within an aquatic environment. Specifically, fish passage is the directed movement (upstream, downstream and laterally to floodplains) of fish past a point in a stream.

Head differential: the difference in water height between the headwater and the tailwater.

Head loss: the vertical difference in water height, for example between two pools in a fishway; this is related to water velocity.

Headwater: the impounded water upstream of a stream barrier, usually defined by depth or variation in height.

Hydraulic gradient: a vector gradient between two or more hydraulic head measurements over the length of the flow path.

Operating range: the range of river levels (heights) for which a fishway is hydraulically designed to be operable.

Performance criteria: parameters used to determine whether a fishway is sufficiently performing its intended function. They fall into two groups: biological, and physical/hydraulic.

Performance standard: when specific values are set around performance criteria in order to meet ecological objectives, these become the performance standard and are measurable.

Potamodromous: a type of fish migration that occurs entirely in fresh water.

Rock ramp: a type of fishway where a low gradient (e.g. 1v:30h) rocky riffle is used to facilitate fish movement. The rocks can be placed in uniform lateral ridges or randomly.

Semelparous: fish that die after their once-in-a-lifetime spawning event.

Slope: also called gradient or inclination; the fishway slope determines the water velocities.

Sustained swimming speed: fish swimming at a cruising speed (three times their body length), which can be maintained for long periods (e.g. >200 min) without fatigue, but which is slower than burst speed.

Tailwater: the water immediately downstream of a stream barrier, usually defined by depth or variation in height.

Turbulence: a measure of the energy within a fishway pool, which is a function of the head loss, slot width, coefficient of discharge, and pool volume; usually a pool average is cited in W/m^3.

Vena contracta: the maximum water velocity through a vertical slot, at which the jet contracts just downstream of the slot. By convention, this figure should be cited for vertical-slot fishways, but water velocity is up to 20% lower if fish choose to avoid the *vena contracta*.

Flow vectors: the directional flow of water (this has particular significance at the entrance and exit of fishways).

Uplands stream: upland rivers and streams are the fast-flowing rivers and streams that drain elevated or mountainous country.

Vertical slot: A pool-type of fishway built within a channel, where water flows from one pool to the next through a full depth vertical slot.

Water velocity: the speed of water relative to ground speed.

7 References

Barrett, J. and Mallen-Cooper, M. (2006). The Murray River's 'Sea to Hume Dam' fish passage program: progress to date and lessons learned. *Ecological Management and Restoration* **7(3)**, 173–183.

Baumgartner, L.J. (2006). *A preliminary assessment of fish passage through a Denil fishway on the Edward River, Australia*. New South Wales Department of Primary Industries report to MDBA. MDBC Project No. MD524. 23 pp.

Baumgartner, L.J., Boys, C.A., Stuart, I.G. and Zampatti, B.P. (2010). Evaluating migratory fish behaviour and fishway performance: testing a combined assessment methodology. *Australian Journal of Zoology* **58**, 154–164.

Baumgartner, L.J. and Harris, J.H. (2007). Passage of non-salmonid fish through a Deelder lock on a lowland river. *River Research and Applications* **23**, 1058–1069.

Baumgartner, L.J., Reynoldson, N. and Gilligan, D.M. (2006). Mortality of larval Murray cod (*Maccullochella peelii peelii*) and golden perch (*Macquaria ambigua*) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* **57(2)**, 187–191 http://dx.doi.org/10.1071/MF05098.

Baumgartner, L., Zampatti, B., Jones, M., Stuart, I. and Mallen-Cooper, M. (2014). Fish passage in the Murray–Darling Basin, Australia: not just an upstream battle. *Ecological Management and Restoration* **15(S1)**, 28–39.

Bowman. M.B. (2002). Legal perspectives on dam removal. *BioScience* **52**, 739–747.

Broadhurst, B.T., Ebner, B.C. and Clear, R.C. (2012). A rock-ramp fishway expands nursery grounds of the endangered Macquarie perch (*Macquaria australasica*). *Australian Journal of Zoology* **60**, 91–100. http://dx.doi.org/10.1071/ZO12002

Cadwallader, P. (1977). *J. O. Langtry's 1949–50 Murray River investigations*. Fisheries and Wildlife Paper No. 13. 70 pp.

Clay, C.H. (1995). *Design of Fishways and Other Fish Facilities,* 2nd edn. Department of Fisheries of Canada, Ottawa. 301 pp.

Close, P. and Aland, G. (2001). *The impact of instream barriers on fish assemblages in lower reaches of the Broken River and Seven Creeks, and preliminary assessment of fish passage through the Euroa Town and Lake Benalla fishways, Victoria.* Produced for Goulburn Broken Catchment Management Authority. Technical Report prepared by Freshwater Ecology for Goulburn Broken Catchment Management Authority.

Crook, D. (2004). Is the home range concept compatible with the movements of two species of lowland river fish? *Journal of Animal Ecology* **73**, 353–366.

Crook, D.A., Koster, W.M., Macdonald, J.I., Nicol, S.J., Belcher, C.A., Dawson, D.R., O'Mahony, J., Lovett, D., Walker, A. and Bannam, L. (2010). Anadromous migrations by female tupong (*Pseudaphritis urvillii*) in coastal streams in Victoria, Australia. *Marine and Freshwater Research* **61**, 474–483.

Crook, D., Macdonald, J., Belcher, C., O'Mahony, D., Dawson, D., Lovett, D., Walker, A. and Bannam, L. (2008). *Lake Condah Restoration Project – biodiversity assessment.* Arthur Rylah Institute for Environmental Research Technical Report Series No. 180. Department of Sustainability and Environment, Heidelberg, Victoria.

David, B.O. and Hamer, M.P. (2012). Remediation of a perched stream culvert with ropes improves fish passage. *Marine and Freshwater Research* **63**, 440–449.

DEPI. (2013). *Victorian Waterway Management Strategy*. Department of Environment and Primary Industries, East Melbourne, Victoria.

Hardwick, R. (2005). *Assessment of barriers to fish passage in the Mallee*. Client report for the Mallee Catchment Management Authority.

Harris, J.H. (1986). Reproduction of the Australian bass, *Macquaria novemaculeata* (Perciformes: Percichthyidae) in the Sydney Basin. *Australian Journal of Marine and Freshwater Research* **37**, 209–235.

Humphries, P. and Walker, K. (2013). *Ecology of Australian Freshwater Fishes*. CSIRO Publishing, Collingwood, Victoria.

Jones, M.J. and O'Connor, J.P. (2014). *Monitoring the performance of fishways and fish passage works*. Arthur Rylah Institute for Environmental Research Technical Report Series No. 257. Department of Environment and Primary Industries, Heidelberg, Victoria.

Jones, M. and Stuart, I. (2008). Regulated floodplains – a trap for unwary fish. *Fisheries Management and Ecology* **15**, 71–79.

Jungwirth, M. (1998). River continuum and fish migration—going beyond the longitudinal river corridor in understanding ecological integrity. Pages 19–32 *in* Jungwirth, M., Schmutz, S. and Weiss, S. (eds) *Fish Migration and Bypasses*. Fishing News Books, Blackwell Science, Oxford, England.

Kingfisher Research (2007). Fish Passage at the Tarwin River Weir. Client Report for the Department of Sustainability and Environment.

Kingfisher Research (2008). Fish Passage at the Shepparton Weir Fishway. Client Report for Goulburn Broken Catchment Management Authority.

Kingfisher Research (2010a). Pollocksford Weir Rock Ramp fishway- concept drawings

Kingfisher Research (2010b). Sunday Creek fishway: Concept, construction and costing. Client Report for Goulburn Broken Catchment Management Authority.

Koehn, J.D., McKenzie, J.A., O'Mahony, D.J., Nicol, S.J., O'Connor, J.P. and O'Connor, W.G. (2009). Movements of Murray cod (*Maccullochella peelii peelii*) in a large Australian lowland river. *Ecology of Freshwater Fish* **18**, 594–602.

