New Zealand
Fish Passage Guidelines

For structures up to 4 metres

New Zealand Fish Passage Advisory Group

NIWA Taihoro Nukurangi

Department of Conservation Te Papa Atawhai

New Zealand Fish Passage Guidelines 2018

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Executive summary

This guidance document sets out recommended practice for the design of instream infrastructure to provide for fish passage. The intent of these guidelines is to set the foundation for the improvement of fish passage management in New Zealand.

The guidelines are based on the principle that good fish passage design achieves the following general objectives:

- Efficient and safe upstream and downstream passage of all aquatic organisms and life stages resident in a waterway with minimal delay or injury.
- A diversity of physical and hydraulic conditions are provided leading to a high diversity of passage opportunities.
- The structure provides no greater impediment to fish movements than adjacent stream reaches.
- Continuity of geomorphic processes such as the movement of sediment and debris.
- Structures have minimal maintenance requirements and are durable.

These objectives can be achieved by seeking to realise the following principles of good fish passage design:

- maintaining continuity of instream habitat,
- minimising alterations to stream alignment,
- minimising alterations to stream gradient,
- maintaining water velocities within a range equivalent to adjacent stream reaches,
- maintaining water depths within a range equivalent to adjacent stream reaches,
- minimising constraints on bankfull channel capacity resulting from the structure,
- avoiding vertical drops, and
- providing an uninterrupted pathway along the bed of the structure.

New structures

Design of new structures should adhere to the principles of good fish passage design, and avoid creating an impediment that delays or obstructs the passage of fish and other organisms moving either upstream or downstream.

Culverts

River crossings are one of the most frequently encountered instream structures in New Zealand. Single-span bridges are the preferred crossing type to avoid impacts on fish passage, followed by stream simulation culvert designs. This is because these crossing types maintain habitat continuity and a diversity of movement pathways through the stream. Minimum standards for culvert design require that:

- Low (Q_L) and high (Q_H) fish passage design flows are defined. As a rule of thumb, $Q_L \leq$ 95% exceedance flow and $Q_H \geq$ 20% exceedance flow.
- Alteration of natural stream channel alignment will be avoided or minimised.
- Alteration of natural stream channel gradient will be avoided or minimised.
- Culvert span will be:
  - 1.3 x bankfull width for streams with a bankfull width ≤3 m.
  - 1.2 x bankfull width + 0.6 m for streams with a bankfull width >3 m.
- Open bottom culverts will be used or the culvert invert will be embedded by 25-50% of culvert height.
- Mean cross-sectional water velocity in the culvert over the fish passage design flow range will be equal to or less than the greater of:
  - mean cross-sectional water velocity in adjacent stream reaches, or
  - the maximum allowable water velocity calculated from fish swimming speeds of agreed target fish species and/or life stages.
- Minimum water depth in the culvert at the low fish passage design flow will be the lesser of:
  - 150 mm for native fish passage, or 250 mm where adult salmonid passage is also required, or
  - mean cross-sectional depth in adjacent stream reaches.
- Well graded substrate will be present throughout the full length of the culvert bed.
- Substrate within the culvert will be stable at the high fish passage design flow.
- Any ancillary structures must not create an impediment to fish passage.
- Vertical drops through the structure will be avoided.

Weirs

Where practicable full width rock-ramp fishways should be used as an alternative to conventional weir designs for raising headwater levels in a river. Minimum fish passage design criteria for weirs are:

- Where a rock-ramp weir is used:
  - The slope should be gentle (1:15 to 1:30). A slope of 1:30 is suitable where weakly swimming species such as inanga and smelt require passage.
  - The weir should create a hydraulically diverse flow environment including low velocity margins and resting areas.

    - The weir should have a V-shaped lateral profile, sloping up at the banks and providing a low-flow channel in the centre. 5-10° is a suitable slope for the lateral cross-section.
    - A continuous low velocity wetted margin should be provided up the weir throughout the fish passage design flow range.
    - Backwatering of upstream habitats because of the weir should be minimised.
- Where a conventional weir design is required:
    - The slope of the weir should be minimised and as a general rule of thumb be less than 1:10 for fall heights ≤1 m and less than 1:15 for fall heights 1-4 m.
    - The weir should have a V-shaped lateral profile, sloping up at the banks and providing a low-flow channel in the centre. 5-10° is a suitable slope for the lateral cross-section.
    - The use of smooth concrete for the downstream weir face should be avoided. Roughness elements should be added to the weir face. A suitable solution would be to cover the weir face with embedded mixed grade rocks 150-200 mm. Rocks should be closely and irregularly spaced to create a hydraulically diverse flow structure across the weir.
    - A continuous low velocity wetted margin should be provided up the weir throughout the fish passage design flow range.
    - Broad-crested weirs are recommended and the downstream edge of the crest should be rounded.
    - Backwatering of upstream habitats because of the weir should be minimised.

Other structures

Best practice is to avoid the use of fords for stream crossings as they are the least preferred crossing type from a fish passage perspective and do not prevent vehicles or animals from entering the waterway.

Flood and tide gates can significantly disrupt the movements of aquatic organisms and alter upstream habitats considerably. Best practice where flood or tide gates are required is to install automated gates that operate the gate only when water levels reach a critical elevation. Where operational constraints prevent the use of automated gate systems, the minimum standard is to install self-regulating “fish friendly” gates. To optimise fish passage, the objective should be to maximise the duration and aperture that the gate is open, particularly on the incoming tide when most juvenile fish are moving upstream. This will also facilitate greater hydrological exchange and help to reduce the habitat impacts upstream of the gate.

Remediation of existing structures

Where existing structures impede the movement of aquatic organisms, removal should always be considered as the first and preferred solution for maximising fish passage at existing structures. Alternatively, replacement with a structure that has been designed to meet minimum design standards will likely offer the most sustainable and effective solution.

For practical reasons many structures cannot be removed, so the addition of new features to existing structures is a more common strategy for enhancing fish passage. The remediation options available at a site will be dependent on factors including the characteristics of the existing structure, cost, accessibility, the reason(s) for reduced fish passage, and the ecological objectives for the site.

Ramp fishways

Ramp fishways are the preferred solution for overcoming vertical drops that impede the movement of aquatic organisms. Full width rock-ramp fishways are the optimal design for overcoming low-head barriers. Rock-ramp structures typically take the form of a series of transverse rock ridges, with pool sections between the ridges that act as resting areas for migrating fish. Recommended design criteria for rock ramps are:

- The overall longitudinal slope of the structure should be 1:30 for small-bodied (<200 mm) fish.
- The ramp should have a v-shaped cross-section or sloped lateral (bank-to-bank) channel profile to allow the fishway to operate over the full fish passage design flow range.
- A head loss between pools of <75 mm is suitable for small-bodied fish.
- The width of the gap between lateral ridge rocks should be 100-150 mm.
- The recommended pool size for a ridge-style rock fishway is 2 m long to allow dissipation of flow and maintain acceptable turbulence levels.
- The minimum recommended water depth is 0.3 m in at least 50% of the pool area in a continuous path ascending through the rock ramp.
- Maximum water velocity as calculated from the head loss in a vertical slot should be <1.2 m s^{-1}.
- Turbulence should be minimised, with little 'white' water in the fishway pools. Stream power should be <25 W m^{-3}.

Concrete rock-ramps can also be used to overcome head drops at structures. Suggested design criteria include:

- The ramp should have a V-shaped (15°) or tilted cross-section to allow the fishway to operate over the full fish passage design flow range.
- Mixed grade irregularly shaped rocks (150-200 mm) should be embedded by 50%, with the longitudinal axis perpendicular to the ramp surface and the widest part of the stone facing in to the flow, and arranged haphazardly with a spacing between rocks of 70-90 mm.
- A continuous low velocity wetted margin should be provided up the ramp throughout the fish passage design flow range.
- The average slope of the ramp should be less than:
  - 1:5 for head differences of ≤0.5 m.

- 1:10 for head differences of ≤1.0 m.
- 1:15 for head differences of 1-4 m.

Pre-constructed, artificial ramps that can be readily attached to structures such as perched culverts can also be used to overcome head drops at structures. Ramps should have a roughened surface, should have a V-shaped (15°) or tilted cross-section, maintain a continuous low velocity wetted margin through the full length of the ramp, and meet the same criteria for ramp slope as concrete rock-ramps.

Baffles

Baffles can be used on the base of culverts or the face of weirs to reduce water velocities and increase fish passage. A range of baffle designs are available. Based on current knowledge, spoiler baffle designs are the recommended solution for enhancing fish passage in culverts with a diameter of >1.2 m.

For culvert slopes up to 2% (1.15° or 1:50) rectangular baffles (0.25 m length, 0.12 m width and 0.12 m height) in a staggered configuration with 0.2 m spacing between rows and 0.12 m spacing between blocks within rows creates the desired continuous low velocity zone along the culvert base and associated resting zones behind baffles. As a general rule-of-thumb baffles should cover approximately one third of the culvert's internal circumference, or the full width of box culverts.

Mussel spat ropes

Mussel spat ropes can be used to facilitate passage of aquatic organisms through culverts where the diameter is <1.2 m. For installation through a culvert it is recommended:

- A minimum of two rope lines are used for a 0.5 m diameter culvert, with more necessary for larger culverts.
- Ropes should be installed so that they are tight and flush with the base of the culvert through the entire length of the culvert and not loose at one end or out of the water.
- Ropes are set out to provide 'swimming lanes' between the ropes.
- Knots (half hitches) can be tied along the sections of rope in the culvert barrel to break up the flow and potentially create additional rest areas for fish.
- Non-loop rope types are used to reduce the likelihood of debris snagging on the ropes.

Bypass structures

Where fish passage barriers cannot be mitigated through structural adjustments, bypass structures may be the only effective solution for enhancing fish passage. There are two main types of bypass structure:

- Nature-like fishways mimic natural stream characteristics in a channel that bypasses the barrier. They are suitable for all structure types, but generally require more space than technical fishways. Because they mimic natural stream conditions they are generally suitable for a wide range of fish species and life stages.

- Technical fishways can take a variety of forms including vertical slot fishways, pool and weir fishways, and Denil passes. To date there are relatively few examples of effective technical fishways in New Zealand, but they have been widely used internationally.

Built barriers

Intentional built barriers are structures that are created with the specific objective of limiting or preventing the movements of certain fish species. Intentional built barriers have been used in New Zealand to successfully protect refuges for native species and to prevent access for exotic and invasive species. They are generally designed to exceed the target fishes' ability to swim, jump or climb past the structure to manage their spread through the river network or into critical habitats.

The design of built barriers requires the input of experts in fish ecology and should be undertaken in consultation with Department of Conservation staff. Incorporation of the following features has proven to be effective in the right situation**:**

- Drops >1-1.5 m. However, if this fall height is not possible, increased focus must be placed on incorporating other features such as overhangs, screens or non-physical barriers (e.g., shallow, high water velocity) to compensate for lower fall heights.
- Downstream apron >2 m length that creates an area of fast water velocity and low water depth to inhibit invasive species jumping.
- Upstream backwater effects are minimized by setting the barrier within a stream reach with reasonable slope. Substrate or other structures could also be added to establish and maintain shallow habitat (e.g., add large rocks or a concrete pad).
- Scour protection downstream and to the sides of the apron to cater for any hydraulic jump that may form, protection in high flows, and generally ensure the structure's integrity will be maintained over time.
- The barrier should be located where the channel is stable with a moderate slope. Waterways in highly erodible soils, steep stream beds and/or made up of very mobile substrates should be avoided where possible due to high erodibility and likelihood of barrier integrity being compromised over time.

Monitoring

Monitoring is the only way to understand how well a structure is working and to ensure that any reduction in fish passage caused by a structure is not adversely impacting upstream communities. It is particularly important to understand these things under circumstances such as:

- High value fish communities or ecosystems are present upstream of the structure.
- Unproven designs are being used.
- Proven designs are being used in novel situations.
- Retrofit solutions form only one component of an instream structure.
- Multiple structures exist within a waterway causing cumulative effects.
- Selective barriers are being used to manage the movement of undesirable species.

Guidance on appropriate monitoring techniques and methods for evaluating fish passage success under different circumstances is provided.

1 Introduction

Many of New Zealand's most widespread fish species (e.g. whitebait and eels) undertake significant migrations as part of their life-cycle. The purpose of these migrations is to access the range of habitats necessary to support different life-stages, e.g. reproduction and rearing, and ecological functions, for example feeding or finding refuge. Instream infrastructure, such as culverts, weirs and dams, can delay or prevent fish movements when adequate provision for fish passage is not provided in their design, installation and maintenance. The consequence is a reduction in the distribution and abundance of some of our most iconic and valued freshwater species.

These guidelines have been developed to assist infrastructure designers and managers, waterway managers, environmental officers, iwi and local communities with understanding and promoting better management of fish passage requirements in New Zealand. The guidelines set out best-practice approaches and minimum design standards for providing fish passage at instream structures based on current knowledge. Due to the site-specific nature of the problem, the guidelines cannot provide a 'cook book' of provisions for all locations. However, the general principles of good fish passage design set out in these guidelines should provide a basis for developing suitable infrastructure designs in the majority of situations most regularly encountered in New Zealand.

1.1 Purpose of the guidelines and intended audience

The intention of these guidelines is to:

- Assist infrastructure designers, waterway managers, environmental officers, iwi and local communities with the issue of fish passage and how to provide for fish migration at instream structures.
- Provide access to and promote the adoption of current state-of-the-art knowledge and best-practice approaches to designing and installing instream structures.
- Inform the management and mitigation of existing barriers, in order to better protect and manage freshwater fish values and critical migration pathways.
- Set minimum standards for the design of instream structures that are consistent with principles of good fish passage design.
- Offer practical, multipurpose and multidisciplinary guidance for ecologists, engineers, planners and infrastructure managers in the planning, design and implementation of instream infrastructure that is compatible with requirements for appropriate fish passage management.
- Provide the foundation for guidance to land holders and their advisors on following the principles of good fish passage design.
- Support improved and more consistent national coordination of fish passage management in New Zealand.

A key objective of these guidelines is to direct a shift away from conventional approaches to designing instream infrastructure and stream crossings to better account for legislative requirements to provide for fish passage. Traditional design approaches focused on optimising hydraulic conveyance often run counter to the need to provide low water velocities, a diverse stream bed and clear pathways for fish passage. Consequently, there are a large number of structures in our waterways that do not meet legislative requirements for providing fish passage. These guidelines provide the necessary information to allow infrastructure designers to integrate the needs of fish into the design process, such that a better balance between different needs, e.g. fish passage, hydraulic conveyance and structural integrity, can be achieved. This will help to maintain the diversity and abundance of freshwater fish and other aquatic organisms in our streams and rivers.

1.2 Scope of the guidelines

The primary focus of these guidelines is managing the effects of physical barriers to fish migration ≤4 m in height. This will encompass the majority of the most commonly encountered structures in our waterways. The guidelines:

- Set out the rationale and legal basis for incorporating the principles of good fish passage design into structure designs in New Zealand.
- Include a summary of current knowledge on the passage requirements of key freshwater fish species, and an overview of structure characteristics that impede fish migrations.
- Highlight the need to consider maintaining barriers in some cases in order to manage the impacts of exotic fish species.
- Based on current knowledge, provide best-practice design criteria and guidance on minimum design standards for installation of new structures.
- Describe best-practice approaches and minimum design standards for remediation of existing structures that impede fish passage. This highlights key design requirements, common pitfalls, and approaches to ensuring retrofit solutions are fit-for-purpose.
- Summarise design criteria for structures that have been successful in preventing the movements of invasive species to protect biodiversity hotspots.
- Provide recommendations on monitoring requirements for demonstrating the effectiveness of fish passage.
- Set out the limitations of current knowledge and highlight future research needs to support improved guidance.

The guidelines recognise the need for ongoing design development and evaluation of fish passage solutions to ensure the best outcomes for our freshwater ecosystems. They acknowledge the need for innovative solutions to address connectivity barriers, but caution against the use of overly speculative, unproven designs that are not well founded in sound theory and the practical implementation of hydraulic and ecological principles. It is important to ensure that new solutions undergo appropriate monitoring and testing to validate their use.

The guidelines do not cover all aspects of structure design and should be used in conjunction with other standard design procedures and technical guidance. They also do not address:

- Fish passage requirements at large dams (>4 m high).
- Non-physical barriers to migration, e.g., degraded water quality.
- The impact of artificial/heavily modified channels on fish passage.

- Design of water intakes and diversions[1].
- The design of behavioural barriers, e.g., lights and acoustic deterrents.

In all cases, users should undertake their own site-specific design assessments and obtain specialist advice and input appropriate to the scale of the project and the value of the potentially impacted ecosystem. This should take in to account and recognise the current limitations to our knowledge and the fact that this guidance is based on current, best-available information that may change over time.

[1] Guidance available on intake screening design in Jamieson et al. (2007) Fish screening: good practice guidelines for Canterbury. NIWA Client Report CHC2007-092: 80

2 Why should fish passage be considered?

2.1 Freshwater fish and fisheries values

There are a wide range of freshwater ecosystems in New Zealand, including rivers, streams, lakes and wetlands. These ecosystems provide key habitats for approximately 50 native freshwater fish species and 10 sports fish species (Goodman et al. 2014). Many of the native species are only found in New Zealand and, therefore, are of significant biodiversity value both nationally and internationally. Freshwater fish are also highly valued in New Zealand due to their status as taonga and kai for Māori, and their importance for supporting cultural, recreational and commercial fisheries, e.g. for whitebait, eels and trout.

New Zealand's freshwater fish species and habitats are threatened by an increasing number of pressures including greater demand for water, deterioration in water quality, loss and degradation of habitats, impacts of invasive species and reductions in river connectivity. These cumulative pressures and a lack of formal protection have had impacts on our native fish, with 74% now being classified as threatened or at risk (Goodman et al. 2014).

Around one third of New Zealand's native freshwater fish spend some part of their lives at sea, which means they need free access to, from, and within freshwater habitats to successfully complete their life-cycles (McDowall 2000). Others are resident in freshwater their whole lives, but still need to move between habitats within waterways. Barriers to migration prevent fish from reaching critical habitats required to complete their life-cycles. Blocking or limiting fish movements within and between waterways is, therefore, a significant and ongoing threat to our native and sports fish. For many native fish species, protecting connectivity between habitats is as important as protecting the habitats themselves. For further details on the key ecological considerations for instream structure design refer to Appendix D.

2.2 Potential adverse effects of instream structures

Instream structures can adversely affect aquatic communities in several ways. This includes disrupting stream processes, altering habitats, and impeding or blocking the movements of organisms. The results are often observed as reductions in fish numbers and changes to species diversity within catchments.

2.2.1 Channel processes and aquatic habitats

The impact that a structure can have on the instream environment is dependent on the structure type, its size and location in the river network, amongst other factors. Typically, habitats are modified through changes to water depth and velocity, alterations to sediment deposition, erosion at and around structures, and by replacement of natural habitats with artificial structures (e.g., culverts). Shifts in the physical and chemical characteristics of water can also occur, such as increased water temperatures and decreased dissolved oxygen concentrations.

Tide gates are often one of the first barriers to upstream movement that fish encounter. Installation of tide gates alters upstream habitats by removing tidal fluctuations, reducing salinity, reducing water velocity, increasing sediment deposition, and can often also result in lower dissolved oxygen and higher water temperatures (Franklin and Hodges 2015; Scott et al. 2016).

Weirs and dams alter downstream flow and sediment regimes, with subsequent impacts on instream physical habitat and water quality (Poff and Hart 2002; Lessard and Hayes 2003). Furthermore, habitats upstream of the structure are modified by the effect of backwatering, with water depths increasing, water velocity reducing, fine sediment deposition increased and alterations in water quality (Poff and Hart 2002; Jellyman and Harding 2012; Birnie-Gauvin et al. 2017).

Culverts are often installed in a way that alters the natural path and gradient of a stream. Flow is also frequently constrained relative to the natural channel leading to faster water velocities. Installation of culvert pipes also replaces varied natural habitats with uniform, artificial conditions without natural substrates (MacDonald and Davies 2007; Doehring et al. 2011b; Cocchiglia et al. 2012; Franklin and Bartels 2012).

These changes in habitat conditions associated with instream structures have been associated with an increase in the abundance of exotic fish species and reductions in native fish abundance (Boys et al. 2012; Jellyman and Harding 2012; Scott et al. 2016; Birnie-Gauvin et al. 2017). This drives the need for improved management of instream structures to ensure the impacts on instream environments is minimised and fish passage managed appropriately.

2.2.2 River fragmentation and species loss

One of the main impacts of instream structures is that they can fragment river habitats and impede or completely block the movements of aquatic organisms. Restrictions on the dispersal of fish and other organisms results in changes to population dynamics, constraints on distribution, increased predation and, ultimately, extirpation and loss of species. While multiple factors determine the effect of instream barriers to connectivity on fish and other aquatic communities (Rolls et al. 2014), there are many examples of studies that demonstrate the negative consequences of fragmentation and disruptions to connectivity on the viability and distribution of fish populations (e.g., Gibson et al. 2005; Fukushima et al. 2007; Lucas et al. 2009; Russon et al. 2011; Franklin and Bartels 2012; Jellyman and Harding 2012).

Fragmentation of river systems is particularly damaging because the structure of stream networks makes it difficult for organisms to avoid barriers to movement when they are present (Fagan 2002). Single barriers can impede or obstruct access to large proportions of available habitat, and it has been shown that barriers located in the lower part of river networks have the largest impact on diadromous fishes (Cote et al. 2009). Given the high number of diadromous fish species in New Zealand, ensuring river connectivity is maintained is often fundamental to protecting the persistence and sustainability of fish populations.

2.3 Characteristics of instream structures that impede fish movements

The key characteristics of instream structures that contribute to impeding the movements of fish and other aquatic organisms are well recognised. A summary of these features for several common low-head structures is provided below, with a more in-depth review provided in Appendix E. Factors such as vertical drops, high water velocities, sharp corners, overhanging edges, a lack of shallow wetted margins and physical blockage are all common features of instream structures that impede the movements of aquatic organisms (e.g., Figure 2-1 to Figure 2-4).

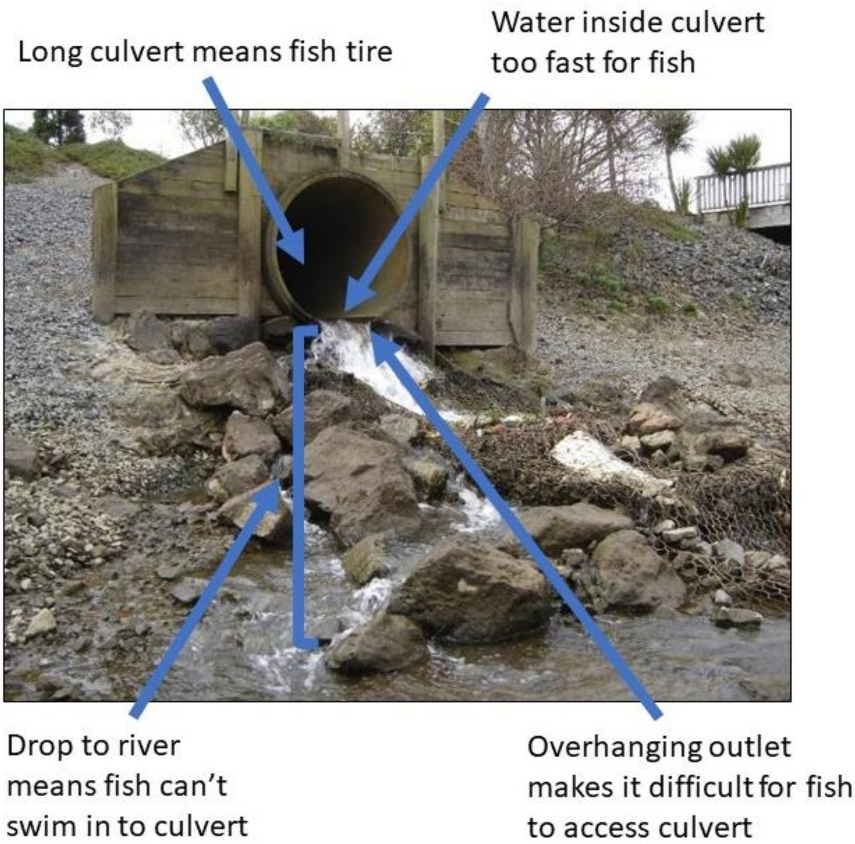

Figure 2-1: Example of a culvert that impedes fish movements.

Figure 2-2: Illustration of how tide gates can impede fish movements.

Figure 2-3: An example of an intake weir identifying features unsuitable for fish passage.

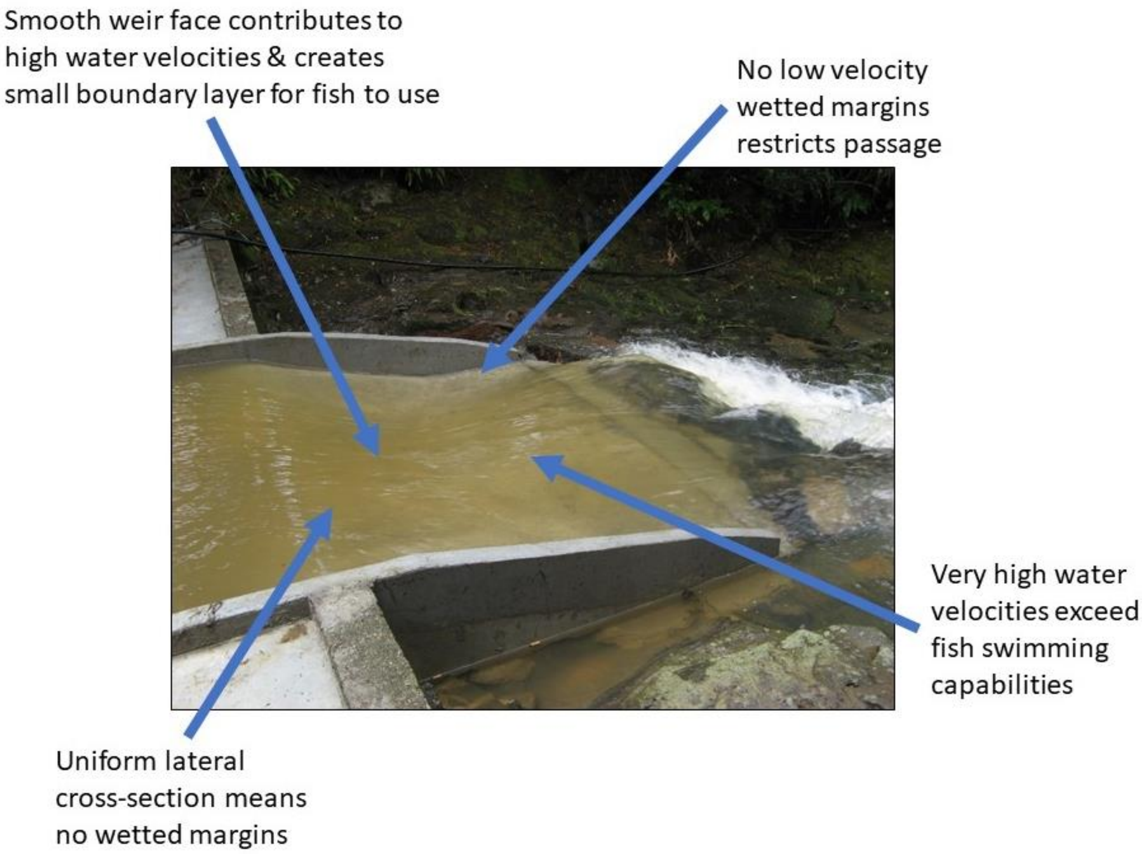

Figure 2-4: A weir with key features unsuitable for fish passage identified.

2.4 Legislative requirements

Regional councils and the Department of Conservation (DOC) have specific responsibilities to manage fish passage in Aotearoa New Zealand waterways. Regional councils have responsibility under the Resource Management Act 1991, the National Policy Statement for Freshwater Management 2020 and the Resource Management (National Environmental Standards for Freshwater) Regulations 2020. DOC has responsibility under the Freshwater Fisheries Regulations 1983.

The Ministry for the Environment has developed a factsheet that sets out the main legislative provisions relating to fish passage, particularly with respect to the National Policy Statement for Freshwater Management 2020 and the Resource Management (National Environmental Standards for Freshwater) Regulations 2020.

3 Planning and design considerations for fish passage at instream structures

3.1 Background

All instream structures have the potential to adversely affect aquatic habitats and stream biota, but careful and considered evidence-based planning and design can be used to minimise these potential impacts. The objective of the following sections is to set out recommendations and guidance based on current knowledge that will allow practitioners to more effectively design, install and manage instream infrastructure for fish passage. The intended outcome is to ensure fish passage design requirements are an integral part of the design process for instream infrastructure in New Zealand. This will reduce fragmentation of our waterways, improve access to critical habitats for our iconic freshwater fish species and enhance biodiversity outcomes for New Zealand.

Design of instream structures that provide effective fish passage requires biological knowledge of fish ecology, behaviour and the capacity of different fish species to negotiate various hydraulic conditions, e.g., velocity and turbulence, combined with hydraulic and civil engineering knowledge and expertise. This will allow development of structures that provide appropriate hydraulic conditions for fish passage, while also fulfilling requirements for hydraulic capacity and operation (Williams et al. 2012; Link and Habit 2014). A critical challenge for practitioners and managers is accounting for the significant variations in fish communities, species, sizes, behaviour and swimming abilities that occur between sites. Designing for fish passage requires that suitable hydraulic conditions that accommodate the different swimming capacities for relevant fish species passing upstream and downstream at a site are provided at the appropriate design flow rates in the waterway during fish migration periods. See Appendix D for a summary of the current knowledge regarding fish ecology, behaviour and swimming capabilities for New Zealand's freshwater fishes.

Historically, fish passage design has been driven by knowledge developed for economically important, large, strong-swimming salmonid species. However, there is increasing recognition that these designs do not cater for multi-species assemblages, and particularly for weak-swimming, small-bodied fish that are more typical here in New Zealand (Mallen-Cooper and Brand 2007; Williams et al. 2012; Link and Habit 2014; Franklin and Baker 2016). Consequently, there is a move towards a more ecosystem-based approach to fish passage designs, with greater amounts of hydraulic heterogeneity to allow both more species and a greater range in sizes of fish to pass.

3.2 Design process

All sites are unique and a case-by-case approach will be required to design instream structures to meet fish passage requirements. A general design process for instream structures is set out in Figure 3-1.

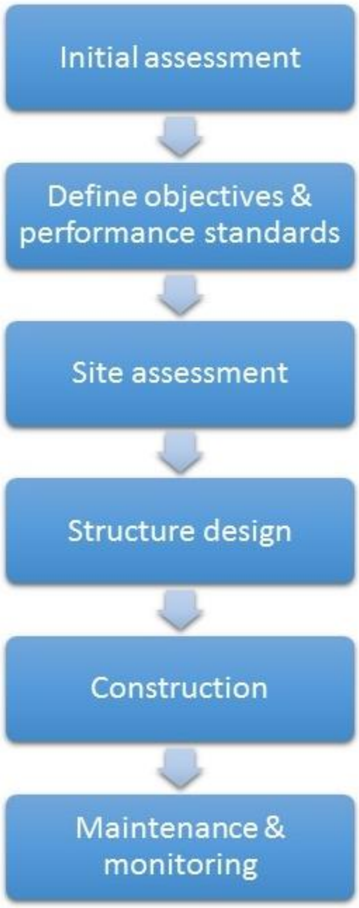

Figure 3-1: General design process for instream structures.

Initial assessment

The initial assessment phase involves collating existing catchment biological and physical information as background for defining objectives and setting performance standards for the structure. This may include an initial site reconnaissance visit to identify site-specific challenges or risks that should be accounted for in the subsequent design phases. Such factors might include locations where the stream channel is unstable laterally and/or longitudinally, places with high bed or debris loads, reaches subject to natural hazards, locations with critical infrastructure, or sites with high instream values. This stage should also include review of all relevant legislative requirements for the structure to determine what approvals or consents are required and an evaluation of the species present.

Defining objectives and performance standards

The information compiled during the initial assessment should be used to define ecological objectives and performance standards for the structure. Setting clear, well-defined objectives and performance standards is an important component of the design process, particularly for complex or highly valued sites, as it provides the basis for determining appropriate design criteria and for measuring and evaluating project success (see Section 3.3 for more details on setting objectives and performance standards).

Site assessment and structure design

Once the objectives and performance standards are set, a site assessment is carried out to provide the reference for structure design. A design concept that fulfils the objectives and performance standards is then developed and, subsequently, final structural design drawings and specifications are prepared before the consenting and construction phase. Guidance and minimum design standards for new instream structures are set out in Section 4.

Construction and maintenance

It is recommended that relevant specialists, including a fish ecologist/biologist, are present during the construction phase for more complex or high value sites to assist with responding to any unforeseen site conditions that may necessitate a deviation from the final design. Following installation of the structure, it is important that a maintenance regime appropriate to the size, location and type of structure be implemented to ensure it remains fit-for-purpose. Monitoring will allow evaluation of whether the structure meets the project objectives and performance standards.

3.3 Defining objectives and performance standards

Defining clear objectives should be an integral element of designing all instream structures. The objectives define the design criteria for a structure, and inform the development of the biological and hydraulic performance standards against which the structure can be evaluated.

Each site is unique and conditions will generally dictate that individual solutions are required in each location. It is, therefore, important to clearly define performance objectives for each structure at an early stage of the design process. These guidelines recommend a hierarchical approach to defining performance objectives and standards like that proposed by O'Connor et al. (2015a) for Australian fishways.

Fish passage performance standards for instream structures should be developed on the basis of clearly defined and justifiable ecological objectives. O'Connor et al. (2015a) suggest that these ecological objectives should generally be broad-level objectives for the ecosystem, such as ‘restore or sustain fish distribution and abundance’, but may also include specific objectives where particular ecological issues are identified. The ecological objectives should identify the likely target species, their approximate abundance and distribution, the recovery potential of species that have been in decline, the life-stages that are migrating, and when, and under what conditions, those migrations take place (O'Connor et al. 2015a). These broad-scale ecological objectives subsequently form the basis of site-specific fish passage objectives such as ‘the structure must pass juvenile inanga between August and January’ (as they migrate upstream following their marine phase).

Once ecological and fish passage objectives have been set, biological and hydraulic performance standards for the structure can be established. Biological performance standards essentially define how fish passage success can be measured at a structure. This may include things such as the movement of particular species or size classes through or across the structure, or changes in the upstream fish community. Hydraulic performance standards define the envelope of hydraulic and physical characteristics of the structure; that is the specific characteristics (e.g., water velocity or turbulence) that if provided will lead to the biological performance standards for the structure being met.

3.3.1 Biological performance standards

Three categories of biological performance standard (O'Connor et al. 2015a) that can be used for assessing whether a structure is meeting its objectives for fish passage are:

1. Changes in fish distribution and abundance.

   Standards can be set at a site, reach or catchment scale for maintaining or extending fish distributions and maintaining or increasing fish abundance. These can apply to individual species, life-stages or whole fish communities and should be set to fulfil the ecological objectives.