Koster, W.M. 2002. *An assessment of the Coburg Lake fishway*. Report to Melbourne Water. Freshwater Ecology, Department of Natural Resources and Environment, Melbourne.

Koster, W. and Crowther, D. (2003). *Assessment of the effect of Horseshoe Bend tunnel on fish passage and aquatic biota in the Thomson River, West Gippsland, Victoria*. Report to West Gippsland Catchment Management Authority, Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria (unpublished).

Koster, W., Dawson, D. and Crook, D. (2013). Downstream spawning migration by the amphidromous Australian grayling (*Prototroctes maraena*) in a coastal river in south-eastern Australia. *Marine and Freshwater Research* **64**, 31–41.

Kroes M.J., Gough P., Schollema P. P. & Wanningen H. (eds) (2006). From sea to source: practical guidance for restoration of fish migration in European rivers. Groningen: Interreg IIIC project 'Community Rivers', 119 pp. Available Online: http://www.hunzeenaas.nl/content/nieuws/documenten/1182_Guidancefromseatosource.pdf

Larinier, M. (2002). Pool fishways, pre-barrages and natural bypass channels. Pages 54–82 *in* Larinier, M., Travade, F. and Porcher, J.P. (eds) Fishways: Biological Basis, Design Criteria and Monitoring. *Bulletin Francais de la Peche et de la Pisciculture* **364**, 54–82.

Lintermans, M. (2007). *Fishes of the Murray Darling Basin: an introductory guide*. MDBC Publication No. 10/07. ISBN 1 921257 20 2.

Lucas, M.C. and Baras, E. (2001). *Migration of Freshwater Fishes*. Blackwell Science, Oxford, UK.

Mallen-Cooper, M. (1999). Developing fishways for non-salmonid fishes: a case study from the Murray River in Australia. Pages 173–195 *in* Odeh, M. (ed.) *Innovations in Fish Passage Technology*. American Fisheries Society, Bethesda, Maryland.

Mallen-Cooper, M. (2000a). Taking the mystery out of migration. Pages 101–111 *in* Hancock, D.A., Smith, D.C. and Koehn, J.D. (eds) *Proceedings of the 1999 Annual Workshop of the Australian Society for Fish Biology, Bendigo, Victoria*. Australian Society for Fish Biology, Sydney.

Mallen-Cooper, M. (2000b). *Review of fish passage in NSW*. Report to NSW Fisheries. Fishway Consulting Services.

Mallen-Cooper, M. and Stuart, I.G. (2007). Optimising Denil fishways for passage of small and large fishes. *Fisheries Management and Ecology* **14**, 61–71.

Mallen-Cooper, M., Zampatti, B., Stuart, I. and Baumgartner, L. (2008). Innovative fishways – manipulating turbulence in the vertical-slot design to improve performance and reduce cost. Produced for Murray–Darling Basin Commission. Fishway Consulting Services.

Marsden, T. (2002). *Goodga Creek Weir – report on fishway layout options*. Client Report For Western Australian Fisheries.

McDowall, R.M. (1996). *Freshwater Fishes of South-eastern Australia*. Reed Books, Sydney.

McGill, D. and Marsden, T. (2000). *Dumbleton weir fish lock assessment*. Queensland Fisheries Service Technical Report, Mackay, Queensland.

McGuckin, J. and Bennett, P. (1999). *An inventory of fishways and potential barriers to fish movement and migration in Victoria*. Waterways Unit, Department of Natural Resources and Environment, Melbourne.

MDBC. (2003). Native Fish Strategy for the Murray–Darling Basin 2003–2013. Murray–Darling Basin Ministerial Council.

Morgan, D. and Beatty, S. (2005). *The Goodga River Fishway – the first vertical-slot fishway in Western Australia: monitoring and evaluation*. Report to the Department of Fisheries, Government of Western Australia. Freshwater Fish Research, Murdoch University, Western Australia.

Morgan, D.L. and Beatty, S.J. (2006). Use of a vertical-slot fishway by galaxiids in Western Australia. *Ecology of Freshwater Fish* **15**, 500–509.

Naughton, G., Caudill, C., Peery, C., Clabough, T., Jepson, M., Bjornn, T. and Stuehrenberg, L. (2007). Experimental evaluation of fishway modifications on the passage behaviour of adult Chinook Salmon and Steelhead at Lower Granite Dam, Snake River, USA. *River Research and Applications* **23**, 99–111.

Northcote, T. (1998). Migratory behaviour of fish and its significance to movement through riverine fish passage facilities. Pages 3-19 *in* Jungwirth, M., Schmutz, S. and Weiss, S (eds) *Fish Migration and Fish Bypasses*. Fishing News Books, Blackwell Science, Oxford, England.

O'Brien, T.A., Mallen-Cooper, M. and Pitman, K.S. (2006). *Instream barriers of the Loddon and Campaspe catchments: assessment and prioritisation for fish passage.* Report to the North Central Catchment Management Authority. Arthur Rylah Institute for Environmental Research Technical Report Series No. 161, Department of Sustainability and Environment, Melbourne; Fishway Consulting Services, St Ives.

O'Brien, T., Ryan, T., Stuart, I. and Saddlier, S. (2010). *Review of fishways in Victoria 1996–2009*. Client Report No. 2010/84 for Sustainable Water Environments Division. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.

O'Connor, J. (2006). *Assessment of the Broken Creek Fishways Installation Program*. Report to Goulburn–Broken Catchment Management Authority. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.

O'Connor, J., Amtstaetter, F., Jones, M. and Mahoney, J. (2013). *Golden Perch movement in the Loddon River and Pyramid Creek: pilot study*. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.

O'Connor, J., Mallen-Cooper, M. and Stuart, I. (2016 in prep). Guidelines for design approval and construction of fishways. Arthur Rylah Institute for Environmental Research. For Water and Catchments Group, Department of Environment, Land, Water and Planning.

O'Connor, J.P., O'Mahony, D.J. and O'Mahony, J.M. (2005). Movements of *Macquaria ambigua*, in the Murray River, south-eastern Australia. *Journal of Fish Biology* **66**, 392–403.

O'Connor, J.P., O'Mahony, D.J., O'Mahony, J.M. and Glenane, T.J. (2006). Some impacts of low and medium head weirs on downstream fish movement in the Murray–Darling Basin in southeastern Australia. *Ecology of Freshwater Fish* **15**, 419–427.

O'Connor, J., Raymond, S. and Dodd, L. (2012). *Offsets for conservation of the EPBC Act-listed Australian grayling, Prototroctes maraena*. Arthur Rylah Institute for Environmental Research Technical Report Series No. 233, Department of Sustainability and Environment, Heidelberg, Victoria.

O'Mahony, J. and Lyon, J. (2007). *Monitoring of the Sydney Beach fishway on the Ovens River*. Arthur Rylah Institute for Institute for Environmental Research Client Report, Department of Sustainability and Environment, Heidelberg, Victoria.

O'Mahony, J. and Saddlier, S. (2007). *Guidelines for Broken Creek fishways operations*. Final (unpublished) report to the Living Murray Program, Murray–Darling Basin Commission, Canberra. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg.

Poff, L. and Hart, D. 2002. How dams vary and why it matters for the emerging science of dam removal. *BioScience* **52(8)**, 659–668.

Porcher, J. (2002). Fishways for eels. Pages 147–155 *in* Larinier, M., Travade, F. and Porcher, J.P. (eds) 'Fishways: biological basis, design criteria and monitoring'. *Bulletin Francais de la Peche et de la Pisciculture* **364**.

Pusey, B., Kennard, M. and Arthington, A. (2004). *Freshwater Fishes of North-eastern Australia*. CSIRO Publishing, Melbourne.