2. Proportional passage of a life-stage of a species in differing flows

   This applies at a site scale and defines the proportion (i.e., percentage) of migrating fish arriving at a structure that must successfully pass in order to meet the ecological objectives. In general, this should be as close to natural (i.e., 100%) as possible and in the case of culverts and fords is required to be 100% by the Freshwater Fisheries Regulations (which state that fish passage must not be impeded at these structures unless a permit for dispensation is granted). In some situations achieving 100% passage success may not be realistic, but departures from this target should be minimised and justified with respect to the ecological objectives set for the project. This may particularly be the case when looking at retrofitting existing structures. Identifying the proportion of fish required to pass to maintain sustainable populations is extremely difficult as it requires detailed knowledge of the ecology of the species. These guidelines, therefore, advocate a precautionary approach based on maintaining natural rates of upstream and downstream migration. However, determining acceptable departures from natural passage rates may be influenced by the ecological objectives of the project, and factors such as the conservation status, cultural value, fishery values or distribution of the target species.

3. Delay in passage of a life-stage of a species in differing flows

   The consequences of migration delay are relatively poorly understood for most native fish species, but will be dependent on the ecological significance of the migration (e.g., delays to spawning migrations may be more significant than delays to dispersal migrations of juvenile diadromous fish). Again, the objective should be to minimise the departure from natural conditions (i.e., 0% delay). Avoiding migration delays is effectively set as the target for culverts and fords by the requirement of the Freshwater Fisheries Regulations that fish passage must not be impeded. This may not always be realistic, but any delays should be minimised and fully justifiable in the context of the ecological objectives.

Performance standards for a site should be clearly defined, specific, measurable and linked to the ecological objectives. An example might be ‘to provide 95% upstream passage of juvenile inanga (<60 mm) with a delay of no more than one day for 90% of flows in the period August to January’. Biological standards will vary between sites, species and life-stages and should be refined as ongoing research enhances understanding of fish ecology and the implications of impeding migration.

3.3.2 Hydraulic performance standards

The hydraulic performance standards are based on the ecological and fish passage objectives, and are informed by the biological performance standards, as these set the target species, life-stages etc., for which hydraulic criteria must be derived. Hydraulic performance standards set the envelope of hydraulic conditions that, if provided, will allow for the passage of the target species and life-stages at the correct time of year and flows (i.e., to allow the biological performance standards to be met). They may include factors such as maximum water velocity, minimum water depth, maximum head-loss, turbulence etc., and are derived from information on swimming abilities, fish size and fish behaviour. Hydraulic performance standards may include characteristics for both attraction flows, and for passage through or across the structure itself. There may be multiple criteria for different species, life-stages and at different times of the year or under different flow conditions.

3.4 Principles of good fish passage design

The key features of instream structures that can result in the movements of fish and other organisms being impeded are widely recognised. These include characteristics such as vertical drops, high water velocities, water that is too shallow, excessive turbulence, sharp corners, overhanging edges, and smooth substrates, among other things (see Appendix E for a detailed review). The principles of good fish passage design seek to ensure that the risk of these features occurring is minimised.

Approaches founded on the principles of stream simulation have now become the international standard for good fish passage design. The stream simulation design philosophy is built on the premise that mimicking natural stream conditions within the structure design should mean the structure will present no more of an obstacle to aquatic animals than the adjacent stream channel (U.S. Department of Agriculture 2008). This has proven to be more effective at catering for the diverse requirements of multi-species assemblages than traditional design approaches that attempted to match hydraulic conditions within or across a structure with knowledge of specific swimming capabilities of individual target species or life-stages.

The aim of the stream simulation design approach is to create within the structure a channel as similar as possible to the adjacent stream channel in both structure and function, resulting in a continuous streambed that simulates natural channel width, depth and slope (Figure 3-2). This provides the diverse water depths, velocities, resting areas and wetted edge habitats that different fish species use during their migrations. Furthermore, it maintains habitats that support macroinvertebrate communities and other biodiversity values.

Figure 3-2: An example of a stream simulation culvert design.

These guidelines are based on the principle that good fish passage design achieves the following general objectives:

- Efficient and safe upstream and downstream passage of all aquatic organisms and life stages with minimal delay or injury.
- A diversity of physical and hydraulic conditions leading to a high diversity of passage opportunities.
- The structure provides no greater impediment to fish movements than adjacent stream reaches.
- Continuity of geomorphic processes such as the movement of sediment and debris.
- Structures have minimal maintenance requirements and are durable.

These objectives can be achieved by seeking to realise the following principles of good fish passage design:

- Maintaining continuity of instream habitat.
- Minimising alterations to stream alignment.
- Minimising alterations to stream gradient.
- Maintaining water velocities within a range equivalent to adjacent stream reaches.

- Maintaining water depths within a range equivalent to adjacent stream reaches.
- Minimising constraints on bankfull channel capacity resulting from the structure.
- Avoiding vertical drops.
- Providing an uninterrupted pathway along the bed of the structure.

The following sections provide guidance on current best-practice approaches and minimum design standards for both designing and installing new instream structures (Section 4), and managing and fixing existing barriers (Section 5). The aim is to provide practical, multipurpose guidance for ecologists, engineers, planners and infrastructure managers in the planning, design and implementation of instream infrastructure that consistent with the principles of good fish passage design. The guidelines do not cover all aspects of structure design (e.g., hydraulic conveyance requirements) and should be used in conjunction with other standard design procedures and technical guidance, and make reference to relevant regional planning rules and other legislation.

3.5 Planning for instream works

It is important to consider timing of works when planning the construction of any instream structure. Most regional plans will have constraints on the timing of instream works intended to minimise potential impacts on the aquatic environment and species. This may include avoiding works during fish migration and/or spawning periods. Please consult local plan rules to ensure compliance with these requirements. A summary of some of the key migration times of freshwater fishes in New Zealand is provided in Appendix D.

Consideration must also be given to the practicalities of undertaking instream works. This may include requirements for redirecting stream flows during works, fish recovery and rescue, sediment control, or the appropriate use of machinery in or adjacent to waterways. Refer to relevant regional guidance on good practice. Health and safety obligations must also be addressed.

3.6 Monitoring and maintenance

Monitoring is required for two primary purposes: 1. to evaluate whether the structure is meeting the specified objectives and performance standards (see Section 6 for more details on this aspect), and 2. to check that the structure remains in good condition and functioning as intended, or whether maintenance is required.

Regular maintenance is essential to preserve the hydraulic and ecological functionality of a structure and/or associated fish pass. There is also a legal requirement under the Freshwater Fisheries Regulations to maintain instream structures so that they continue to provide fish passage. Furthermore, failure to ensure that effective fish passage is maintained will often result in structures becoming non-compliant with regional planning rules that require fish passage.

Over time all structures will collect debris that can alter the hydraulic conditions throughout the structure and potentially create a physical or behavioural barrier to fish movements. For example, where spoiler baffles are installed, waterborne debris or large bedload movements can build up between the baffles reducing their efficacy in reducing water velocities and providing physical resting areas for fish. It is anticipated that sediment deposition will be transient and removed in subsequent flood waters, however, stubborn debris may require physical removal.

Structural damage can also occur as fabrics deteriorate and components become damaged in flood flows. Artificial substrates such as spat ropes and spoiler baffle sheets can be prone to flood damage if they are not securely and effectively fastened to the instream structure. Poorly designed rock-ramps can also result in erosion of the streambed and/or the displacement of rocks during flood waters (e.g., Figure 3-3).

Development of a maintenance programme will be site and structure specific, but it should be focused around the migration period when the pass needs to operate. Several factors will determine the appropriate frequency of inspections including the type of structure, the location in the catchment, the hydrology of the river, geology of the catchment and mobility of sediments, and the type of marginal, emergent and submerged vegetation within the stream. It is advisable to develop a risk assessment matrix based on site specific factors to help inform a suitable inspection and maintenance schedule.

Monitoring and maintenance requirements over the life-time of the structure should be considered from the outset of the design process. The higher initial construction costs of more complex designs or larger structures can sometimes be balanced by lower long-term monitoring and maintenance requirements as they provide greater capacity and resilience to extreme events. Cost minimisation at the construction phase, e.g., using smaller culverts that constrain the channel, can contribute to accelerating downstream erosion and scouring that over time results in perching and undercutting of the culvert outlet, creating fish migration barriers. This may increase maintenance requirements and future compliance costs.

Figure 3-3: Rock-ramp installed in the Aropaoanui River, before (top) and after (bottom) an 80 m^3 s^{-1} flood. The rock-ramp was installed to overcome the barrier created by a historic weir (visible in the bottom picture after the rock-ramp was washed away). However, the rock-ramp design was insufficient to withstand the flood meaning that reconstruction is required to restore fish passage at the weir. Credit: Andy Hicks.

4 Design requirements for new instream structures

The process of designing new structures provides an opportunity to ensure that human development of our waterways does not impose further barriers to the migration of fish. Design of new structures should adhere to the principles of good fish passage design set out in Section 3.4 and avoid creating an impediment that delays or obstructs the passage of fish migrating either upstream or downstream. Best practice is to maintain the natural stream bed and banks, and to build a structure that surrounds the stream rather than modifying it. Instead of considering first the functional aspects of the design, and subsequently addressing fish passage elements as a secondary consideration, good practice considers the passage of fish (and other organisms) past the structure as integral to designing a structure that is fit-for-purpose.

Specific design guidance is given in the sections that follow, however, some general objectives are:

- Upstream and downstream fish passage should be provided during known migratory windows for the species found in the stream, over a range of flow conditions.
- Consideration should be given to both juveniles and adults, and species that swim close to the bed and those that swim close to the surface.
- A continuous flow path should be provided, starting with downstream attraction flows and leading the fish through the structure and past the upstream exit.
- Water velocities and depths downstream of, throughout, and upstream of the structure should be appropriate for the swimming capabilities of fish present in the stream.
- Hydraulic homogeneity should be avoided; some slower flowing shelter areas should be provided to allow fish to rest.
- Excess turbulence should be avoided.
- Avoid waterfall-like profiles, hydraulic jumps, and protruding structures that completely separate the water surface upstream from that downstream (for example water backed up behind a sluice gate, and flowing at a much shallower depth downstream).
- Adequate natural light should be provided.
- Neither upstream or downstream fish passage should be obstructed.
- Debris accumulation should be minimised to maintain the intended characteristics of the structure over time.
- Abrupt changes in the flow regime during periods of high flow due to the structure changing from an open channel environment to a closed channel environment should be minimised.
- The structure should not be undermined or otherwise compromised over time by the flow and geomorphic conditions at the site.

The guidance provided in the following sections is based on currently available information and knowledge.

Where sufficient information is available, specific design criteria and minimum design standards are provided to assist with the development of fish friendly structure designs. However, knowledge gaps remain, meaning that in some circumstances design guidance is provided as broader 'rules-of-thumb' or as qualitative design principles. As knowledge and experience improves over time, it is expected that this guidance will be updated and refined. It is acknowledged that there is an inherent risk involved in designing structures based on incomplete knowledge that may be superseded over time. However, this risk can be minimised by following the principles of good fish passage design and applying a conservative approach to interpreting design criteria and minimum design standards.

4.1 What type of structure is best for fish passage?

The most appropriate structure in any given location will be dependent on the purpose of the structure and local conditions. This should be determined as part of the design process as set out in Section 3.2. However, from a fish passage perspective, some structures or structure designs are more fish friendly than others. In general, structures that preserve the continuity of stream habitats, geomorphology and stream processes (e.g., sediment transport) will have the lowest impact on aquatic ecosystems. This should, therefore, be taken in to consideration when selecting the most appropriate structure design.

River crossings are one of the most frequently encountered low-head instream structures in New Zealand. Inappropriate design of river crossings can significantly impede fish movements. This primarily occurs when structures constrict waterways and fail to maintain continuity of natural stream habitats. Figure 4-1 and Table 4.1 summarise the suitability of a range of commonly encountered river crossing types for providing fish passage. Single-span bridges are the preferred crossing type from a fish passage perspective, followed by stream simulation culvert designs. This is because these crossing types are best at maintaining the stream conditions to which fish are adapted for moving in. More traditional single barrel culverts can be designed and installed in a way that is more sympathetic to the needs of migrating fish and that meet minimum standards for fish passage design. However, there is typically greater uncertainty around design criteria and a greater risk of impeding fish passage with this approach. Multi-barrel culverts and fords should generally be avoided from the perspective of catering for unimpeded fish passage. See Section 4.2 for further details on culvert design for fish passage and section 4.4 for information on fords.

Head control structures, such as weirs and sluices, are another commonly encountered instream structure. They can be built for a variety of purposes, e.g., water intakes or flow gauging, but often create an obstruction to fish movements. Again, certain designs are more sympathetic to the requirements of migrating fish than others (Figure 4-2). Low-head concrete weirs can often be replaced with rock-ramp fishways that can effectively pass fish, otherwise broad-crested weirs with a rounded crest are preferred, and vertical weirs with sharp or overhanging crests should be avoided. See section 4.3 for further details on weir design for fish passage.

Flood control structures, such as tide gates, flood gates and pumping stations, typically act as barriers to fish migration. Ideally these structures should be avoided. However, where such infrastructure is necessary, it is preferable to install more fish friendly designs such as automated or self-regulating tide gates. See section 4.5 for information on flood/tide gate design considerations. It was outside the scope of this document to consider flood pumping station design because at present there is insufficient information available to provide robust design guidance.

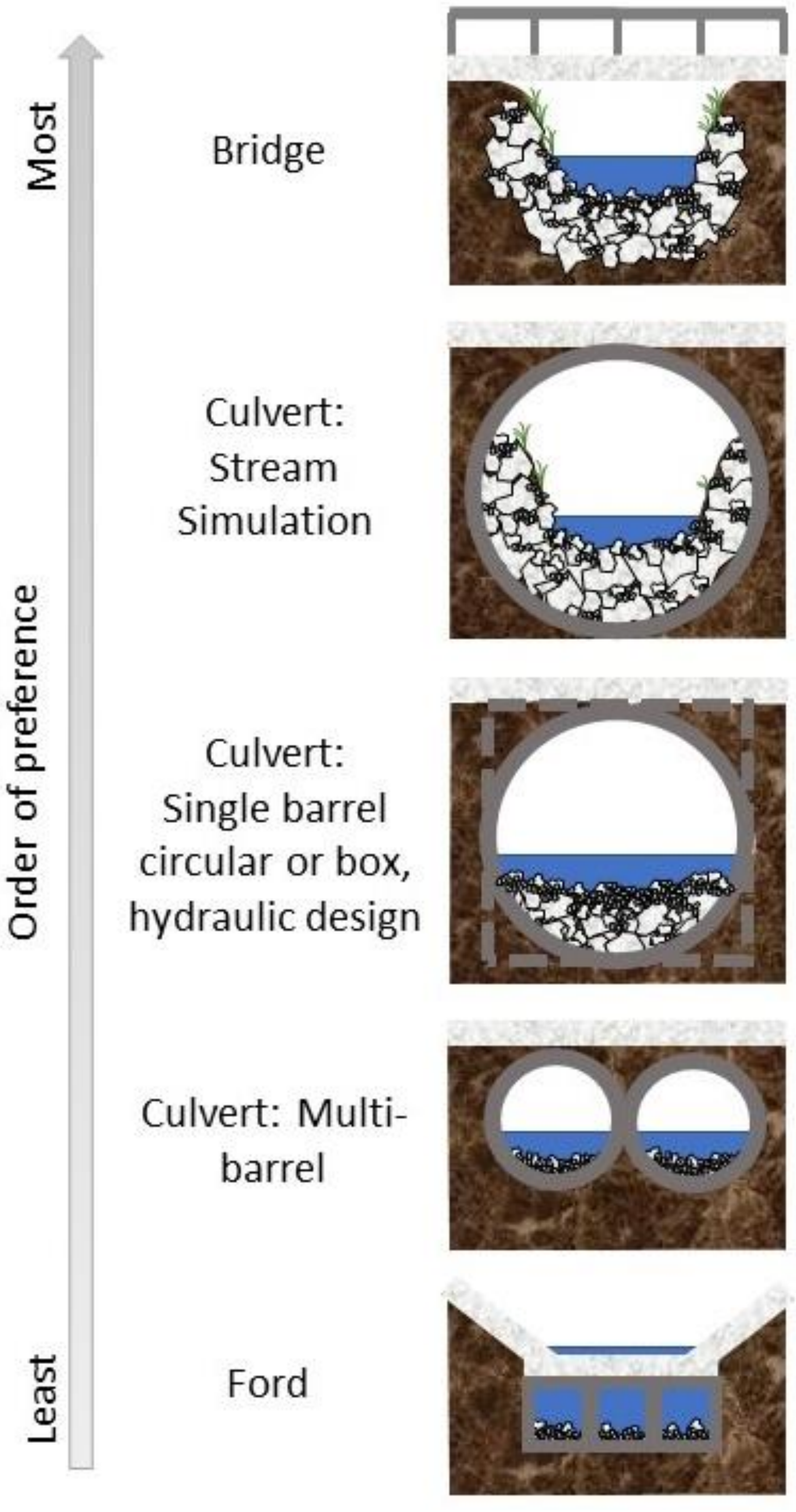

Figure 4-1: Order of preference for road crossing design, based on the degree of connectivity each design facilitates. Modified from U.S. Department of Agriculture (2008).

Table 4.1: Types of road crossings over streams and relevant features of these crossings for fish passage.

Crossing type	Fish Passage Features
Bridge	Preserves natural stream bed and banks. Allows natural water depths and velocities to be maintained. Substrate is natural. Preserves stream gradient and processes. Minimal disturbance due to construction. Bridge pylons can be a site for local scour and morphology changes.
Culvert: Stream simulation design	Natural stream bed is preserved or restored after construction. Provides water depth and velocity heterogeneity. Substrate is natural. Preserves stream gradient and processes. The structure side walls replace the stream banks, so natural banks are not maintained. Construction disruptive to stream habitats.
Culvert: hydraulic design	The culvert should be countersunk and natural substrate can be introduced if the culvert is suitably large. Gradient is homogeneous, although stream gradient should be maintained. Water velocities are typically elevated from natural stream velocities, but velocity heterogeneity can be provided where natural substrate is retained in the culvert. Construction is disruptive to stream habitats. Stream processes tend to be interrupted.
Culvert: Multi-barrel	Maintaining natural substrates within the culvert barrels is more challenging because culvert barrels are typically smaller than an equivalent capacity single culvert meaning that artificially introducing natural substrate is problematic. Stream cross-section is disrupted by the multiple barrels, resulting in a greater probability of flow constriction at the culvert inlets. Water velocities are typically elevated from natural stream velocities. Construction is disruptive.
Ford	Bed and banks are typically artificial, water depths are reduced and water velocities are elevated. Often creates a vertical barrier on the downstream face. Construction is disruptive.

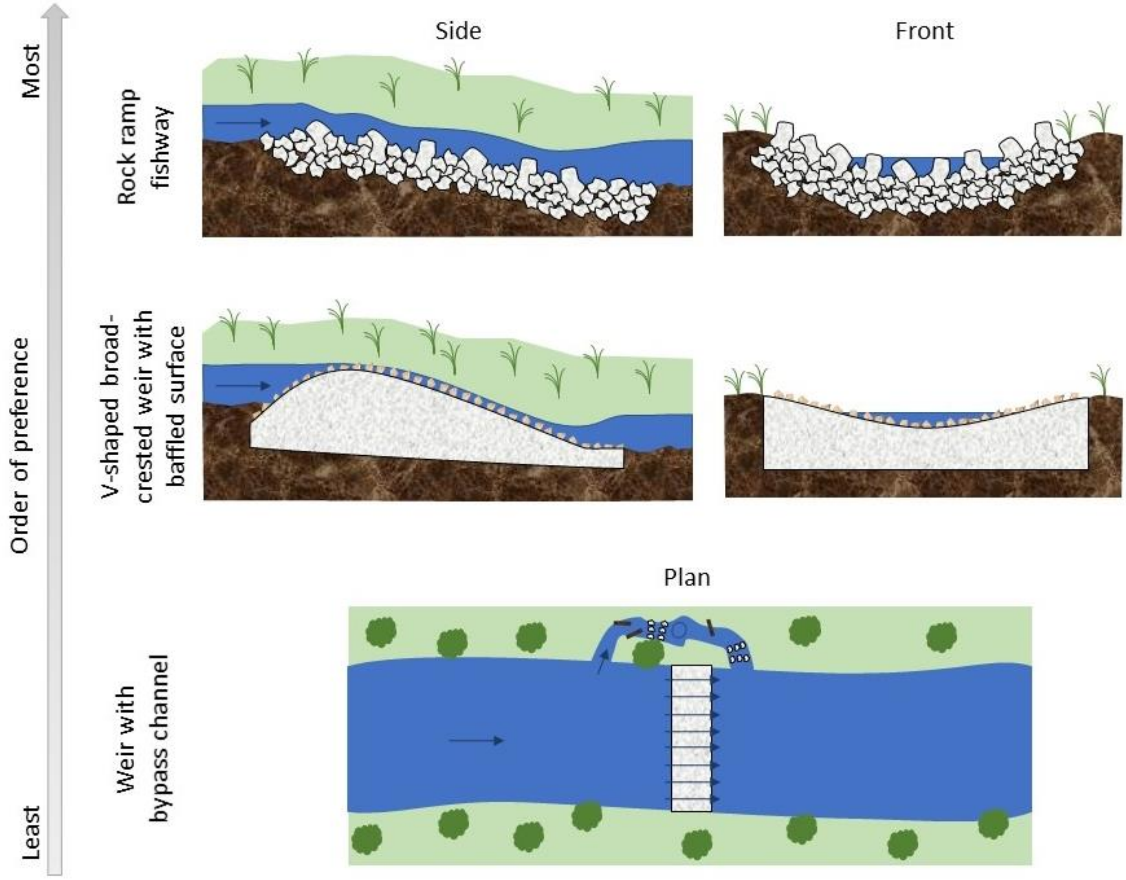

Figure 4-2: Order of preference for head control structure designs, based on the degree of connectivity each design facilitates.

4.2 Culverts

Culverts are one of the most commonly used structures for river crossings in New Zealand. The Freshwater Fisheries Regulations 1983 require that culverts must not impede the movement of fish unless approval (in the form of a permit) is received from DOC.

The following sections set out the key principles of culvert design from a fish passage perspective. It is acknowledged that hydraulic conveyance is also an important design parameter for culverts, and existing technical guidance on this aspect of design should be consulted in parallel with this document during the design process.

Two approaches to culvert design that are consistent with providing passage for fish and other organisms are described in these guidelines: stream simulation and hydraulic design. Stream simulation culvert design (see Section 4.2.1) is a holistic approach to designing river crossings that creates a natural and dynamic channel through the crossing structure similar in dimensions and characteristics to the adjacent natural channel (U.S. Department of Agriculture 2008). Passage through the culvert should, therefore, present no greater impediment to fish movements than adjacent stream reaches. The stream simulation approach represents international best-practice for the design of culverts to allow passage of aquatic organisms and is the recommended best-practice approach for New Zealand.

The hydraulic design approach represents the minimum design standards for culverts from a fish passage perspective (see Section 4.2.2). In the context of these guidelines, a hydraulic culvert design describes an approach whereby the culvert is designed to meet specific hydraulic performance standards that meet the requirements of the target fish communities. The hydraulic performance standards may be defined either with reference to known hydraulic requirements of target fish species and/or life stages, or based on reproducing hydraulic conditions in adjacent stream reaches. The current paucity of comprehensive information about the swimming capabilities of New Zealand freshwater fishes (see Appendix D for a review of fish swimming data) is a major limitation to defining species specific hydraulic performance standards. A worked example is provided for inanga in Section 4.2.2. The alternative approach based on replicating adjacent stream hydraulic characteristics within and around the culvert provides a less data intensive alternative that can still be implemented in a way that is consistent with the principles of good fish passage design.

4.2.1 Best Practice: Stream simulation culvert design

Best-practice culvert design criteria

- Alteration of natural stream channel alignment should be avoided or minimised.
- Alteration of natural stream channel gradient should be avoided or minimised.
- Culvert span will be greater than bankfull width. A rule-of-thumb is that the stream bed inside the culvert should be 1.2 x bankfull width + 0.6 m.
- Open bottom culverts will be used or the culvert invert will be embedded by 25-50% of culvert height.
- Substrate matching the composition and stability of the reference stream will be present throughout the full length of the culvert bed.
  - D_{84} is a recommended benchmark grain size for bed mobility analyses.

4.3.1.1 Background

Stream simulation has become an increasingly common culvert design method around the world (Barnard et al. 2015). The approach emerged as a more holistic design philosophy for stream crossings, based on integrating geomorphic, engineering and ecological approaches to design (U.S. Department of Agriculture 2008). The approach aims to overcome the problem of fish passage and loss of instream habitat frequently associated with traditional culvert designs focused on optimising hydraulic conveyance by mimicking adjacent natural stream characteristics within the culvert. On this basis, it is assumed that movement of fish and other organisms through the culvert will be equivalent to adjacent stream reaches, i.e., unimpeded passage. Furthermore, physical habitat continuity and ecosystem processes, such as transport of sediment and particulate matter, are maintained (e.g.,Olson et al. 2017; Timm et al. 2017). Evidence from overseas indicates that culverts designed using the stream simulation approach are also typically more resilient to hydrological extremes than traditional culvert designs, and that the relatively modest increases in initial investment to implement stream simulation designs yield substantial societal and economic benefits (Gillespie et al. 2014).

In contrast to hydraulic design approaches, stream simulation design does not target specific fish species or life stages for passage. Designers also do not have to match species-specific water velocity, depth or other hydraulic criteria. Instead, the objective is to create a continuous streambed that simulates natural channel width, depth, and slope connecting the stream reaches upstream and downstream of the structure. This maintains the natural diversity and complexity of water velocities and depths, hiding and resting areas, and edge habitats that different species use for movement.

The ecological and biological performance standards for the structure will help to guide the design specification for the stream simulation design. It is acknowledged that a stream simulation culvert design cannot recreate all features of a natural channel, and some features such as natural light, channel bends, and bank and flood-plain features typically cannot be included. The objectives defined during the design process will guide which features are essential to the simulation. For fish passage, the primary considerations will be reproducing in-channel features. Critical to achieving reproduction of the full range of in-channel features is creating a structure that encompasses at least the natural bankfull width of the channel. This is one of the most significant departures from the traditional hydraulic conveyance focused culvert designs that are found commonly in New Zealand, and thus the primary feature that requires a shift in mindset by structure designers.

4.3.1.2 Design principles

There are several general principles that characterise stream simulation culvert designs, and that contribute to their suitability for providing unimpeded fish passage:

- The overall objective is to maintain continuity of stream characteristics *and* processes through the culvert across the design flow range.
- The goal is to ensure that the simulated channel adjusts to accommodate a range of flood discharges and sediment/debris inputs, without compromising fish passage or having detrimental impacts on the upstream or downstream river reaches.
- Adjacent stream reaches are used as a reference for design so that conditions within the culvert present no greater challenge to fish movement than the natural stream.
- The natural stream alignment and gradient are maintained through the culvert.
- The culvert is sized to accommodate the natural bankfull width, plus an allowance for constructed channel banks (Figure 4-3).
- The culvert base (invert) is open (e.g., an arch culvert) or is embedded (typically 25–50% of its rise) so that natural stream habitats and substrates are provided and maintained within the culvert (Figure 4-3).
- Bed stability in the culvert should match that of the adjacent stream reaches.

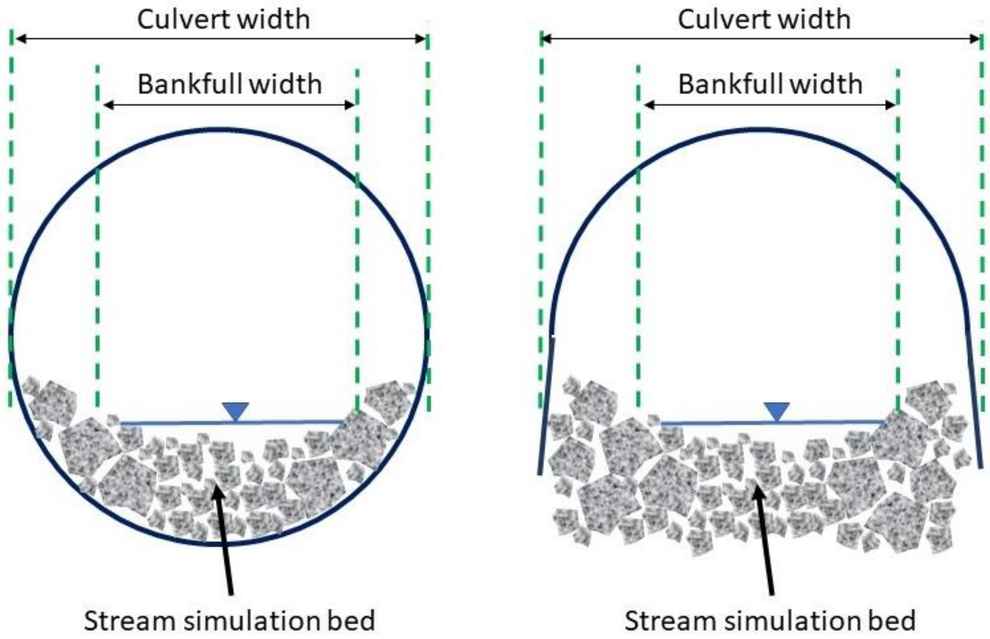

Figure 4-3: Illustration of indicative culvert sizing relative to bankfull width for a stream simulation design using an embedded round culvert or arch culvert.

4.3.1.3 Design process

Stream simulation design is inherently interdisciplinary. Practitioners with experience in various relevant fields should be involved in the design process – including engineering, biology, hydrology and geomorphology.

Stream simulation projects involve several stages (U.S. Department of Agriculture 2008). Extensive guidance on the stream simulation approach is provided in U.S. Department of Agriculture (2008) and will not be reproduced here. Practitioners should refer to the original document[2] for detailed guidance and implementation purposes, but a summary of the main steps and discussion of some of the key challenges in implementing the approach are provided here.

Initial assessment

The first step in the design process is to undertake a catchment-scale review and site reconnaissance. The objective is to assess the suitability of the site for a stream simulation culvert and to establish the preliminary scope for the project. Stream simulation designs are most suited to locations with a relatively stable channel form, so a critical component of this stage is to characterise the lateral and longitudinal stability of the stream channel. This should include considering how the channel may change over the lifetime of the structure through both natural (e.g., large floods) and anthropogenic (e.g., land use change) drivers. Accounting for processes such as channel incision, bed aggradation or degradation, or lateral channel migration increases the complexity of the design process, but does not necessarily preclude the use of the stream simulation approach. At this stage, preliminary project objectives should be defined.

[2] Available at: https://www.fs.fed.us/eng/pubs/pdf/StreamSimulation/hi_res/%20FullDoc.pdf [Accessed January 2018]

It is recommended that the initial site visit be carried out by an interdisciplinary team, so that all potential issues and risks are identified from the outset of the project. Following review of the initial assessment, a decision on whether to proceed with a stream simulation culvert design, or whether an alternative crossing type is required, can be made. Details of what should be considered during the initial site assessment are presented in Chapter 4 of U.S. Department of Agriculture (2008).

Site assessment

After the initial pre-design phase to verify the suitability of the site for a stream simulation design, the next step is to undertake a detailed assessment of the design reach. This should include longitudinal and cross-sectional profiles of the channel, bed material assessment, consideration of secondary flow paths, and longitudinal and cross sections of the roadway to cross it. A similar assessment is also conducted for the reference reach.

Selection of an appropriate reference site is critical to developing a suitable design for the simulated channel within the culvert. The reference reach is typically sited nearby and upstream of the prospective culvert site. It must be stable and have a similar bed slope, channel cross-section and substrate to the reach where the culvert is to be placed (see Figure 4-4). In streams with relatively natural geomorphology, selection of the reference reach will likely be relatively straightforward. However, where stream morphology has been modified by human impacts, this process can be more challenging. Under such circumstances it is necessary to consider whether over the lifetime of the structure, the channel condition is likely to remain in its modified state and whether that condition is stable. If this is the case, then a local reference modified reach should be selected that is representative of the current channel shape, size and stability. If naturalisation of the channel is expected, for example through channel rehabilitation, suitable reference sites at nearby unimpacted streams may be a suitable surrogate.

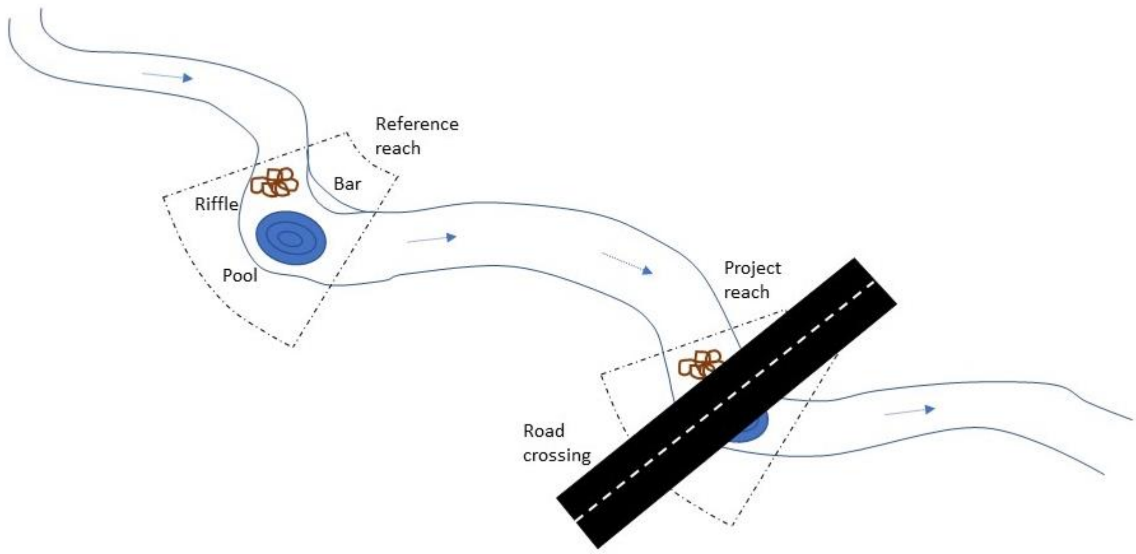

Figure 4-4: Schematic of the reference reach and the project reach. The reference reach is typically nearby and upstream of the stream simulation project reach. The reference reach should be stable and with a similar bed slope, channel cross-section, and substrate to the project reach.

An important part of the site visit is to identify the bankfull width, as this is used as a benchmark for sizing the stream simulation design reach. The bankfull elevation is the point where water fills the channel, just before beginning to spill into the floodplain. The bankfull width is the wetted width (i.e., the width of the water) when flow is at the bankfull elevation (Figure 4-5). The frequency with which bankfull flows occur varies with channel morphology, flow regime, and watershed conditions, but has been suggested to typically occur every one to two years (Leopold et al. 1964). Bankfull flow is considered important for maintaining channel form, which is why it is used as a benchmark for sizing stream simulation crossings.

Characterising bed and bank material and structure is another crucial consideration during the site visit. The bed material size distribution in the reference reach is the basis for determining the design bed material for the stream simulation reach. It is also important to determine the size of key rocks or other features that may act as grade control or energy dissipation features in the reference reach as the sizing of these pieces will inform the design of any stabilising features in the simulation reach. Understanding bed substrate composition and mobility (e.g., through evaluation of critical shear stress) in the reach immediately upstream of the stream crossing site is also important as this will act as the source for resupplying substrate to the simulation reach during high flows. Substrate mobility should be matched between the upstream and simulated reaches to avoid substrate being denuded from the simulation reach during elevated flows and not replaced.