Reynolds, L.F. (1983). Migration patterns of five fish species in the Murray–Darling river system. *Australian Journal of Marine and Freshwater Research* **34**, 857–871.

Ryan, T., Stuart, I., O'Brien, T. and Saddlier, S, (2010). *Instream barrier assessment and prioritisation of the Lower Barwon River and Otways Streams*. Report for the Corangamite Catchment Management Authority.

Schmidt, D.J., Crook, D.A., O'Connor, J.P. and Hughes, J.M. (2011). Genetic analysis of threatened Australian grayling *Prototroctes maraena* suggests recruitment to coastal rivers from an unstructured marine larval source population. *Journal of Fish Biology* **78**, 98–111.

Schmidt, D.J., Crook, D.A., Macdonald, J.I., Huey, J.A., Zampatti, B.P., Chilcott, S, Raadik, T.A. and Hughes, J.M. (2014). Migration history and stock structure of two putatively diadromous teleost fishes, as determined by genetic and otolith analyses. *Freshwater Science* **33**, 193–206.

Soloman, D.J. and Beach, H.H. (2004). *Manual for the provision of upstream migration facilities for eel and elvers.* Science Report SC020075/SR2. Environment Agency, Bristol.

Stuart, I., Baumgartner, L. and Zampatti, B. (2008b). Lock gates improve passage of small-bodied fish and crustaceans in a low gradient vertical-slot fishway. *Fisheries Management and Ecology* **15**, 241–248.

Stuart, I., Berghuis, A., Long, P. and Mallen-Cooper, M. (2007). Do fish locks have potential in tropical rivers? *River Research and Applications* **23**, 269–286.

Stuart, I., Koehn, J., O'Brien, T., McKenzie, J. and Quinn, G. (2010). Too close for comfort: a fishway exit and a power station inlet. *Marine and Freshwater Research* **61**, 23–33.

Stuart, I. and Mallen-Cooper, M. (1999). An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical/sub-tropical river. *Regulated Rivers: Research and Management* **15**, 575–590.

Stuart, I. and Sharpe, C. (2012). *Assessment of Gunbower and Thomson's weir fishways.* Kingfisher Research. A report for North Central Catchment Management Authority. 45 pp.

Stuart, I., Zampatti, B. and Baumgartner, L. (2008a). Can a low-gradient vertical-slot fishway provide passage for a lowland river fish community? *Marine and Freshwater Research* **59**, 332–346.

Thorncraft, G. and Harris, J.H. (1997). Rock-ramp and lock fishways as tools for solving fish passage problems in New South Wales, Australia. Pages 203–226 *in* Berghuis, A.P., Long, P.E. and Stuart, I.G. (eds) *Second National Fishway Technical Workshop Proceedings*, *June 1997, Rockhampton, Queensland.* Department of Primary Industries, Brisbane.

Thorncraft, G. and Harris, J. (2000). *Fish passage and fishways in New South Wales: a status report*. Office of Conservation NSW Fisheries, Sydney Cooperative Research Centre for Freshwater Ecology Technical Report 1/2000.

Zampatti, B., Bice, C. and Jennings, P. (2011). *Movements of female Tupong in the lower lakes of the River Murray*. SARDI Aquatic Sciences Report No. 577. 32 pp.

Appendix 1: Pool hydraulics

Another complicating factor is that the accepted worldwide convention for citing head loss in a vertical slot is at the *vena contracta*, or the narrowest point of the water jet as it passes through the slot (where water velocity is at the *maximum*). Hence, for 0.1 m head loss, the maximum water velocity, at the *vena contracta*, is 1.4 m/s, but if fish choose to avoid this flow and swim to the sides of the slot, then the water velocity can be as little as 1.05 ms^{-1}.

The water velocity equation is: $V = \sqrt(2g\Delta h)$,

where:

V = water velocity (m/s)

g = acceleration due to gravity (9.8 m/s), which is a constant

Δh = head loss between pools (m).

For example, to calculate water velocity in a fishway with 0.1 m head loss, 1.4 m/s water velocities, 0.3-m-wide slots, 1 m pool depth, 0.294 m^3/s discharge and large pools (3 m long × 2 m wide × 1 m deep), the discharge is given by:

water velocity for the example fishway:

$V = \sqrt{}(2 \times 9.8 \times 0.1) = 1.4$ m/s

Fishway discharge

Fishway discharge (Q) is a function of the vertical-slot geometry and the water velocity. The discharge of water through a slot or through a fishway is a very important standard as it is a major factor influencing pool turbulence, fish attraction at the entrance, and also the ability of the fishway to operate at low flows. For many fishways on coastal rivers, particularly on tidal barriers, the discharge of the fishway is a recurring concern for managers and stakeholders, who prioritise limiting freshwater flow to the estuary. In these situations, vertical-slot fishways can be designed to operate with very little outflow (e.g. <3 ML/d), but it is also important to note that a fishway will not ‘drain’ a weirpool below the upstream channel invert level, nor will a fishway reduce a weirpool that has significant inflow. De-watering gates at the top of the fishway have *no regulating function*, as discharge is completely controlled by the slot, and this area is a common source of confusion for operators (see *Section 3: Operation Performance Standards*).

Discharge is often expressed by engineers in cumecs (cubic metres per second or m^3/s), but many fish biologists work in ML/d (megalitres per day); the conversion is 1 cumec = 86.4 ML/d. The fishway discharge equation is:

Q = Cd(VA),

where:

Q = discharge (ML/d)

Cd = coefficient of discharge (usually 0.7)

V = water velocity (m/s)

A = slot area.

For a vertical-slot fishway with 0.1 m head loss, 1.4 m/s water velocities, 0.3-m-wide slots, 1 m pool depth, 0.294 m^3/s discharge, and large pools (3 m long × 2 m wide × 1 m deep), the discharge is:

$Q = 0.7(1.4 \times 0.3) = 0.294$ cumecs (m^3/s).

Alternatively, 0.294 cumecs is equivalent to 25.4 ML/d (0.294 × 86.4).

When citing discharge (Q) and turbulence, it is important to state the coefficient of discharge (Cd), which is a measure of the contraction of the jet of water in a fishway. For most vertical-slot fishways, this figure is close to 0.7.

Turbulence

Turbulence is now recognised as an important factor for fish ascending fishways, particularly for small fish (Mallen-Cooper et al. 2008). Turbulence is the measure of the energy dissipation from flowing water into a fishway pool and is related to the pool volume and the head loss (and thus water velocity) of each pool. The volume of the pool is obtained from the dimensions (length, width and depth), and the energy is determined by the discharge (Q) of water into each pool (in turn determined by head loss and slot width). High turbulence can be a barrier to fish passage, because quiet water resting areas are effectively eliminated. In Australia prior to 1995, MDB fishways had a turbulence level of 105 W/m^3, but two decades later this was reduced to 25 W/m^3 for small fish (Mallen-Cooper et al. 2008, Stuart et al. 2008a). It is important to note that the power equation results in a single number, which is an *average* and thus overestimates power in the quiet zones of a fishway pool (i.e. behind the small baffle) and underestimates power in the high-energy areas (i.e. the impact zone on the channel wall immediately downstream of the slot). The average turbulence figure citation is a convention and broadly reflects fishway pool hydraulics.

The fishway power (W/m^3) equation is:

$P = (Q\Delta h\Gamma)/v$,

where:

> P = Power, watts/m^3 (W/m^3)
>
> Q = discharge (m^{3}s)
>
> Δh = head loss between pools (m)
>
> Γ = the weight density of water (9777 Newtons/m^3 at 25°C)
>
> V = pool volume (m^3) (calculated from length × width × depth)

For a vertical-slot fishway with 0.1 m head loss, 1.4 m water velocities, 0.3-m-wide slots, 1 m pool depth, 0.294 m^3/s discharge, and large pools (3 m long × 2 m wide × 1 m deep), the discharge is:

$P = (0.294 \times 0.1 \times 9777)/6 = 48$ W/m^3.