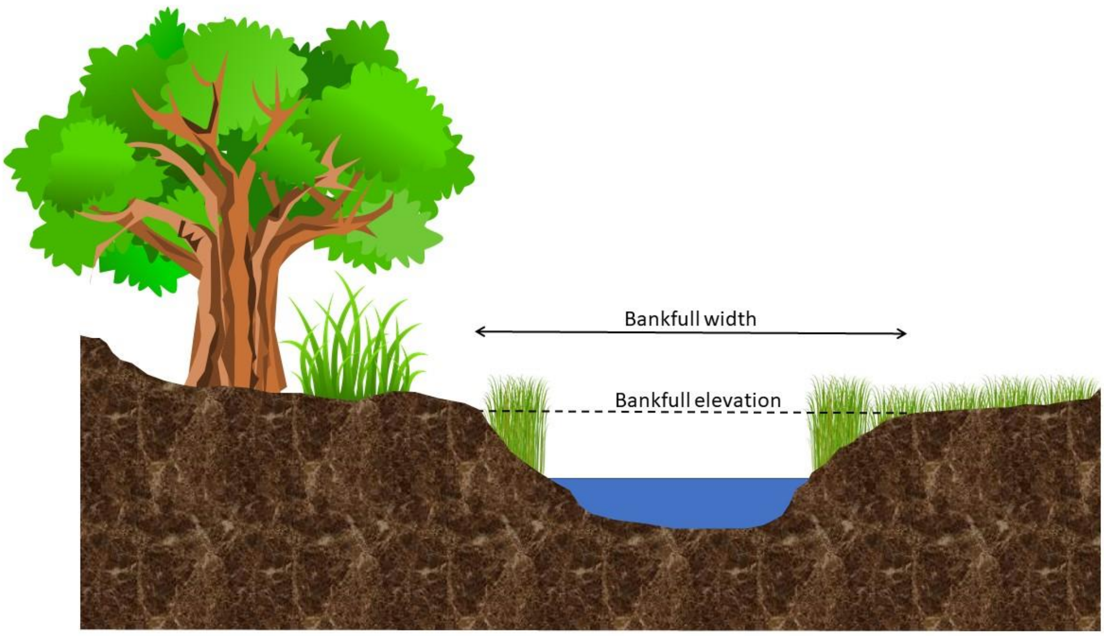

Figure 4-5: Illustration of bankfull elevation and bankfull width.

The result of the site assessment should be a geomorphic characterisation of the reach, an engineering site plan map for design and detailed project objectives. Assessment of the reference reach will provide the template for the simulated streambed. Further details on this stage of the project are available in Chapter 5 of U.S. Department of Agriculture (2008).

Stream simulation design

Based on the outcomes of the first two stages, the team now develops the stream simulation design. The key steps in this process are to:

1. determine the project alignment and long profile
2. design the bed material size and arrangement
3. design the culvert to fit around the stream simulation channel, and
4. verify the simulated bed stability within the structure at the design flows.

This stage of the design process can be iterative as different issues arise requiring decisions to be revisited. It is important at this stage to ensure all members of the interdisciplinary team remain involved in the design process to address any issues relevant to all fields (biology, geomorphology, hydrology, engineering, construction) as they arise.

Ideally the alignment and long profile of the project will approximate the natural channel pattern and slope as this tends to result in the greatest long-term stability of the structure. Where alignment is skewed relative to the natural stream path, it often increases the risk of scour, backwatering and debris blockage at the inlet. The longitudinal profile of the new stream bed is also important and should connect with stable points in the channel upstream and downstream of the structure. For completely new structures, it is generally relatively straightforward to achieve as the project long profile should match the existing stream. However, where an existing structure is being replaced, consideration must be given to re-establishing a natural profile and the extent of the project may need to be extended to consider stable grade controls upstream and downstream of the structure.

Once the culvert layout has been determined, the stream simulation channel must be designed. This step must consider the particle size distribution of the bed material, channel width and cross-section shape, bedforms and roughness conditions. These features are each determined based on the characteristics of the reference reach. It is recommended that the bed material consists of a wide range of particle sizes and includes sufficient fines (particles <2 mm diameter) to fill voids between larger particles and reduce infiltration into the channel bed.

The bank and channel margin features are also a crucial component of the design, both for supporting channel stability and for ensuring the provision of a diversity of channel edge habitats. The bank edge of the simulated stream reach is intended to be permanent and should extend beyond the culvert inlet and outlet. Consequently, it is necessary to size the material used for construction of the banks to ensure that it remains stable in the peak design flows.

Once the stream simulation channel has been designed, the culvert structure is designed to fit around the simulated channel and accommodate the peak design flows. A typical rule-of-thumb is that the width of the bed inside the culvert should be 1.2 x bankfull stream width + 0.6 m (Barnard et al. 2013) and the culvert must be sized accordingly to accommodate this. Preliminary sizing of the culvert is required to calculate bed stability in the simulated channel at the different design flows, and may have to be altered if the results of the bed stability and flow capacity analyses do not meet the design criteria.

The purpose of the bed mobility analysis is to ensure that the bed materials in the simulation reach move at the same flows as those in the reference reach. This is critical for ensuring a balance in sediment transport into and out of the culvert. The mobility analysis is done on the larger grain sizes in the bed, with D_{84} being a recommended benchmark size (U.S. Department of Agriculture 2008).

For further details on this stage of the project see Chapter 6 of U.S. Department of Agriculture (2008). This also addresses some of the risks to channel and structure stability and methods for mitigating these risks.

Final design & construction

At this stage, the structural design is completed, and construction drawings and specifications are prepared and finalised for contracting. Subsequently, construction of the stream simulation reach and stream crossing occurs. Specialists involved in the design should continue to be informed of the construction process and be involved as necessary to help negotiate any challenges as they arise on site. It is important to ensure that the project is built to specification and that any departures from that specification are agreed with the interdisciplinary design team. All relevant consents required for dewatering and construction should be in place, along with appropriate plans for sediment and pollution control during the construction phase. These rules will generally be determined in regional plans under the requirements of the RMA91.

Maintenance and monitoring

Maintenance requirements of stream simulations can be expected to be lower than for traditional or modified culverts, as they are larger in size and, therefore, less prone to blockage. Monitoring should be undertaken to assess whether the fish passage and any other stream simulation objectives are being met. This will be particularly important as this culvert design approach is implemented in New Zealand. International experiences suggest good success in achieving ecological, geomorphic, hydrological and structural stability objectives using the stream simulation approach. Experience of implementing the approach in New Zealand systems will be important to guiding where refinements in the guidance may be required in future to reflect any particularities in our environment. However, because the overall design philosophy is grounded in geomorphic design principles, this should provide a sound foundation for transferring this approach to New Zealand systems.

4.2.2 Minimum design standards: Hydraulic culvert design for fish passage

Minimum culvert design standards

- Low (Q_L) and high (Q_H) fish passage design flows should be defined. As a rule of thumb, $Q_L \leq 95\%$ exceedance flow and $Q_H \geq 20\%$ exceedance flow.
- Alteration of natural stream channel alignment should be avoided or minimised.
- Alteration of natural stream channel gradient should be avoided or minimised.
- Culvert span will be:
  - 1.3 x bankfull width for streams with a bankfull width ≤3 m.
  - 1.2 x bankfull width + 0.6 m for streams with a bankfull width >3 m.
- Open bottom culverts will be used or the culvert invert will be embedded by 25-50% of culvert height.
- Mean cross-sectional water velocity in the culvert over the fish passage design flow range will be equal to or less than the greater of:
  - mean cross-sectional water velocity in adjacent stream reaches, or
  - the maximum allowable water velocity calculated from fish swimming speeds of agreed target fish species and/or life stages.
- Minimum water depth in the culvert at the low fish passage design flow will be the lesser of:
  - 150 mm for native fish passage, or 250 mm where adult salmonid passage is also required, or
  - mean cross-sectional depth in adjacent stream reaches.
- Well graded substrate will be present throughout the full length of the culvert bed.
- Substrate within the culvert will be stable at the high fish passage design flow.
- Any ancillary structures must not create an impediment to fish passage.
- Vertical drops through the structure will be avoided.

4.2.2.1 Background

Culverts have traditionally been sized to maximise hydraulic conveyance while minimizing the size of the culverts and, hence, the cost. The factor missing from this optimisation exercise is to also minimise the impediments to fish passing through the culvert. While this is not mutually exclusive with a goal of ensuring adequate hydraulic conveyance to avoid road flooding due to river flow, the design approach required is very different to more traditional culvert design practices.

The hydraulic design approach for fish passage relies on engineering specific hydraulic conditions within a culvert that meet identified biological needs in addition to hydraulic conveyance requirements. This approach to catering for fish passage initially emerged from circumstances where the hydraulic performance standards to inform design were defined by the swimming and jumping capabilities of a single life stage of a specific target fish species (generally salmonids). Culverts could then be designed to meet the specific hydraulic design criteria required to allow passage for the target fish species. However, as the focus of fish passage management has broadened from catering for single species to supporting multiple species and life stages, the challenge of both defining hydraulic performance standards and designing structures to meet diverse hydraulic requirements has become more complex. Furthermore, the focus on hydraulic performance, rather than the continuity of stream processes and habitat, has been recognised to impact on ecosystem health. Consequently, an alternative approach to defining the hydraulic performance standards for culverts has emerged, focused on mimicking the range of hydraulic conditions present in adjacent stream reaches. This is based on the assumption that conditions in the stream set the boundaries for natural movement rates of aquatic organisms.

4.2.2.2 Design principles

Effective hydraulic design of culverts for fish passage requires simultaneous consideration of the hydraulic effects of culvert size, slope, material and elevation to create water depths, velocities, and a hydraulic profile suitable for fish swimming abilities. This must be achieved across the range of flows required to support fish passage, i.e., between the low (Q_L) and high (Q_H) fish passage design flows (see below for further details on defining design flows). At present, knowledge of the swimming capabilities and behaviour of most of our native fish species is relatively poor. This presents a significant challenge to developing effective hydraulic performance standards to inform design criteria for providing fish passage through culverts. Consequently, in these guidelines greater emphasis is placed on defining hydraulic performance standards relative to conditions in adjacent stream reaches.

Traditional culvert design iteratively determines the optimal culvert size (or sizes if multiple barrels are used), and the resultant water depth and velocity for a peak design flow (Q_P), by comparing the depth of flow through the culvert under inlet and outlet control conditions. In contrast, hydraulic design for fish passage requires an open channel design approach. The culvert is not intended to provide a constriction to the flow up to the bankfull flow, and should not be designed to operate in pressurized conditions over the fish passage design flow range.

The way to approach the hydraulic design of culverts for fish passage, therefore, is to consider this an open channel design problem. While the design should consider the size of culvert necessary to convey the peak design flow (Q_P), this will typically not be the limiting factor on the diameter or width of the culvert. Rather the culvert should encompass the width of the stream channel. Conveyance calculations should then confirm that the culvert is large enough to convey the peak design flow (Q_P). The bed slope of the culvert should be close to natural stream bed slope, and maintaining subcritical flow within the culvert should be an objective of the design. Water velocity through the culvert should not generate shear at the bed that is exceeds the critical shear stress associated with the substrate in the culvert at the high fish passage design flow (Q_H).

The hydraulic design approach is largely based on achieving a maximum water velocity that the target fish species can swim against while negotiating the full length of the culvert. Consequently, the longer the culvert, the lower the maximum allowable water velocity. The required culvert length, therefore, sets the template against which decisions on culvert size, slope and roughness must be made to achieve the maximum allowable water velocity.

4.2.2.3 Design process

Initial assessment

In common with the stream simulation design approach, the first step in the design process is to undertake a catchment-scale review and site reconnaissance. The objective is to assess the suitability of the site for a culvert and to establish the preliminary scope for the project. As for stream simulation designs, hydraulic culvert designs are most suited to locations with a relatively stable channel form, so a critical component of this stage is to characterise the lateral and longitudinal stability of the stream channel. This should include considering how the channel may change over the lifetime of the structure through both natural (e.g., large floods) and anthropogenic (e.g., land use change) drivers. Accounting for processes such as channel incision, bed aggradation or degradation, or lateral channel migration increases the complexity of the design process. At this stage, preliminary project objectives should be defined.

A critical component of the initial assessment is to determine the target species, life stages and minimum sizes for which passage must be provided at the site. At this stage the decision should also be made as to whether the hydraulic performance standards for the structure will be defined based on known swimming capabilities and behaviour of the target organisms, or by emulating local stream characteristics.

Design flows

The migration periods of the target fish species identified in the initial assessment should be used to inform the fish passage design flow range. This effectively sets the range of flows over which the hydraulic performance standards for the structure must be met. The fish passage low flow (Q_L) is the lowest flow at which fish passage must be provided. As a rule of thumb, Q_L can be set at the 95% exceedance flow (i.e., the flow that is equalled or exceeded 95% of the time), which approximates to the mean annual low flow in many rivers in New Zealand. The fish passage high flow (Q_H) is the highest flow at which the hydraulic performance standards for fish passage should be met. A rule of thumb is to use the 20% exceedance flow for Q_H.

The design peak flood flow (Q_P) is a reasonable estimation of the highest flow that the culvert should be designed to pass without causing a significant increase in upstream flooding. The appropriate standard for Q_P should be determined with reference to relevant regional plan rules, local drainage standards and technical design guidance for roadways and infrastructure.

Defining allowable water velocities

Water velocity is one of the main factors influencing the upstream passage of aquatic organisms through culverts. Consequently, defining water velocity standards for the structure is critical to ensuring ecological objectives are met. There are two main approaches to defining water velocity standards for a culvert; using knowledge of fish swimming speeds and behaviour, or by using conditions in adjacent stream reaches to define the envelope of allowable water velocities.

Fish swimming capabilities

To make upstream progress through a culvert, fish must be able to swim at a speed that exceeds the velocity of water they are swimming in to. The lower the water velocity, the lower the swimming speed required to make upstream progress, and the greater the distance a fish can travel before becoming exhausted. Practically speaking, culvert length at a given stream crossing is usually fixed or tightly constrained. Consequently, maximum allowable water velocities must be chosen that allow fish to pass the full length of the culvert without reaching exhaustion across the fish passage design flow range.

The trade-off between water velocity, fish swimming speed and the distance that can be travelled (i.e., culvert length) can be described by Equation 1:

$$U_w = U_f - (L/t) \quad (1)$$

where U_w is the culvert design water velocity, U_f is the swimming speed of the fish, L is the length to be travelled, and t is the time to fatigue at U_f (i.e., the time taken for a fish to reach exhaustion when swimming continuously at a given speed). If solved for different values of U_f the resultant curve can be used to identify suitable design water velocities that should theoretically allow fish to pass a culvert of a given length (e.g., Figure 4-6). It should be noted that this relationship will vary between individuals and species, with fish size, environmental conditions (e.g., water temperature), and the distance to be travelled. It is important, therefore, to ensure that in determining U_f, representative values are used for the species, life stages and conditions expected at the site of interest.

There are two values of U_f for most values of U_w. The smaller of these values represents a situation where the fish swims at a slow speed for a long time to pass the culvert, reaching total exhaustion at the upstream end. The larger value represents a situation where the fish swims at a higher speed for a shorter period of time to pass the length of the culvert; again reaching total exhaustion at the upstream end. The lower swimming speed for a given water velocity, therefore, represents *time based* fatigue, whereas the upper speed represents *speed based* fatigue. For a given water velocity, fish swimming speeds between the smaller and larger values on the curve are sustainable for the length of the culvert without inducing total exhaustion.

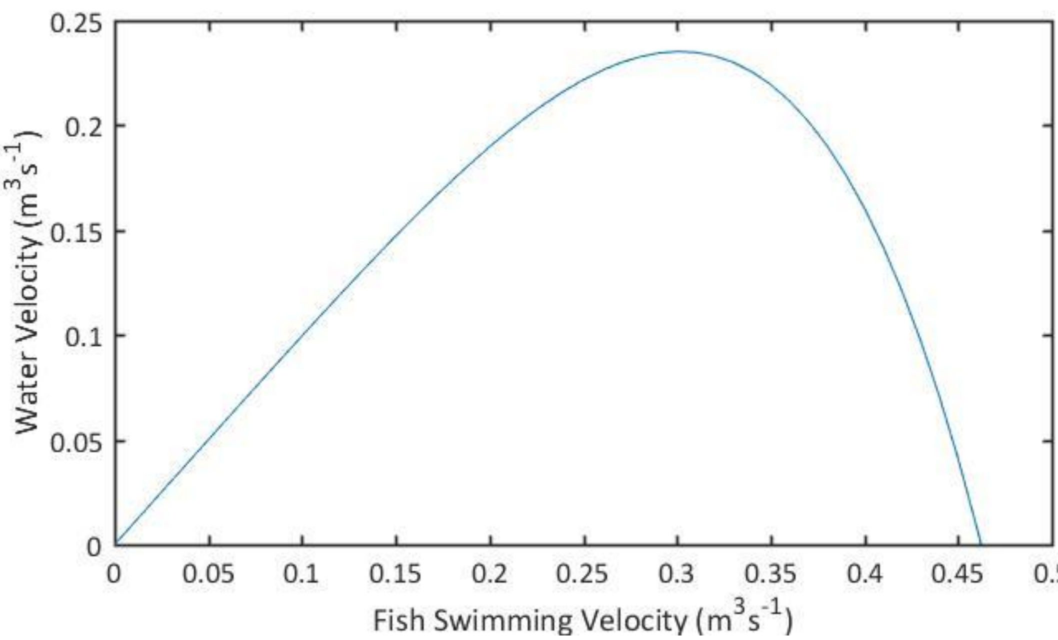

Figure 4-6: Example of a curve describing the swimming speeds required for a 5 cm inanga to successfully pass a 10 m fishway. Based on data from Nikora et al. (2003) for tests conducted at 16 – 22 °C.