Appendix 2: Current Victorian fishways

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Barwon River	Baum's Weir	55	263470	5774310	CCMA	rock ramp	1998	3	5	unknown	CCMA	40	none	ecological consultants		none	WOW as reference only
Barwon River	Buckley Falls – modified capping	55	264000	5774030	CCMA	temp. rock ramp	1998	2	5	unknown	CCMA	1	none	ecological consultants		none	WOW as reference only
Barwon River	gauging weir @ Pollocksford	55	253529	5774488	CCMA	lateral-ridge rock ramp	1999 and 2010	6	1	unknown	DSE	60	none	ecological/ engineering consultants	Kingfisher Research (2010a)		WOW as reference only
Barwon River	lower breakwater	55	273920	5766640	CCMA	rock ramp/vertical slot	1995/2013 vertical slot	6	6	unknown	CCMA	15	preliminary only	ecological/ engineering consultants	proposed	proposed	WOW as reference only
Barwon River	old bluestone weir near Inverleigh	55	243750	5777920	CCMA	rock ramp	2001	6	5	unknown	CCMA	20	none	ecological consultants		none	WOW as reference only
Barwon River	stream gauge @ Inverleigh (McMillans)	54	762320	5773570	CCMA	rock ramp	2008	5	4	Private	DSE	60	none	ecological consultants		none	WOW as reference only
Barwon River	stream gauge @ Ricketts Marsh (Conns)	54	747660	5754284	CCMA	rock ramp	2001 and 2008	4	2	unknown	DSE	120	none	ecological consultants		none	WOW as reference only
Blind Creek	Anglesea Estuary Tributary	54	778403	5743939	CCMA	culvert removal	2007	5	4	Surf Coast Shire	SCS	5	none	engineering consultants		none	
Carisbrook Creek	old road crossing	54	744300	5713800	CCMA	culvert removal	2000	5	4	unknown	CCMA	15	none	ecological consultants		none	WOW as reference only
Cumberland River	gauging weir @ Lorne	54	756800	5726500	CCMA	rock ramp	2007	5	2	unknown	DSE	69	none	ecological consultants		none	WOW as reference only
Cumberland River	road crossing at caravan park	54	756940	5726243	CCMA	modified culvert	2007	4	4	private	CCMA	15	none	ecological consultants		none	WOW as reference only
Curdies River	private crossing D/S (Nisjken property)	54	668420	5739850	CCMA	culvert removal	2010	5	4	private	private	10	none	CCMA		none	
Curdies River	gauging weir @ Curdie	54	670300	5744000	CCMA	rock ramp/weir removal 2013	1999 and 2010/2013	6	2	unknown	DSE	25	none	ecological/ engineering consultants		none	WOW as reference only
Dewing Creek	weir at Barwon Downs – flows to East Barwon	54	741790	5738610	CCMA	hybrid rock ramp/slot	Prop. 2011 – Phil M email 30/3/11 constructed ~2012	2	1	Barwon Water	BW	14.5 max.	none	unknown		none	
East Barham River	Barham River Road	54	727711	5707669	CCMA	barrier removed	2007	5	4	unknown	CCMA	52	none	ecological consultants		none	WOW as reference only
East Barham River	gauging weir @ Apollo Bay	54	728100	5707114	CCMA	rock ramp	2001 and 2010	6	2	unknown	DSE	57	none	ecological/ engineering consultants		none	WOW as reference only
Gellibrand River	ford below Stevensons Falls	54	731394	5727805	CCMA	rock ramp	2008	6	4	unknown	CCMA	21	none	ecological consultants		none	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Gellibrand River	gauging weir @ Burrupa	54	695641	5714161	CCMA	rock ramp	unknown	5	2	unknown	DSE	80	none	ecological consultants		none	WOW as reference only
Gellibrand River	North Otway Pump Station (Wannon Water)	54	706320	5729460	CCMA	rock ramp	2000 and 2010	5	1	Wannon Water	CCMA	80	2012	CMA		none	
Gellibrand River	gauging weir @ Carlisle River	54	706495	5729385	CCMA	rock ramp	2001 and 2006 and 2010	5	1	unknown	DSE	54	none	ecological consultants		none	WOW as reference only
Gellibrand River	Clancy access ford crossing	54	722955	5731805	CCMA	modified ford	2011	3	4	Colac Otway Shire	COS	30	none	CMA			
Gellibrand River	gauging weir @ Gellibrand	54	722461	5731952	CCMA	weir cut	2011	5	2	DELWP	unknown	2	none	ecological consultants			
Gellibrand River	gauging weir @ Upper Gellibrand	54	731434	5728345	CCMA	rock ramp	2008	5	2	unknown	DSE	24	none	ecological consultants		none	WOW as reference only
Grassy Creek	farm culvert	55	240500	5736400	CCMA	modified culvert	1999	4	4	private	private	9	none	ecological consultants		none	WOW as reference only
Grassy Creek	farm culvert	55	240700	5736400	CCMA	modified culvert	1999	4	4	private	private	9.3	none	ecological consultants		none	WOW as reference only
Grassy Creek	small farm weir	55	240900	5736400	CCMA	rock ramp	1999	4	5	private	private	9	none	ecological consultants		none	WOW as reference only
Jamieson River	old road crossing	54	754100	5723700	CCMA	removed	1998	5	4	private	unknown	10	none	ecological consultants		none	WOW as reference only
Kennedys Creek	gauging weir @ McIntyres Bridge	54	696649	5726554	CCMA	lateral-ridge rock ramp	1999 and2011	5	2	unknown	DSE	15	none	ecological consultants		none	WOW as reference only
Lardners Creek	Gellibrand east Road – stream gauge	54	721785	5731881	CCMA	rock ramp	2010	4	2	unknown	CCMA	14	none	ecological consultants	none	none	WOW as reference only
Loves Creek	Gauging weir @ Gellibrand	54	724316	5737455	CCMA	rock ramp	1998	4	2	unknown	DSE	20	none	ecological consultants		none	WOW as reference only
Scotts Creek	Murfitts Rd weir (grade control weir)	54	687260	5742450	CCMA	rock ramp	2010	4	7	unknown	CCMA	10	none	CCMA			
Scotts Creek	Digneys Bridge	54	673586	5742558	CCMA	rock ramp	2010	5	2	unknown	DSE	33	none	ecological consultants	none	none	WOW as reference only
Skenes Creek	private ford crossing (Bufe)	54	734980	5711128	CCMA	lateral-ridge rock ramps	2011	6	4	private	private	10	2010/2012	ecological consultants			
Skenes Creek	pipe culvert crossing (Skenes Creek Valley Rd)	54	735251	5710868	CCMA	lateral-ridge rock ramps	2011	6	4	unknown	DSE	2	2010/2013	ecological consultants		none	WOW as reference only
St George River	footbridge U/s GOR	54	758257	5728480	CCMA	bedrock cut	2012	4	2	DELWP	DEPI	5	none	CCMA			
St George River	disused stream gauge at Allenvale	54	757832	5729130	CCMA	weir cut	2012	4	4	DELWP	DEPI	10	none	CCMA			