In most cases in New Zealand, it will be required that passage be provided for all fish species and life stages expected to be normally resident or migrating through the site of the structure. In this situation, the maximum allowable water velocity will be defined by the requirements of the weakest species and/or life stage. Data currently available on swimming speeds for New Zealand's freshwater fishes are reviewed in Appendix D. While a range of data are available, many of these data are not in a form suitable for robustly evaluating water velocity design criteria. This is because of factors such as sample sizes being too small to represent the range of capabilities expected in a population, an adequate range of fish sizes not being evaluated, the tested swimming durations were too short for anything but very short culverts, or information on parameters such as the water temperatures at which tests were carried out were not reported. Consequently, at present the only species with published relationships between fish swimming speed and time to fatigue suitable for calculating allowable water velocities is inanga (Equation (2); Nikora et al. 2003). Fortunately, inanga are generally considered representative of weaker swimming native fish species (e.g., Baker 2014). In the absence of suitable information for other species it may, therefore, be appropriate to use inanga as an indicator species for calculation of maximum allowable water velocities. However, as relationships between swimming speed and time to fatigue become more readily available for other species in the future, this assumption can be tested. The process of determining the maximum allowable water velocity for fish and the design water velocity is explained in a worked example below.

Worked example: Determining maximum allowable water velocity for a 75 mm inanga through a 10 m long culvert

The first step of the process is to determine the target species and expected size ranges expected to be present at the site of the new structure. In this example we are assuming that the target species is inanga, and that the minimum size required to pass is 75 mm. Site constraints mean that the culvert length is set at 10 m. We need to know, therefore, what is the maximum water velocity over a 10 m distance that an inanga of 75 mm can pass before reaching fatigue.

The median relationship between fish swimming velocity, U_f (m s^{-1}), time to fatigue, t (s), and fish length, L_f (m), developed for inanga by Nikora et al. (2003) is shown in Equation (2):

$$U_f = 8.86 {L_f}^{0.76} t^{-0.22} \quad (2)$$

This applies within the range of t = 1 to 400 seconds and across fish lengths ranging from a mean of 48 mm (SD ± 2.5 mm) to 91.8 mm (SD ± 10.3 mm) at water temperatures of 16-20 °C. By combining Equation (2) with Equation (1) we can determine the maximum water velocity that will allow passage for an inanga of the target size. The resulting equation, Equation (3), gives the design water velocity in terms of fish swimming velocity (U_f) and culvert length (L) for inanga:

$$U_w = U_f - \frac{L}{(U_f/(8.86 \times {L_f}^{0.76}))^{\frac{-1}{0.22}}} \quad (3)$$

This equation essentially defines an outer envelope of passable water velocities for a given culvert length and size of inanga, with the peak of the curve representing the maximum water velocity that is theoretically passable.

The values for the minimum fish size and culvert length (75 mm and 10 m respectively for this example) are substituted into Equation (3) resulting in an equation relating fish swimming velocity to water velocity. The relationship for this example is illustrated in Figure 4-7.

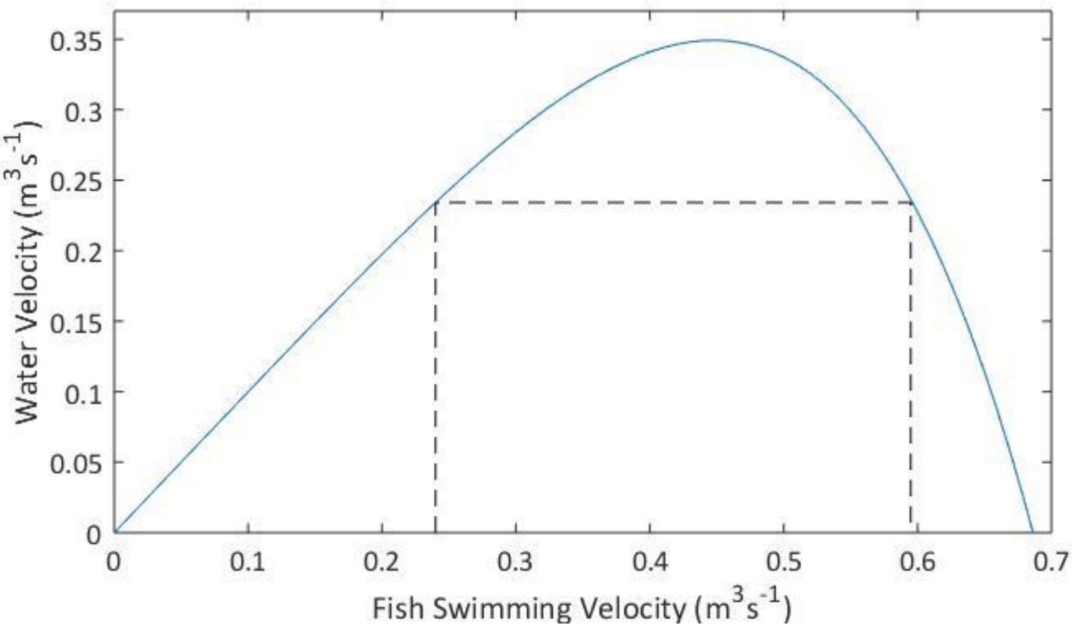

Figure 4-7: Relationship between design water velocity (U_w) and fish swimming velocity (U_f) for a 75 mm inanga in a 10 m culvert. Data based on Nikora et al. (2003).

The highest passable water velocity (i.e., the peak of the curve in Figure 4-7) is 0.35 m s^{-1}. However, this maximum water velocity should not be selected as the design velocity, as this precludes choice of swimming speed for the fish (i.e., they must swim continuously at the optimum velocity (0.35 m s^{-1}) for the entire culvert length to pass successfully), and more importantly it does not allow for the natural variability in swimming ability between individual fish. Furthermore, Equation (2) is derived from a line of best fit, meaning that in effect it represents the capabilities of the 'average' fish. Assuming a normal distribution, this means that on average 50% of the fish will be better swimmers than described by the equation, but more importantly 50% of the fish will be weaker swimmers. Consequently, the maximum allowable water velocity must be set below the highest passable water velocity if the majority of fish are to pass. In the absence of quantitative information on the variability in fish swimming capabilities, as a general rule-of-thumb it is recommended that the design water velocity is set at 70% of the highest passable water velocity, i.e., 0.24 m s^{-1} for this example. The maximum allowable design water velocity represents the average cross-sectional water velocity in the culvert.

To assist with application of these design criteria as described above, a look-up table of allowable water velocities for inanga for a range of culvert sizes is provided in Table F-1. Relationships for other species will be added to Table F-1 as they become available.

Stream conditions

Where insufficient data are available to define robust water quality design criteria for multiple species, or where there are multiple competing requirements across a range of flow conditions, it may be more straightforward to set allowable water velocities with reference to stream conditions.

This approach is based on the assumption that if the range of water velocities in the culvert are equivalent to those in the stream, then the water velocities in the culvert should present no greater impediment to the movement of organisms than the water velocities in the adjacent stream. In effect, this represents a simplified version of the stream simulation design approach.

Water velocities within a stream reach will vary with time, depth, across a cross-section and longitudinally (Gordon et al. 2004). The objective of this approach is to capture this variability and ensure that conditions within the culvert are within equivalent ranges. The hydrology procedure in Protocol 3 of the New Zealand Stream Habitat Assessment Protocols (Harding et al. 2009) would be a suitable method for characterising the diversity of mean cross-sectional water velocity within a stream reach. This method recommends that up to three cross-sections per major habitat type (e.g.,pool, riffle, run) be established and that water velocity and depth be measured at approximately 10 offsets across each transect (Figure 4-8). Mean cross-sectional water velocity is calculated by averaging the water velocity measurements at each offset within a cross-section. The variation in water velocities can be calculated as the standard deviation of the mean water velocities from cross-sections, rather than each individual velocity measurement (Harding et al. 2009). As a minimum, it would be expected that mean stream cross-sectional water velocities would be calculated from at least three cross-sections located in representative run habitats in reaches near to the culvert site.

Allowable water velocities for the culvert are defined by the mean and standard deviation of stream cross-sectional water velocities. Mean cross-sectional water velocities within the culvert should, therefore, be equivalent to those observed in the stream across the fish passage design flow range.

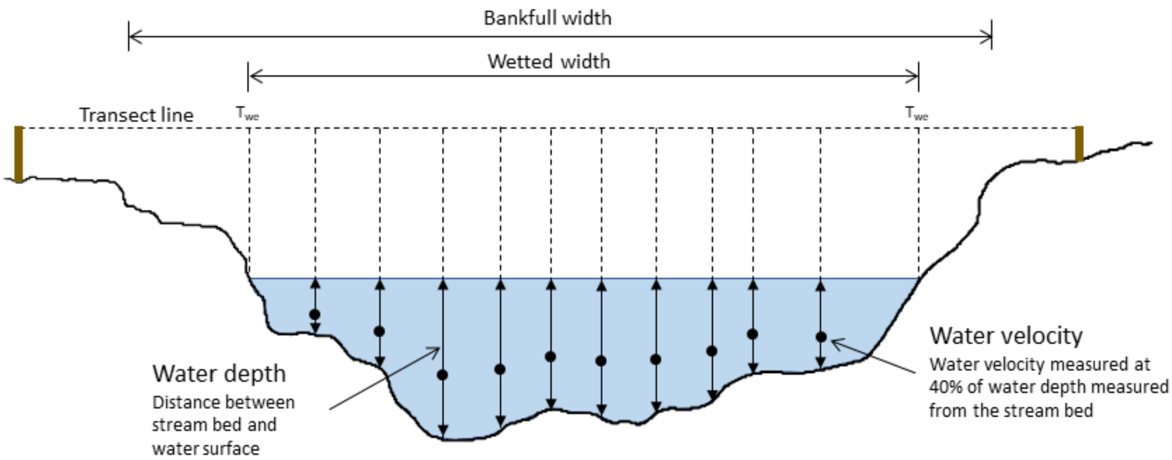

Figure 4-8: A typical stream channel cross-section. The transect line shows the location of the offsets at the water's edge (T_{we}) and where water velocity and depth are measured. Bankfull width is also indicated. Adapted from Harding et al. (2009).

Defining minimum water depths

It is important to ensure that water depths within the culvert are sufficient to allow passage of all target fish species and life stages. Minimum water depths in the culvert should be determined at the low fish passage design flow (Q_L). As a general rule of thumb, a minimum water depth of 150 mm will be sufficient for passage of adult native fish such as banded kōkopu or grey mullet. Where adult salmonids require passage, a minimum water depth of 250 mm is appropriate.

In some streams, the minimum water depth will naturally be less than these suggested minima at Q_L. Under these circumstances it is appropriate to use the natural stream environment as the benchmark for defining water depth criteria for the culvert. Mean cross-sectional water depth in adjacent stream reaches can be calculated using the same method as described above for water velocity.
Mean cross-sectional water depth within the culvert at Q_L should be greater than the minimum mean cross-sectional water depth observed in the stream at Q_L.

At a minimum, water depths should be great enough to fully submerge the largest fish requiring passage, and should be based on the body-depth of the fish. A possible exception to this is where the only fish requiring passage are juvenile climbing species (see Appendix D), in which case low water depths may be used to exclude known exotic species if present in the catchment (Stevenson and Baker 2009).

Hydraulic design

Once the design flows, allowable water velocities and minimum water depth have been determined, culvert design can commence. The objective is to optimise the design to meet performance requirements for both fish passage and conveyance of peak design flows (Q_P).

Culvert alignment and slope

It is recommended that as far as practicable, all culverts should be constructed such that they maintain the natural alignment and slope of the stream. This helps to maintain continuity of habitat and connectivity for aquatic organisms and channel processes. However, it is recognised that in some circumstances site constraints may require deviations from this practice.

From a fish passage perspective, it is most critical that a gradient be maintained that is continuously accessible to the target fish species and life stages from the downstream reach of the stream, into, through and out of the culvert at the upstream end. Ideally the gradient would be the same as the stream bed slope. In streams with high gradients, this may be achievable if an arched culvert which preserves the natural stream bed is used. However, artificial culverts on high gradients may introduce excessively high water velocities (Kapitize 2010). In this case, roughened substrates will be required to achieve the hydraulic design criteria for fish passage (see below).

Bed slope need not be uniform, however, the slope should not impede passage due to: a fall or bed discontinuity; an inappropriate crest configuration (where the term crest can apply to any upstream to downstream change in bed slope); or impassably high water velocities or shallow water depths that result from the slope.

Culvert sizing

Culvert size is determined by the need to convey the peak design flow (Q_P) and to meet the performance standards for water velocity, water depth and substrate stability over the fish passage design flow range. In general, the culvert size required to meet the conveyance requirements of Q_P will be less than that required to achieve the fish passage performance standards up to Q_H.

International experience indicates that sizing the culvert relative to stream bankfull width (Figure 4-5) is an effective benchmark for fulfilling fish passage design requirements. The objective is to ensure that the culvert will not constrict the bankfull flow. Based on existing international guidance (e.g., Barnard et al. 2013; Kilgore et al. 2010), the following rules of thumb are suggested for New Zealand waterways:

- For streams with a bankfull width ≤3 m, the culvert span should be 1.3 x bankfull width.
- For streams with a bankfull width >3 m, the culvert span should be 1.2 x bankfull width + 0.6 m.

Once the initial culvert size is set, mean culvert water velocities, water depth, substrate stability and conveyance can be calculated. If the performance standards for these parameters are not met, there may be a need to resize the culvert.

Culvert length is generally dictated by the site conditions and specific infrastructure needs, but should be minimised as far as practicable and excessively long culverts should be avoided. Where culvert length exceeds the swimming capabilities of the target fish species at the maximum allowable water velocity, low velocity, low turbulence resting areas with cover will have to be provided within the culvert barrel. In general, this should be provided through the retention of natural substrate and bedforms within the culvert.

Culvert embedment

Maintaining continuity of instream habitat throughout the culvert will provide considerable benefits for fish passage. Substrate retention will help to increase the heterogeneity of the water velocity and depth profiles in the culvert, and create boundary layer conditions more suited to fish movements. The embedment depth is determined based on culvert and substrate sizes, but should be in the range of 25 to 50% of the culvert rise.

Bed roughness

The low water velocity and turbulence requirements of many native fish species mean that it can be challenging to develop suitable hydraulic designs in the absence of additional channel roughness within the culvert barrel. The preferred approach for achieving this is to maintain continuity of natural stream substrates throughout the full extent of the culvert by embedding the culvert invert. Integrating substrates of the same size gradation as the natural stream in to the culvert design provides greater hydraulic diversity, offering a greater variety of migration pathways and low velocity resting areas suitable for passage of multi-species assemblages and different life stages. Advice on developing the particle-size distribution curves for the culvert substrate mix is given in Kilgore et al. (2010). Culvert baffles can also be used to achieve greater roughness, thus improving conditions for fish passage, but baffle installation should primarily be considered a retrofit solution and as a last resort for new structures. For more information on baffle design, see Section 5.3.3.

In contrast to the stream simulation approach, which is specifically intended to accommodate bed movement and sediment transport, in the hydraulic design approach channel roughness elements are more typically designed to minimise bed movement. This is to help ensure that the hydraulic performance standards of the structure are maintained over time and are not compromised by bed changes. Bed stability is influenced by culvert size, flows, and bed particle size. Ensuring that the culvert bed span is equal to or greater than the stream width will help maintain bed stability by preventing velocity increases due to constriction of the flow. Furthermore, the requirement to counter-sinking the culvert invert will assist with substrate retention and stability (Kapitize 2010, Barnard et al. 2013). Maintaining subcritical flow within the culvert is also preferable (Barnard et al. 2013).

Unfortunately, there are no definitive methods for determining bed stability in artificially roughened channels, but using a critical shear stress approach can indicate the size of substrate that is appropriate for the design flow. Guidance for utilising this in a design approach is given in Kilgore et al. (2010). The maximum shear stress on the bed under fish passage high flow conditions, Q_H, should not exceed the critical shear stress for the particles making up the substrate. For a substrate of mixed particle size, the threshold bed shear stress method may be appropriate (Gordon et al. 2004).

In general, bed material should be placed within the culvert so that a low-flow channel is provided through the culvert at Q_L. Channel side slopes above the low-flow channel should then be sloped up to the culvert walls. Hydraulic calculations for the culvert should include a check of water depth to ensure that flow depths at Q_L stay above a minimum depth threshold and that mean cross-sectional water velocities meet the performance standards.

Open channel design for culverts

Hydraulic design of culverts for fish passage should follow an open channel design approach rather than a typical culvert hydraulic design approach. As discussed in the previous sections, the culvert should be:

- laid on a slope that promotes retention of substrate
- should not be designed to flow full under design flow conditions
- should not involve a constriction of flow at the entrance of the culvert over the fish passage design flow range, and
- should be partially filled with substrate that should be retained under design flow conditions.

These constraints preclude the use of traditional culvert design approaches. Instead, an open channel design approach should be used to determine the relationship between design flow, velocity, slope and bed roughness.

Standard approaches to open channel design assume normal flow over a relatively smooth substrate. Manning's roughness or the Darcy-Weisbach friction factor can be used in the hydraulic design of culverts for fish passage, however the size of the roughened substrate is of the same order as the depth of flow, which is atypical for open channel design. Consequently, Manning's roughness or Darcy-Weisbach friction factors can be much larger than is typical in open channel design. The general relationship between velocity, depth, slope and these friction factors is given in Equation (4, which gives the Manning's equation and the equivalent open channel formulation of the Darcy-Weisbach equation.

$$V = \frac{1}{n} R^{2/3} g S^{1/2} = \left(\frac{8gRS}{f} \right)^{1/2} \qquad (4)$$

Where: n is the Manning roughness factor
R is the hydraulic radius
g is the gravitational acceleration constant
S is the friction slope of the channel
f is the Darcy-Weisbach friction factor

While the Darcy-Weisbach friction factor accounts for reduced effect of roughness with increasing depth, Manning's n does not. Two researchers have looked at the relationship between sediment size and friction factors (Limerinos 1970, Mussetter 1989).