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Thompson Creek	Horseshoe Bend Road	55	268171	5760808	CCMA	box culvert and baffles	2004	4	4	unknown	CCMA	79	none	ecological consultants		none	WOW as reference only
Thompson Creek	Point Impossible Road wetlands culvert	55	270342	5757614	CCMA	box culvert	2004	5	4	unknown	CCMA	10	none	ecological consultants		none	WOW as reference only
Thompson Creek	tidal barrage	55	271303	5759880	CCMA	rock ramp	2000	3	6	unknown	CCMA	11	none	ecological consultants		none	WOW as reference only
West Barham River	redundant weir	54	728642	5705960	CCMA	barrier removed	2008	6	1	private	CCMA	40	none	ecological consultants		none	WOW as reference only
Waurn Ponds Creek	pedestrian crossing – notch removed, rock ramp constructed	55	792617	5767597	CCMA	rock ramp	1999?										
Wild Dog Creek	'Binnawee' upstream of GOR	54	732862	5710146	CCMA	barrier removed	2009	5	5	private	CCMA	35	none	ecological consultants		none	WOW as reference only
Yahoo Creek	redundant weir	54	725424	5738126	CCMA	barrier removed	2011	6	2	DELWP	DEPI	15	none	CCMA			
Betka River	water supply pump weir	55	737200	5836700	EGCMA	rock ramp	2000	2	1	SRW	SRW/EGC MA	50	none	ecological consultants		none	WOW as reference only
Gippsland Lakes	Eastern Beach Cunningham Arm causeway	55	589327	5807606	EGCMA	barrier removed	2003	5	4	EGCMA	EGCMA	5	none	ecological consultants		none	WOW as reference only
Mitchell River	Bairnsdale Barrage (Hillside Weir – rock)	55	552140	5813330	EGCMA	rock ramp	2001 – washed out 2009	1	6	SRW	EGCMA	450	none	ecological consultants		none	WOW as reference only
Campaspe River	Echuca gauging weir	55	296267	5997646	NCCMA	lateral-ridge rock ramp	proposed 2014	construction mid-2014	2	DSE	DSE		none	none	none	none	WOW as reference only
Gunbower Creek	Cohuna Weir	55	248916	6033844	NCCMA	vertical slot proposed	proposed	not constructed	1	GMW	GMW		none	none	none	none	WOW as reference only
Gunbower Creek	Gunbower Weir	55	263413	6018000	NCCMA	vertical slot	completed 2012	completed 2009	1	GMW	GMW		Stuart and Sharpe 2012	ecological/ engineering consultants (SKM design - Ross Middleton)	none – drafted by CMA but not finalised; nothing official	none	WOW as reference only
Gunbower Creek	Thompson's Weir	55	263406	6017940	NCCMA	rock ramp fishway 2012	fishway constructed then de-commissioned 2012	3 – works in a very limited fashion currently; scheduled for re-design post 2014	1	GMW	GMW		Stuart and Sharpe 2012	SKM design - Ross Middleton	none	none	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Gunbower Creek	Hipwell Road Weir – in Gunbower Creek	55	2611438	6028664	NCCMA	vertical slot	completed late 2103	completed late 2103	7 – environ mental watering	MDBA	GMW		Funding available from MDBA	ecological/ engineering consultants - URS Steve Slarke and MMC	to be completed prior to structure being handed over to GMW operations	GMW maintenance manual will be completed	WOW as reference only
Taylor's Lagoon	currently unregulated	55			NCCMA	new regulating structure proposed in GMW CP Business Case to remove lagoon from irrigation system and return to the environment	subject to success of Business Case			GMW	GMW						
Cockatoo Lagoon	pipe culverts and vertical lift gate	55			NCCMA	Proposed in GMW CP Business Case to Australian Government: remove lagoon from irrigation system and return to the environment. Replace pipe culvert with box culverts (flows without fish passage when closed). Replace vertical-lift gate with side-winding gate.	subject to success of Business Case			GMW	GMW						
Pyramid Creek	Box Creek Weir	55			NCCMA	fish lock	construction to be completed by August 2015	not yet constructed	1	GMW	GMW	provi des acces s to Kow Swa mp		ecological/ engineering consultants - detailed design by GHD with Dr Ivor Stuart	none – will be completed at end of constructio n	GMW maintenance manual will be completed	WOW as reference only
Loddon River	Kerang Weir	54	764144	6045014	NCCMA	vertical slot	2008	4	1	GMW	GMW	40	pre- and post-fish surveys	ecological/ engineering consultants	none	none	WOW as reference only
Loddon River	sill at bridge upstream of Kerang Weir	54	764040	6044951	NCCMA	Rectangular channel in sill	2008	5	4	unknown	GMW	1	none	none	none	none	WOW as reference only
Spur Creek	Hipwells Rd Offtake regulator – on channel	55	2611438	6028664	NCCMA	fish lock	complete late 2013	complete	7 – environ mental watering	MDBA	GMW	N/A	funding available from MDBA	ecological/ engineering consultants - - URS Steve Slarke and MMC	to be completed prior to structure being handed over to GMW operations	GMW maintenance manual will be completed	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Yarran Creek	Yarran Ck regulator	55	249730	6038821	NCCMA	vertical slot	completed 2010/2011	completed	7 – environ mental watering	MDBA	GMW		funding available from MDBA	SKM Ross Middleton	none – but to be completed	GMW maintenance manual will be completed by 2014	WOW as reference only
Avoca River	mosquito sills				NCCMA	Rock ramp	2014	not constructed	flow control	NCCMA	NCCMA			SKM	maintain existing height		
Loddon River	chute				NCCMA	to be determined	2014	not constructed	7 diversion	NCCMA	NCCMA			TBA	none		
Albert River	river crossing at Hiawatha Falls	55	453839	5735217	WGCMA	unknown	reported August 2004	2	4	unknown	DSE	9	none	none	none	none	WOW as reference only
Alsop Creek	gauging station at Loch	55	387451	5752350	WGCMA	rock ramp		2	2	unknown	DSE	5	none	none	none	none	WOW as reference only
Archies Creek	water diversion	55	374733	5732099	WGCMA	rock ramp	reported August 2004	2	1	unknown	unknown	21	none	none	none	none	WOW as reference only
Billy's Creek	gauging weir at Jerralang	55	448178	5755411	WGCMA	rock ramp		2	2	unknown	DSE	5	none	none	none	none	WOW as reference only
Flynn Creek	gauging weir	55	473758	5777511	WGCMA	rock ramp	reported August 2004	2	2	unknown	DSE	6	none	none	none	none	WOW as reference only
Franklin River	concrete wall ('Old Hydro') at Toora	55	439770	5724093	WGCMA	unknown	reported August 2004	2	5	unknown	DSE	44	none	none	none	none	WOW as reference only
Franklin River	river crossing at Toora	55	440550	5724945	WGCMA	unknown	reported August 2004	2	4	unknown	unknown	3	none	none	none	none	WOW as reference only
Macks Creek	gauging station at Macks Creek	55	437710	5742005	WGCMA	rock ramp	reported August 2004	2	2	unknown	DSE	11	none	none	none	none	WOW as reference only
Middle Creek	gauging station at Tarra Valley				WGCMA	rock ramp		2	2	unknown	DSE	5	none	none	none	none	WOW as reference only
Ness Gully	gauging station at Korumburra	55	397227	5747251	WGCMA	rock ramp	reported August 2004	2	2	unknown	DSE	1	none	none	none	none	WOW as reference only
Spring Creek	gauging station at Won Wron	55	475145	5742416	WGCMA	rock ramp	reported August 2004	2	2	unknown	DSE	8	none	none	none	none	WOW as reference only
Tarra River	water diversion	55	471684	5734392	WGCMA	unknown	reported August 2004	2	1	unknown	DSE	5	none	none	none	none	WOW as reference only
Tarwin River	weir at South Gippsland Highway	55	412172	5729155	WGCMA	lateral-ridge rock ramp	2010	5	1	WG CMA	DSE	25	O'Connor 2010	ecological/ engineering consultants	Kingfisher Research 2007	Kingfisher Research 2007	WOW as reference only
Tarwin River East	gauging station at Turtons Creek	55	481238	5733552	WGCMA	rock ramp	reported August 2004	2	2	unknown	DSE	25	none	none	none	none	WOW as reference only
Thomson River	Cowwarr knife-edge weir	55	469820	5794492	WGCMA	rock ramp	1998 – upgrade complete 2013	5	2	unknown	DSE	20	Koster 2002	ecological/ engineering consultants	none	none	WOW as reference only
Thomson River	Easton Weir	55	435600	5826300	WGCMA	rock ramp	1995	2	1	unknown	SRW	230	none	none	none	none	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Thomson River	Horseshoe tunnel	55	448800	5797500	WGCMA	bypass proposed	proposed 2010/2011	not constructed	5	unknown	WGCMA	250	pre-fishway assessment (Koster and Crowther 2003)	none	none	none	WOW as reference only
Thomson River	Rainbow Creek confluence	55	481835	5793887	WGCMA	rock ramp	1998 – upgrade due 2009	2	7	WG CMA	DSE	20	none	none	none	none	WOW as reference only
Tidal River	Storage pump weir	55	442400	5680300	WGCMA	rock ramp	2000	2	1	PV	PV	20	none	none	none	none	WOW as reference only
Big Pats Creek	McLeans Road	55	389750	5820106	MW	debris blockage removed	2007/2008	6	7	MW	MW	5	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	11 Mile Road (concrete drop structure)	55	380000	5777600	MW	rock ramp	1999	4	3	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	Ellis Road (rock chutes)	55	390680	578500	MW	rock chutes	2000	5	3	MW	MW	5		ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	Evans Road (steel sheet drop structure)	55	387300	5780400	MW	rock ramp	2000	4	3	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	Iona gauge (steel sheet)	55	384800	5779000	MW	rock ramp	2000	4	3	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	Tonimbuk Gauge (steel sheet)	55	390800	5789200	MW	rock ramp	2000	4	3	MW	MW	120	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	Vervale (steel sheet drop structure)	55	383800	5778800	MW	rock ramp	1999	4	3	MW	MW	10	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Bunyip River	water tower (concrete drop structure)	55	367200	5771600	MW	rock ramp	1998	4	3	MW	MW	14	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Cardinia Creek	Chadwick Road	55	357907	5794744	MW	rock ramp	2007/2008	4	2	MW	MW	4	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Cardinia Creek	McCormicks Road	55	359890	5779740	MW	rock ramp		2	3	MW	MW	4	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Cardinia Creek	barriers downstream of Thompsons Road	55	358810	5782500	MW	rock ramp	2005/2006	4	3	MW	MW	8	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Cardinia Creek	drop structure near Thomsons Road	55	358200	5782840	MW	Bypass	2005/2006	4	3	MW	MW	20	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Cardinia Creek	Princes Freeway crossing, Beaconsfield	55			MW	lateral-ridge rock ramp	2013	4		MW	MW			ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Dandenong Creek	Ferntree Gully Road	55	342220	5802820	MW	rock ramp	2010	2	1	MW	MW		pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Darebin Creek	Bell St crossing stabilisation	55	326736	5820210	MW	rock ramp	2000	3	3	MW	MW	10	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Darebin Creek	Darebin Parklands ford	55	329922	5817656	MW	rock ramp	1999	2	4	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Darebin Creek	Latrobe Golf Course weir	55	327334	5825527	MW	rock ramp	1999	4	1	MW	MW	80	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Deep Creek	concrete weir at Bolinda	55	306700	5855300	MW	rock ramp	2004	2	1	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Deep Creek	disused gauge at Darraweit Guim	55	312700	5858500	MW	unknown	2004	2	2	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Deep Creek	ford at Darraweit Guim	55	312700	5858500	MW	rock ramp	2004	2	4	MW	MW	5	none	None	none	MW Capital Maintenance Program	MW CEPHA
Deep Creek	weir at Bulla	55	305913	5832795	MW	rock ramp	2004	2	1	MW	MW	5	none	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Dunns Creek	Dunns Creek Road	55	329219	5754039	MW	rock ramp	2009/10	2	4	MW	MW	5	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Emu Creek	Clarkefield	55	299700	5850900	MW	rock ramp	2004	2	2	MW	MW	5	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Eumemmerring Creek	Abbotts Road	55	343934	5789042	MW	rock ramp	2007/08	2	2	MW	MW	10	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Grace Burn Creek	Wallace Parade	55	371076	5831678	MW	rock ramp	2007/08	2	1	MW	MW	5	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Hoddles Creek	Glenview Road	55	375441	5815704	MW	rock ramp	2007/08	2	4	MW	MW	5	pre-fish survey	ecological/ engineering consultants		MW Capital Maintenance Program	MW CEPHA
Jacksons Creek	gauging weir @ Sunbury	55	300565	5838012	MW	no fishway	no fishway	no fishway	2	MW	MW	5	none	None	none	unknown	
Lang Lang River	Heads Road drop structure	55	380864	5767438	MW	vertical slot	Designed 2010	not constructed	3	MW	MW	0	none	ecological/ engineering consultants	TBD	MW Capital Maintenance Program	MW CEPHA
Lerderderg River	diversion weir in gorge	55	270925	5837765	MW	pool and weir	1980	1	1	MW	MW	0	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Little Yarra River	gauging station @ Yarra Junction	55	379073	5817451	MW	partial rock ramp	2005/2006	4	2	MW	MW	100	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Maribyrnong River	Arundell Rd Weir	55	308800	5824700	MW	partial rock ramp	1999 and 2009	4	1	MW	MW	10	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Maribyrnong River	Brimbank Park Ford	55	308600	5822000	MW	culvert and rock ramp	2001 and 2009	2	4	MW	MW	1	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Maribyrnong River	Garden Avenue Weir/Ford – Brimbank Park	55	309310	5822250	MW	partial rock ramp	2001 and 2009	2	2	MW	MW	10	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Maribyrnong River	McNabs Weir	55	308100	5824900	MW	partial rock ramp	2002 (in re-design)	3	1	MW	MW	200	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Maribyrnong River	old weir near Keilor Park Drive/Brimbank Park	55	310340	5822025	MW	unknown	unknown	not constructed	unknown	MW	MW	0	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Merri Creek	Coburg Lake	55	321300	5821500	MW	rock ramp	2001	2	1	MW	MW	90	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Merri Creek	Craigieburn East gauge – dilution monitoring	55			MW	rock ramp		6	2	MW	MW	10		ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Merricks Creek	culverts – Balnarring Road	55	334439	5749848	MW	rock ramp	2005	4	4	MW	MW	1	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Merricks Creek	culverts – Bittern–Dromana	55	334549	5753244	MW	rock ramp	2005	4	4	MW	MW	0.2	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Merricks Creek	Disused gauge at Hanns Creek Reserve	55	334221	5751749	MW	weir removed	2005	6	2	MW	MW	15	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Mordialloc Creek	waterways Estate wetland	55	335198	5790611	MW	partial rock ramp	2006/2007	3	4	MW	MW	9.5	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Mordialloc/ Dandenong Creek	Pillars Crossing	55	336126	5789627	MW	rock ramp	2006/2007	1	1	MW	MW	4	pre-fish survey	ecological/ engineering consultants	maintain flows to Mordialloc Ck/ Patterson River	MW Capital Maintenance Program	MW CEPHA
Mullum Mullum Creek	downstream of Reynolds Road	55	340080	5818630	MW	rock ramp	unknown	2	3	MW	MW	5		ecological/ engineering consultants	maintain flows to Mordialloc Ck/ Patterson River	MW Capital Maintenance Program	MW CEPHA
Patterson River	National Water Sports Centre	55	337537	5786154	MW	partial rock ramp	2006/2007	3	5	MW	MW	16.9	pre-fish survey	ecological/ engineering consultants	None	MW Capital Maintenance Program	MW CEPHA
Patterson River	Pillars Crossing	55	340500	5788900	MW	rock ramp	2007/2008	1	2	MW	MW	4	pre-fish survey	ecological/ engineering consultants	maintain flows to Mordialloc Ck/ Patterson River	MW Capital Maintenance Program	MW CEPHA
Stoney Creek	Research–Warrandyte Road	55	342356	5823070	MW	rock ramp	2007/2008	2	2	MW	MW	5	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Tarago River	Gauging station at Fishers Road, Robin Hood	55	397546	5783864	MW	rock ramp	2009	3	2	MW	MW	72	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Trib Coolart Creek	culverts – Stanleys Road	55	332141	5750920	MW	Box culvert	2005	4	4	MW	MW	3	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Watsons Creek	Eltham–Yarra Glen Road	55	346276	5829353	MW	rock ramp	2007/08	2	1	MW	MW	10	pre-fish survey	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Woori Yallock Creek	gauging weir @ Woori Yallock, Seville East	55	368990	5818644	MW	rock ramp	2006/2007	3	2	MW	MW	174	pre- and post-fish surveys	ecological/ engineering consultants	none	MW Capital Maintenance Program	MW CEPHA