Limerinos' equation is:

$$n = \left(0.0926R^{1/6}\right)\left(1.16 + 2log\left(\frac{R}{D_{84}}\right)\right) \tag{5}$$

Where: D_{84} is the length of the intermediate axis of the 84th percentile particle

Data for Equation (5**Error! Reference source not found.** come from experiments over the range $0.9 < R/D_{84} < 69$ and $0.02 < n < 0.107$. The error range for $n/R^{1/6}$ is +42.9 percent to -33.7 percent.

Mussetter's equation is:

$$\left(\frac{8}{f}\right)^{1/2} = 1.11\left(\frac{d_m}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S_f^{\ -0.39} \tag{6}$$

Where: d_m is the mean depth of flow

D_{50} is the length of the intermediate axis of the 50% percentile particle.

Data for Equation (6 come from experiments over the range $0.0054 < S < 0.168$, $0.25 < R/D_{84} < 3.72$, $0.001 < f < 7.06$ ($0.036 < n < 4.2$). Errors are smaller than for Limerinos' equation, with an error range +3.8 percent to +12 percent.

Barnard et al. (2013) states that Limerinos' equation produces more accurate predictions of roughness in higher-velocities, and predicts smaller roughness values in low flow conditions than Mussetter's equation. Ultimately the species and conditions for which the passage is designed should determine the exact design methods and equations used.

Ancillary structures

Ancillary structures, such as headwalls and aprons, have been widely used to improve the structural stability of stream culverts. However, such features frequently impede the movement of fish. Apron design is particularly critical from a fish passage perspective, with high water velocities, shallow water depths, and vertical drops at the downstream end frequently causing problems for fish movements. It is essential, therefore, that the design of ancillary structures is also guided by the principles of good fish passage design.

Both the stream simulation and hydraulic design approaches outlined above will significantly decrease the requirement for ancillary structures, particularly aprons. The geomorphic design approach and greater culvert sizes improve the morphological stability of structures over time by largely eliminating the disruptions in stream alignment, slope, physical habitat and flows that often necessitate the use of ancillary structures to manage erosion at traditionally designed culverts.

Where local site constraints necessitate the inclusion of ancillary structures in the overall structure design, there are several basic features that can be incorporated to improve their suitability for maintaining fish passage. Aprons are the main structural element that impact fish movements. The best way to minimise the impact of aprons is to ensure that they are fully submerged, for example through ensuring the downstream water level is maintained above the apron height (Figure 4-9). This eliminates the main problems created by aprons; shallow water, high water velocity, and vertical drop-offs. Where creating a backwater effect is not feasible, the key structural features to be incorporated in the design are a V-shaped cross-section to create a low-flow channel, the addition of roughness elements to reduce water velocity, and the avoidance of vertical drop-offs at the downstream end (Figure 4-9 and Figure 4-10).

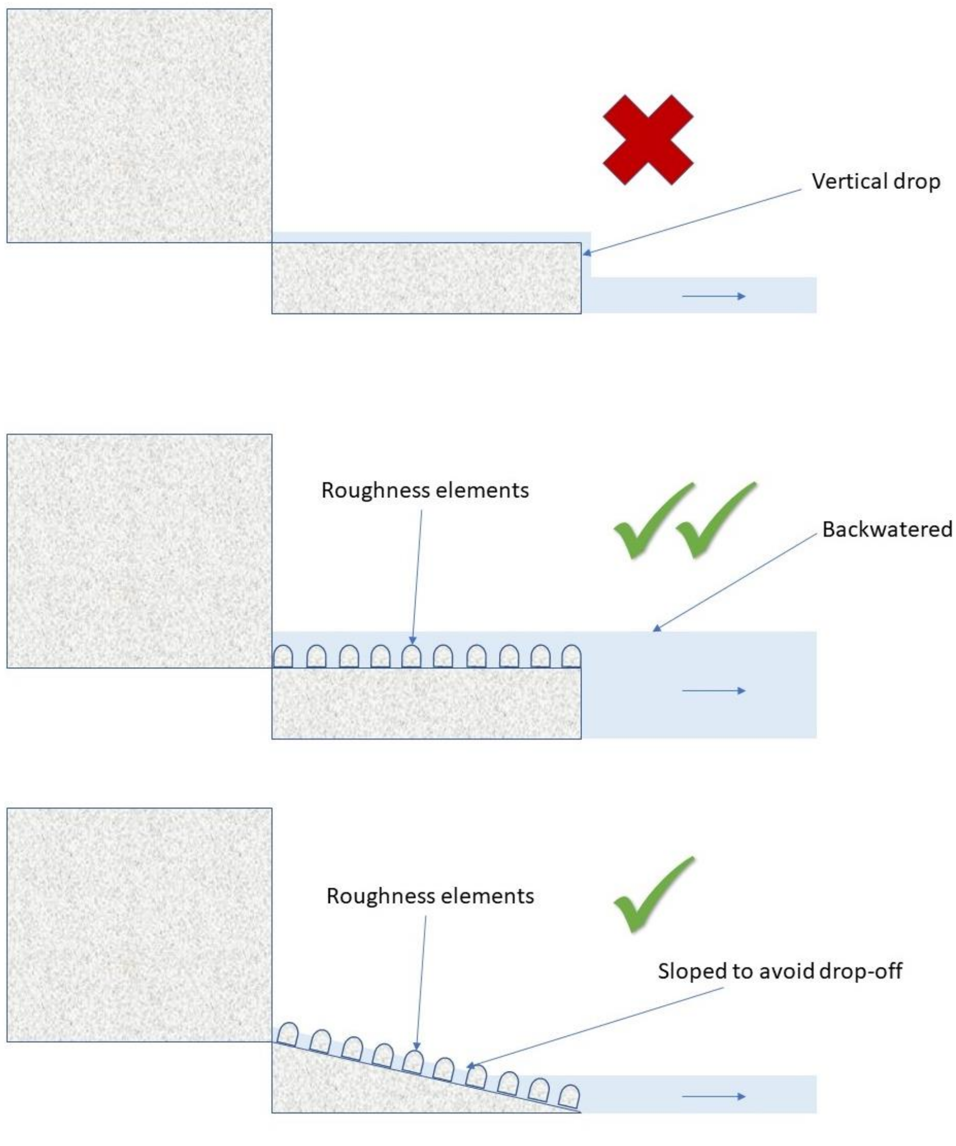

Figure 4-9: Critical design features for culvert aprons – side profile. 1. Avoid vertical drop-offs and shallow water; 2. Backwatering the apron is the preferred option; 3. A sloped apron (≤15°) with added roughness can be effective.

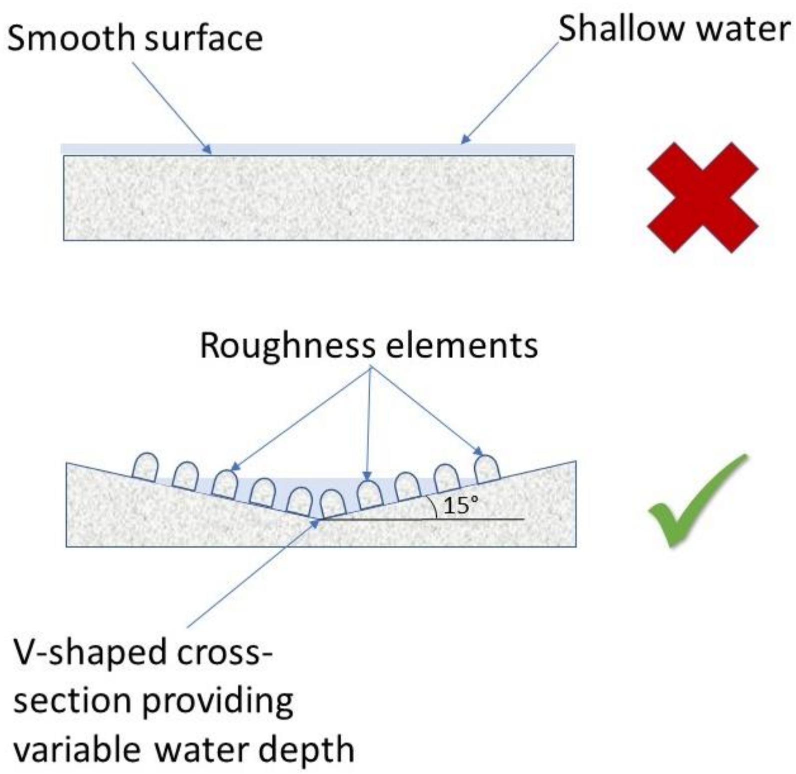

Figure 4-10: Critical design features for culvert aprons – cross-section profile. 1. Avoid flat, shallow apron designs; 2. Incorporate V-shape cross-section (approximately 15° angle) to provide variable depth and include roughness elements.

Optimum roughness element configurations have not been explored, but mixed grade irregularly shaped rocks (150-200 mm) have been used effectively as roughness elements on fish ramps and would be suitable for aprons. Rocks should be placed haphazardly (as opposed to in uniform lines) and be set with their longest axis perpendicular to the surface and embedded by 50%, with the widest part of the stone facing into the flow (Figure 4-11 and Figure 4-12). Spacing between rocks of 70-90 mm on low gradient aprons (<5°) should be suitable for most juvenile fish.

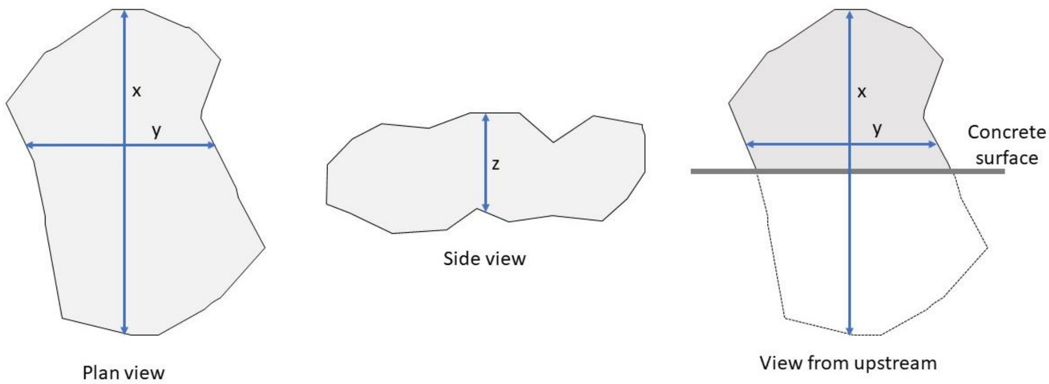

Figure 4-11: Rocks should be embedded into the concrete with the longitudinal axis perpendicular to the concrete surface with the widest part of the stone facing in to the flow.

Figure 4-12: An example of rock size and spacing suitable for increasing roughness on a weir.

Final design & construction

At this stage, the structural design is completed, and construction drawings and specifications are prepared and finalised for contracting. Subsequently, construction of the stream crossing occurs. Specialists involved in the design should continue to be informed of the construction process and be involved as necessary to help negotiate any challenges as they arise on site. It is important to ensure that the project is built to specification and that any departures from that specification are agreed with the design team. All relevant consents required for dewatering and construction should be in place, along with appropriate plans for sediment and pollution control during the construction phase. These rules will generally be determined in regional plans under the requirements of the RMA.

Maintenance and monitoring

It is important that regular maintenance of the structure is carried out to ensure that it remains fit for purpose. Monitoring would allow assessment of whether the fish passage and any other stream simulation objectives are being met. Guidance on monitoring methodologies is provided in Section 6. It is not expected that all sites be monitored, but evaluating the effectiveness of a cross-section of new structures built using this design will be informative in developing future design guidance.

4.3 Weirs

Minimum design standards for weirs

- Where practicable use a full width rock-ramp fishway as an alternative to a conventional weir for raising headwater levels in a river.
- The slope of a rock-ramp weir should be gentle. A slope of 1:30 is suitable where weakly swimming species such as inanga and smelt require passage.
- Rock-ramp weirs should create a hydraulically diverse flow environment including low velocity margins and resting areas.
- All weirs should have a V-shaped lateral profile, sloping up at the banks and providing a low-flow channel in the centre. 5-10° is a suitable slope for the lateral cross-section.
- The slope of conventional weir designs should be minimised and as a general rule of thumb be less than 1:10 for fall heights ≤1 m and less than 1:15 for fall heights 1-4 m.
- The use of smooth concrete for the downstream weir face should be avoided. Roughness elements should be added to the weir face. A suitable solution would be to cover the weir face with embedded mixed grade rocks 150-200 mm. Rocks should be closely and irregularly spaced to create a hydraulically diverse flow structure across the weir.
- A continuous low velocity wetted margin should be provided up the weir throughout the fish passage design flow range.
- Broad-crested weirs are recommended and the downstream edge of the crest should be rounded.
- Backwatering of upstream habitats because of the weir should be minimised.

4.3.1 Background

Weirs are fundamentally different to culverts in that there is no "stream simulation" approach that can be applied to their design. They are inherently an interruption to the slope of the stream bed. Weirs may combine several obstacles to upstream and downstream passage of fish including: fall heights that prevent swimming species from migrating upstream, crest shapes that may be insurmountable to climbing species, shallow water depths either upstream or downstream of the weir, increased water velocities, and inappropriate attraction flows. Furthermore, the backwater effect upstream of weirs inundates and alters instream physical habitat, typically resulting in a shift towards slower flowing and deeper habitats. Consequently, where possible, the installation of new weirs should be avoided.

Weirs may be built for a range of purposes, including flow gauging, flood control, and maintenance of a prescribed upstream water level (e.g., for abstraction). Flow gauging weirs have relatively strict technical requirements for maintaining the accuracy of hydrological measurements, imposing limitations on the shape of the weir and any possible fish passage provisions that can be included. However, recognition of the environmental impact of gauging weirs, in combination with technological improvements in other gauging techniques means that this type of weir is increasingly redundant. Consequently, installation of new flow gauging weirs should largely be unnecessary. Where maintenance of a minimum upstream water level is the intended purpose of the weir (i.e., a head control structure), a wider variety of options for providing fish passage can be considered. Some of the key features of fish friendly weir design are discussed below.

Relatively little work has been undertaken in New Zealand to specifically evaluate weir design requirements for passage of native fish species. Consequently, recommendations in these guidelines are based on international good practice in combination with local experience and expert interpretation of experimental work that has been carried out on fish ramp designs in New Zealand.

4.3.2 Design principles

Conventional weir designs that incorporate smooth concrete bottoms and steep hydraulic drops are unsuitable for providing fish passage and should be avoided where practicable. Good practice where the objective of a weir is simply to maintain a minimum headwater level is to use a full width rock-ramp fishway as an alternative to a traditional weir structure. A rock ramp can be used to disperse the hydraulic head over a greater distance than a vertical or very steeply inclined concrete weir by keeping the hydraulic gradient gentle (e.g., 1:15 to 1:30). Such low-gradient rock ramps exhibit a high level of structural diversity, imitating natural stream conditions, and providing a multitude of opportunities for passage of different organisms.

Where more nature-like solutions are not practicable there are several design principles that should be considered:

- Vertical and steep hydraulic drops should be avoided.
- Undershot weirs should be avoided.
- Broad-crested weir designs should be used.
- Weir crests should be rounded.
- The weir should have a V-shaped lateral profile providing shallow, low velocity wetted margins on the weir face across the fish passage design flow range.
- The slope of the downstream weir face should be minimised.
- The use of smooth concrete on the weir face should be avoided or minimised.
- Vertical wing walls should be avoided.
- Back watering of upstream habitats should be minimised.

4.3.3 Design process

Initial assessment and design flows

The standard catchment-scale review and site reconnaissance process should be undertaken to evaluate channel stability and the operating range for the structure. The initial assessment of the site and purpose of the structure should consider whether a weir is the most suitable option, or whether the desired outcome can be achieved by some other means with a lower impact on river connectivity. For example, can the desired purpose be achieved by pumping from the stream to off-stream water storage, or deriving a flow rating curve at a morphologically stable site that does not require the construction of a weir?

Where a weir is determined to be the only practicable solution, the suitability of a full width rock ramp fishway for achieving the required headwater level should be evaluated. Only where this is not practicable should a more conventional weir design be selected.

The species and life stages of interest, and the smallest size fish of each species that require passage, should be determined for the site. Fish passage design flows should be determined for the target species.

Weir design

Weir Type

Where practicable the weir should be built as a rock-ramp fishway (e.g., Figure 4-13). Details on the design of rock-ramp fishways suitable for New Zealand fish species are provided in Section 5.3.2 and technical guidance on the design and construction of rock-ramp fishways is provided in DVWK (2002). Full river width rock-ramp fishways are the optimal design for overcoming low-head barriers (≤1 m) on many river types, and are also suitable in many locations for larger head differences (<4 m) where sufficient stream length is available to accommodate the low slope designs. Where a more conventional weir is required, broad-crested weir designs with a sloped downstream face should be chosen. Guidance on key design features of these weirs are provided in the following sections. Incorporation of partial width rock-ramp fishways with conventional weir designs should also be considered.

Figure 4-13: A rock-ramp style weir on the Waipa River at Otorohanga that also has a fish pass along the true left bank. The fish pass provides passage at low flows when the large rocks forming the downstream face of the weir are exposed and swimming species cannot surmount the weir. Credit: Eleanor Gee.