Yarra River	Dight's Falls	55	324000	5814828	MW	rock ramp and vertical slot	1994 and vertical slot 2012	5	1	MW/PV	PV	1200	pre- and post-fish surveys	ecological/ engineering consultants	TBD	MW Capital Maintenance Program	MW CEPHA
Murray River	Mildura Weir	55			GMW	Denil	completed 2013	commissionin g late 2013		GMW	GMW		none	ecological/ engineering consultants	none	none	WOW as reference only
Murray River	Yarrawonga Weir	55			GMW	fish lock	1996			GMW	GMW		none	ecological/ engineering consultants	none	none	WOW as reference only
Chalka Creek	Chalka Creek North				Mallee CMA	rock ramp	no fishway			GMW constructin g							see Steve Nicol email 23/11/12
Chalka Creek	Chalka Creek South				Mallee CMA	rock ramp	no fishway			GMW constructin g							see Steve Nicol email 23/1/13
Mullarroo Creek	inlet ford crossing				Mallee CMA	vertical slot	completed 2012/13	complete						ecological/ engineering consultants			
Boosey Creek	Katamatite Weir				GBCMA	rock ramp	2000	2	1	GMW	GMW	30	none	unknown	unknown	unknown	WOW as reference only
Boosey Creek	Mid Boosey				GBCMA	unknown	investigate 2002	2	1	GMW	GMW	12	none	unknown	unknown	unknown	WOW as reference only
Boosey Creek	Tungamah Weir				GBCMA	unknown	designed at 2002	2	1	GMW	GMW	36	none	unknown	unknown	unknown	WOW as reference only
Broken Creek	Chinaman's Weir	55	337822	6009296	GBCMA	vertical slot	2000	5	1	GMW	GMW	5	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Gilmours Bridge gauge				GBCMA	rock ramp	2000	2	2	GMW	DSE			unknown	unknown	unknown	WOW as reference only
Broken Creek	Harding's Weir	55	327311	6008830	GBCMA	vertical slot	1999	5	1	GMW	GMW	13	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Irvine's Weir-Tungamah				GBCMA	rock ramp	2010	not constructed	unknow n	GMW	GMW	0			unknown	unknown	WOW as reference only
Broken Creek	Katandra Weir (Broken Weir)	55	374664	6003186	GBCMA	vertical slot	1999	2	1	GMW	GMW	100		ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Kennedy's Weir	55	320900	6011700	GBCMA	vertical slot	1997	5	1	GMW	GMW	9	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Luckes Weir	55	331779	6009193	GBCMA	vertical slot	2000	5	1	GMW	GMW	9	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Broken Creek	Magnasson's (Ball's) Weir	55	334657	6010840	GBCMA	vertical slot	2002	5	1	GMW	GMW	5	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Melville St Numurkah Weir	55	359736	6004469	GBCMA	vertical slot	2001	5	1	GMW	GMW	25	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Nathalia Town Weir	55	338887	6007294	GBCMA	vertical slot	1999	5	1	GMW	GMW	45	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	O'Reilly's Weir-Tungamah	55	398850	5996975	GBCMA	rock ramp designed	not constructed	not constructed	1	GMW	GMW	0			unknown	unknown	WOW as reference only
Broken Creek	Rices Weir	55	316400	5917600	GBCMA	vertical slot	1997	5	1	GMW	GMW	13	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Schiers Weir	55	323300	5917600	GBCMA	vertical slot	1998	5	1	GMW	GMW	9	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken Creek	Station St Numurkah Weir	55	359065	6003988	GBCMA	vertical slot	2003	5	1	GMW	GMW	1	O'Connor 2006	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken River	Benalla Weir	55	408362	5954782	GBCMA	vertical slot	2000	4	1	GMW	GMW	100	Close and Aland 2001	ecological/ engineering consultants	O'Mahony and Saddlier 2007	unknown	WOW as reference only
Broken River	Broken Creek Offtake				GBCMA	investigate	investigate	5	1	GMW	GMW				unknown	unknown	WOW as reference only
Broken River	Casey's Weir	55	405069	5962808	GBCMA	vertical slot	2005	5	1	GMW	GMW	40	O'Connor 2006		unknown	unknown	WOW as reference only
Broken River	Gowangardie Weir	55	381990	5967067	GBCMA	remove/v-slot proposed	deferred 02/03	not constructed	1	GMW	GMW	0			unknown	unknown	WOW as reference only
Broken River	Hollands Creek Offtake				GBCMA	unknown	investigate 2002	2	1	GMW	GMW				unknown	unknown	WOW as reference only
Broken River	Rupertsdale ford	55			GBCMA	bridge 2013				GBCMA	GBCMA			ecological/ engineering consultants	unknown	unknown	WOW as reference only
Broken River	Harris property crossing	55			GBCMA	rock ramp	investigation 2013	investigation 2013		GBCMA	GBCMA			ecological/ engineering consultants	unknown	unknown	WOW as reference only
Broken River	Broken River Weir (Mokoan offtake)	55			GBCMA	investigation 2013	investigation 2013	investigation 2013		GBCMA	GBCMA	48.5		ecological/ engineering consultants	unknown	unknown	WOW as reference only
Castle Creek	East Goulburn Main Channel Syphon				GBCMA	rock ramp	2002	2	7	GMW	GMW	5			unknown	unknown	WOW as reference only
Castle, Creightons, Pranjip Creeks	grade controls x 5 completed				GBCMA	erosion rock ramp	2000	2	3	GBCMA	GBCMA	20			unknown	unknown	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Goulburn River	Cooks Cut				GBCMA	erosion rock ramp	1998	2	3	GBCMA	GBCMA	5			unknown	unknown	WOW as reference only
Goulburn River	Fidge's Cutting				GBCMA	erosion rock ramp	2000	2	3	GBCMA	GBCMA	5			unknown	unknown	WOW as reference only
Goulburn River	Jordan's Bend				GBCMA	erosion rock ramp	2000	2	3	GBCMA	GBCMA	5			unknown	unknown	WOW as reference only
Goulburn River	Nobbies Cut				GBCMA	erosion rock ramp	2001	2	3	GBCMA	GBCMA	5			unknown	unknown	WOW as reference only
Goulburn River	Pells Cut				GBCMA	erosion rock ramp	1999	2	3	GBCMA	GBCMA	5			unknown	unknown	WOW as reference only
Goulburn River	Shepparton Weir	55	353740	5974626	GBCMA	rock ramp	2009	5	1	GBCMA	DSE	100	O'Mahony and Lyon 2007	ecological/ engineering consultants	Kingfisher Research (2008)	Kingfisher Research (2008)	WOW as reference only
Goulburn River	Thomson's Cuttting				GBCMA	rock ramp	1998	2	unknow n	GBCMA	GBCMA	5			unknown	unknown	WOW as reference only
Gulf Creek	Gulf regulators				GBCMA	vertical slot proposed	in design 2010	not constructed	unknow n	GMW	GMW	0		ecological/ engineering consultants	unknown	unknown	WOW as reference only
Hollands Creek	Mokoan Offtake Weir				GBCMA	unknown	investigate 2002	2	1	GMW	GMW	5			unknown	unknown	WOW as reference only
Honeysuckle Creek	Honeysuckle Reservoir removal	55	387850	5938715	GBCMA	removed chute	2005	2	1	GMW	GMW	10			unknown	unknown	WOW as reference only
Hughes Creek	Avenel gauge	55	346900	5908700	GBCMA	rock ramp	2000	2	2	GMW	DSE	50	Snobs Creek – 2000	ecological/ engineering consultants	unknown	unknown	WOW as reference only
Nine Mile Creek	Katandra Weir (Nine Mile Weir)	55	374664	6003186	GBCMA	vertical slot		2	1	GMW	GMW	20		engineering consultants	unknown	unknown	WOW as reference only
Nine Mile Creek	Shep Drain 12 outfall weir				GBCMA	rock ramp	2000	2	1	GMW	GMW	10			unknown	unknown	WOW as reference only
Nine Mile Creek	Wunghnu Weir	55			GBCMA	rock ramp	2000 and upgrade proposed mid-2014	5	1	GMW	GMW	10			unknown	unknown	WOW as reference only
Pranjip Creek	East Goulburn Main Channel Syphon	55	348626	5945817	GBCMA	rock ramp	2002	2	7	GMW	GMW	5			unknown	unknown	WOW as reference only
Seven Creeks	East Goulburn Main Channel Syphon	55	360132	5955771	GBCMA	unknown	investigate 2002	2	7	GMW	GMW	10			unknown	unknown	WOW as reference only
Seven Creeks	Euroa Park Weir	55	372726	5931634	GBCMA	Vertical slot	2000	5	5	GMW	GMW	60	Close and Aland 2001	ecological/ engineering consultants	unknown	unknown	WOW as reference only
Sugarloaf Creek	ford road crossing	55	330101	5899313	GBCMA	lateral-ridge rock ramp	2010	5	4	unknown	GBCMA	3	none	ecological/ engineering consultants	none	Kingfisher Research (2010b)	WOW as reference only
Ovens River	Sydney Beach Weir (Wangaratta)	55	439000	5976800	NECMA	bypass	2000 and upgrade completed 2012	6	5	unknown	GMW	160	O'Mahony and Lyon 2007	none	none	none	WOW as reference only

Waterway	Barrier	Zone	Easting	Northing	CMA region	Fishway type	Construction date	Fish effectiveness	Barrier purpose	Owner	Manager	Km u/s	Assess-date/type	Design consultation	Operating rules	Maintenance plan	Legislation/Guidelines referred to, e.g. Works on waterways Permit
Ovens River	Tea Garden Creek diversion	55	457600	5965670	NECMA	fishway proposed	designed – funding issue	not constructed	1	unknown	GMW		none	none	none	none	WOW as reference only
Snowy Creek	Snowy Creek Weir	55	533817	5956523	NECMA	rock ramp	1998	2	5	local COM	Mitta Mitta COM	40	none	unknown	no rules, informal operation of boards in summer	Mitta Mitta Swimming Reserve Risk Assessment and Treatment Plan – Draft: January 2007	WOW as reference only

Appendix 3: Timing of Victorian fish movements

Common name	Stage	Direction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Silver Perch	Larva													
	Juvenile													
	Adult	upstream									■	■	■	■
Murray Hardyhead	Larva	unknown												
	Juvenile													
	Adult													
Unspecked Hardyhead	Larva													
	Juvenile													
	Adult													
Two-spined Blackfish	Larva													
	Juvenile													
	Adult													
Barred Galaxias	Larva													
	Juvenile													
	Adult													
Riffle Galaxias	Larva													
	Juvenile													
	Adult													
Western Carp Gudgeon	Larva													
	Juvenile													
	Adult													
Trout Cod	Larva											■	■	
	Juvenile													
	Adult									■	■	■	■	■
Murray Cod	Larva	Downstream										■	■	
	Juvenile													
	Adult	Upstream and downstream								■	■	■	■	■
Golden Perch	Larva	Downstream										■	■	

Common name	Stage	Direction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Juvenile	Upstream	■	■								■	■	■
	Adult	Upstream and downstream									■	■	■	■
Macquarie Perch	Larva													
	Juvenile													
	Adult	Upstream									■	■	■	■
Murray–Darling Rainbowfish	Larva													
	Juvenile													
	Adult													
Southern Purple-spotted Gudgeon	Larva													
	Juvenile													
	Adult													
Bony Herring	Larva													
	Juvenile													
	Adult													
Freshwater Catfish	Larva													
	Juvenile													
	Adult													
Short-finned Eel	Elver	Upstream	■	■	■	■							■	■
	Adult	Upstream and downstream	■								■	■	■	■
	Adult	Downstream	■	■	■	■	■							
Long-finned Eel	Elver	Upstream	■	■	■									
	Adult	Upstream and downstream	■									■	■	■
	Adult	Downstream												
Common Galaxias	Larva	Downstream						■	■	■				
	Juvenile		■								■	■	■	■
	Adult	Upstream and downstream				■	■	■	■					
Spotted Galaxias	Larva	Downstream						■	■	■				
	Juvenile	Upstream									■	■	■	■
	Adult													
Dwarf Galaxias	Larva													
	Juvenile													

Common name	**Stage**	**Direction**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	Adult													
Pouched Lamprey	Ammocoete													
	Adult	Downstream						■	■	■	■	■	■	
	Adult	Upstream							■	■	■	■	■	■
Striped Gudgeon	Larva													
	Juvenile													
	Adult													
Cox's Gudgeon	Larva													
	Juvenile													
	Adult													
Empire Gudgeon	Larva													
	Juvenile													
	Adult													
Australian Whitebait	Larva													
	Juvenile													
	Adult													
Australian Bass	Larva		■	■	■	■						■	■	■
	Juvenile													
	Adult	Downstream and upstream				■	■	■	■	■	■	■	■	
Short-headed Lamprey	Ammocoete													
	Adult	Upstream								■	■	■	■	■
	Adult	Downstream							■	■	■	■	■	
Flinders Pygmy Perch	Larva													
	Juvenile													
	Adult													
Variegated Pygmy Perch	Larva													
	Juvenile													
	Adult													
Australian Mudfish	Larva									■	■	■		
	Juvenile													
	Adult													

Common name	Stage	Direction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Freshwater Herring	Larva													
	Juvenile													
	Adult													
Australian Grayling	Larva	Downstream				■	■	■						
	Juvenile	Upstream									■	■	■	■
	Adult	Downstream and upstream				■	■	■						
Tupong	Larva													
	Juvenile	Upstream	■	■	■								■	■
	Adult	Downstream					■	■	■					
Broad-finned Galaxias	Larva	Downstream						■	■	■				
	Juvenile	Upstream									■	■	■	
	Adult													
Obscure Galaxias	Larva													
	Juvenile													
	Adult													
Southern Pygmy Perch	Larva													
	Juvenile													
	Adult													
Yarra Pygmy Perch	Larva													
	Juvenile													
	Adult													
Flat-headed Gudgeon	Larva													
	Juvenile													
	Adult													
Dwarf flat-headed Gudgeon	Larva													
	Juvenile													
	Adult													
Australian Smelt	Larva													
	Juvenile	Upstream	■	■	■	■								
	Adult													
River Blackfish	Larva													

Common name	Stage	Direction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Juvenile													
	Adult													
Mountain Galaxias	Larva													
	Juvenile													
	Adult													

www.delwp.vic.gov.au