Undershot weirs (sluice gates) should be avoided as they have been shown to subject fish to considerably higher pressures, shear stresses, and risk of physical strike, and have been found to be significantly more problematic for fish to negotiate than overshot weirs (Baumgartner et al. 2006). Australian studies have shown that downstream-drifting larvae of Murray cod and golden perch have a significantly higher mortality associated with passage through an undershot low-head weir than an overshot low-head weir (Baumgartner et al. 2006). Downstream movement of the larval stage is common among New Zealand's native fish and it is reasonable to assume that similar outcomes would occur at undershot weirs here. Furthermore, several of our upstream migrating native species can climb wetted surfaces (McDowall 2000). Undershot weirs will prevent the use of this movement strategy, but passage at overshot weirs may be achievable where the right conditions are provided. Where possible, therefore, overshot weir designs should be chosen (Harris et al. 2017).

Lateral profile

Both rock-ramp and conventional weir designs should have a V-shaped lateral profile that rises towards the river banks producing zones of calmer flow in the marginal areas and a low-flow channel towards the centre of the weir (Figure 4-14). The angle of the V-shape should generally be in the range of 5-10° for a full width weir (Figure 4-14).

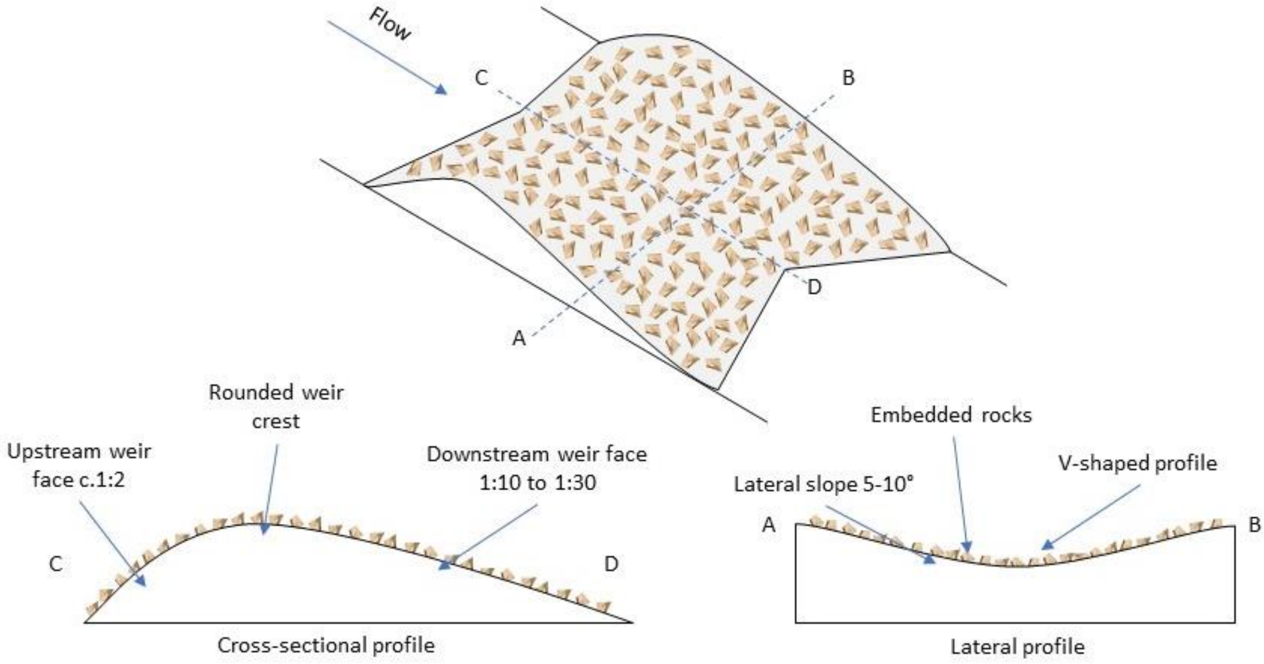

Figure 4-14: Key features of a conventional weir design for fish passage.

Downstream weir face

The gradient of the downstream weir face should be gentle. The slope of rock-ramp fishways should be between 1:15 and 1:30, with the 1:30 design recommended for weakly swimming native fish species such as inanga. The slope of conventional weir designs should also be minimised and as a general rule of thumb be less than 1:10 for fall heights of ≤1 m or less than 1:15 for fall heights of 1-4 m (Figure 4-14). Where the head difference is low (<1 m) and only climbing species are present, steeper slopes of up to 1:2 may be suitable.

The design velocity on the downstream face of the weir should provide for fish passage of target species and life stages at the fish passage design flows (Q_L to Q_H). When deciding the upper flow beyond which passage will be impeded, the guiding principal should be that if the reach would have been passable by fish in the absence of the weir, then passage should not be impeded by the weir's presence. Guidance on the interpretation of fish swimming speed equations for determining design water velocities and weir face length is given in Section 4.2.2.

In the absence of a published relationship for the species of interest, a rule-of-thumb of providing a continuous pathway with water velocities ≤0.3 m s^{-1} has been used to guide culvert design, and can also be applied to velocities on the downstream face of the weir to allow passage of most native species (Stevenson and Baker 2009). It is worth noting that velocities above 1.0 m s^{-1} are unlikely to allow fish passage. As relationships for swimming speed and time to fatigue become more readily available in the future, however, these relationships should replace such rules-of-thumb.

Once the maximum passable water velocity has been determined, hydraulic design equations should be used to determine the slope at which this velocity occurs over the fish passage design flow range taking in to consideration weir geometry (i.e., width, shape of the downstream face, substrate on the downstream face). For a given head drop, the slope will then determine the length of the weir.

In the case that an acceptable velocity can only be achieved with a length that is insurmountable by fish, then two possibilities exist for providing fish passage. Where the site allows, it may be possible to build two shorter weirs, thus halving the head drop and providing a resting pool for fish to recuperate in between the two weirs. Alternately a fish pass, e.g., a partial width rock-ramp fishway, should be installed as part of the weir structure.

Once design velocities have been determined, the associated water depths should be calculated to ascertain whether the depth will provide an impediment to passage of the species of interest. The water depth on the downstream face of the weir over the fish passage design flow range should allow swimming of obligate swimming species (i.e., must be greater than the maximum body depth of the fish).

The use of smooth concrete for the downstream weir face should be avoided where practicable. Roughness should be added to the weir face to create a boundary layer suitable for the movement of fish and to help reduce average water velocities (Figure 4-14). A suitable solution would be to cover the weir face with embedded mixed grade rocks of 150 to 200 mm. Rocks should be closely (70-90 mm) and irregularly spaced to create a hydraulically diverse flow structure across the weir (e.g., Figure 4-11 and Figure 4-12). Rocks should be orientated with the long axis perpendicular to the weir face and embedded by at least 50%. The widest axis of the rocks should be orientated in to the flow. The inclusion of this feature is of high importance for provision of fish passage.

When designing the downstream weir face, several features must be avoided. Vertical weir faces are and overhanging/under-cut downstream faces should be avoided, as this also prevents passage of climbing species. There should be no steps or lips on face of the weir, as this can create nappe flow with higher levels of turbulence and water level discontinuities, making it harder for fish to negotiate (Baudoin et al. 2015). If a vertical face is necessary for the purpose of the weir and the species of interest includes life stages or species that cannot climb, then a fish pass should be constructed as an integral part of the weir. Partial width rock-ramp fishways often provide a suitable solution. Bypass structures provide an alternative option in this case. These structures are discussed in Sections 5.3.2 and 5.3.4 respectively.

Crest design

Broad-crested weir designs are recommended and sharp crested designs should be avoided. Broad-crested designs reduce the likelihood of nappe flow occurring, which can impede the passage of fish.

The downstream edge of the crest should be rounded rather than sharp, to allow climbing fish to negotiate the top edge and continue upstream (see Appendix E). If the weir crest requires a notch then it should be v-shaped, as this has been found to assist passage of common bullies when compared with semi-circular or rectangular notches (Baker 2003).

Upstream weir face

Recent overseas research on eels has indicated that the slope of the upstream weir face may have an important influence on the behaviour and movement of fish migrating downstream (Silva et al. 2016). The findings of that study suggest that a 30° incline helps to reduce the maximum water velocity upstream of, and passing over, the weir crest, creating improved conditions for downstream passage (see Appendix E). Rounded (Ogee style) weir crests are also recommended to provide a gradual acceleration of water towards the crest (O'Connor et al. 2016).

Attraction flows

Attraction flows are most important where the weir has an integrated fishway or bypass. Attraction flows should be available over the entire range of flows, to enable fish to find the path that will allow them to pass over the weir. False attraction flows that do not lead fish to the best upstream pathway can provide a major impediment to passage (Harris et al. 2017). Attraction flows should meet the following requirements (O'Connor et al. 2016):

- No eddies or recirculation.
- The attraction flow is at the upstream limit of migration or focused on a known area where the target fish species have been found to congregate near the upstream limit of migration imposed by the barrier.
- Other flows do not mask the flow attracting fish to the path which will allow them to pass upstream of the weir.

For more detailed guidance on attraction flows at weirs see O'Connor et al. (2016).

Ancillary structures

Vertical wing walls at the edge of the weir should be avoided. Sloping wing walls should be used to ensure that under higher flows a low velocity, shallow wetted margin remains available at the edges of the weir that can assist in providing fish passage.

4.4 Fords

4.4.1 Background

Fords can be a very problematic stream crossing for fish passage, as they often combine many of the negative features of culverts and weirs, involve modification of the stream bed, and allow vehicle access to the stream. Consequently, wherever possible, the construction of new fords should be avoided and alternative river crossings used.

Fords that do not have a raised roadway typically still involve modifications to the river bed that reduce substrate and hydraulic complexity, and increase water velocities over the ford (e.g., Figure 4-15). Increasingly, fords have been raised above the natural stream bed to help mitigate disturbance of the stream bed during vehicle crossings. These crossings are also sometimes termed causeways. Simple raised roadway fords (e.g., Figure 4-16) often impede fish passage by some combination of a steep downstream face, a sharp crest, shallow water, and high water velocities over the ford. They also impact on geomorphic processes, disrupting sediment transport. These impacts can be reduced by incorporating culverts into the ford to pass the stream under the roadway under low to moderate flow conditions (e.g., Figure 4-17). In this case the water velocity or depth in the culvert, or the length of the culvert, may still impede fish passage if poorly designed.

Figure 4-15: Low profile ford crossing.

Figure 4-16: Raised roadway ford crossing. The vertical drop on the downstream side will block fish movements. Shallow water depth and elevated water velocities across the ford pavement can also impede movements.

Figure 4-17: Raised roadway ford crossing with culverts. At low flows water passes through the culverts in the ford, rather than over the roadway. The small culverts used in this ford severely constrict the river channel and will result in accelerated water velocities through the culvert barrel that may be impassable to fish.

4.4.2 Design principles

Best practice is to avoid the use of fords for stream crossings as they are the least preferred crossing type from a fish passage perspective and do not prevent vehicles or animals from entering the waterway (Figure 4-1). Where a ford is deemed necessary, the principles of good fish passage design (Section 3.4) should be applied. Low profile and standard raised roadway ford designs should be avoided. Causeway ford designs incorporating culverts are the minimum standard for fords. The objective is to ensure that a continuous pathway for fish passage is maintained across the structure over the fish passage design flow range.

4.4.3 Design process

Initial assessment

A priority for the initial site assessment is to ensure that an alternative stream crossing type cannot be used. Where a ford is deemed necessary, the standard catchment-scale review and site reconnaissance process should be undertaken to evaluate channel stability and the operating range for the structure.

Design flows

The migration periods of the target fish species identified in the initial assessment should be used to inform the fish passage design flow range. This sets the range of flows over which the hydraulic performance standards for the structure must be met. The fish passage low flow (Q_L) is the lowest flow at which fish passage must be provided and as a rule of thumb can be set at the 95% exceedance flow. The fish passage high flow (Q_H) is the highest flow at which the hydraulic performance standards for fish passage should be met. A rule of thumb is to use the 20% exceedance flow for Q_H.

The design peak flood flow (Q_P) is a reasonable estimation of the highest flow that the ford should be designed to pass without causing a significant increase in upstream flooding. The appropriate standard for Q_P should be determined with reference to relevant regional plan rules, local drainage standards and technical design guidance for roadways and infrastructure. For fords there will also likely be thresholds set for the return interval flow event (Q_i) that will inundate the road.

Ford design

Ford design should follow the guidance for hydraulic culvert design. The following key features must be incorporated in the design:

- Reduction of the channel cross-sectional area at the ford over the fish passage design flow range should be avoided or minimised.
- Where stream size dictates (i.e., bankfull width is too great for a single span culvert), multiple box culverts may be required to span the full wetted width of the stream without significantly constricting cross-sectional area.
- Circular culverts should be avoided where multiple barrels are required.
- Substrate must be maintained through the full length of the culverts and remain stable across the fish passage design flow range.
- Alteration of natural stream channel alignment should be avoided or minimised.
- Alteration of natural stream channel gradient should be avoided or minimised.
- Determine the design water velocities over the fish passage design flows (Q_L to Q_H) to facilitate passage of the target fish species and sizes. Determine the water velocity requirements for the smallest sized fish of each species to require passage, and then choose the lowest of these velocities for design. Alternatively use the adjacent stream as a reference for defining water velocity requirements.
- Check the water depths associated with the design velocities, and ensure that they are deep enough to allow passage of the target fish species and life stages. Where possible provide heterogeneity of water depth through all elements of the structure.
- Check that the slope of each part of the culvert, and the transition between slopes, does not provide an impediment to passage.
- Ensure that the surface of the ford is roughened (e.g., through embedding rocks) to facilitate passage of fish over the ford when flows overtop the structure.
- The lateral profile of the ford should be V-shaped to ensure that wetted margins are maintained across the ford when it is overtopped during elevated flows.

Final design & construction

At this stage, the structural design is completed, and construction drawings and specifications are prepared and finalised for contracting. Subsequently, construction of the stream crossing occurs. Specialists involved in the design should continue to be informed of the construction process and be involved as necessary to help negotiate any challenges as they arise on site.

It is important to ensure that the project is built to specification and that any departures from that specification are agreed with the design team. All relevant consents required for dewatering and construction should be in place, along with appropriate plans for sediment and pollution control during the construction phase. These rules will generally be determined in regional plans under the requirements of the RMA.

Maintenance and monitoring

It is important that regular maintenance of the structure is carried out to ensure that it remains fit for purpose. Monitoring would allow assessment of whether the fish passage and any other objectives are being met. Guidance on monitoring methodologies is provided in Section 6. It is not expected that all sites be monitored, but evaluating the effectiveness of a cross-section of new structures built using this design will be informative in developing future design guidance.

4.5 Tide and flood gates

Tide and flood gates are used to control tidal or floodwater fluctuations, respectively. All tide and flood gates are considered barriers to fish passage. Furthermore, they degrade upstream habitats by interrupting hydrological exchange and altering water temperature and salinity dynamics (Franklin and Hodges 2015).

Tide and flood gates may take a variety of forms, but most commonly in New Zealand take the form of passive gate designs. Gates are hinged either at the top or side and a positive head differential on the downstream side (i.e., higher water level) will close the gate. A positive head difference on the upstream side will cause the gate to open and release water downstream (Figure 4-18). When the gate is closed, no fish can pass (Doehring et al. 2011a) and, even when it is open, passage can be impeded by high water velocities or limited opening. It is extremely challenging to provide effective fish passage at tide and flood gates, thus installation of new gates is strongly discouraged. Where no suitable alternative is feasible, there are several design features that can be used to lower the potential impacts on fish movement.

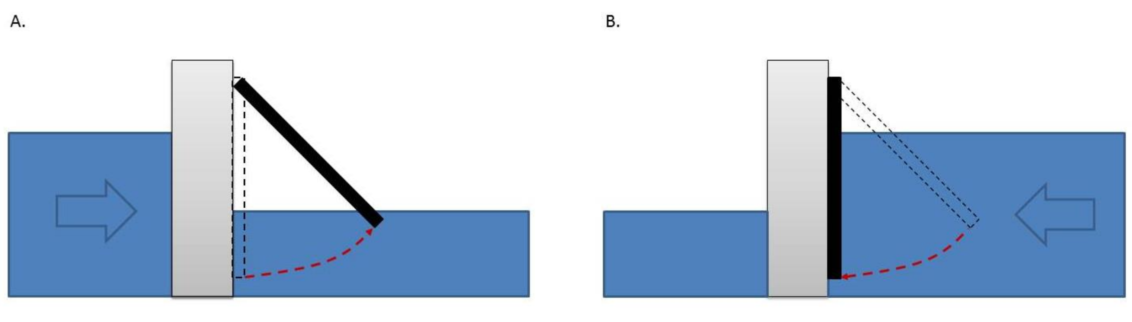

Figure 4-18: Illustration of how passive tide gates work. A. When water levels on the upstream side are higher than downstream, the gate opens. B. When water levels on the downstream side are higher than the upstream side, the gate closes.

In many cases, inundation control is only required under specific circumstances (e.g., during floods for flood gates, or during spring tides at tide gates). Despite this, most passive gate designs remain operational outside these circumstances and close regularly even when not required for flood control purposes. In this situation, active gate designs using automatic electric or hydraulically powered gates that operate the gate only when water levels reach a critical elevation can be effective and significantly reduce the impact on fish movements and upstream physical habitat. Use of active gate designs is best practice.

Where operational constraints prevent the use of automated gate systems, fish passage at tide gates can be improved by using lightweight gate materials, side-hinged gates or self-regulating gates. Orifices within the gates have also been used, although evidence for their effectiveness remains somewhat inconclusive (Wright et al. 2016). Historically, tide and flood gates were most often constructed of cast iron or wood. Newer aluminium and plastic gates are preferred to the old designs because the lighter gates open more easily allowing for better fish passage and drainage. Side-hinged gates are preferable to top-hung gates because they require a smaller hydraulic head to open them, they open wider and for longer, providing more opportunity for fish to pass through the gate.

Self-regulating tide gates, sometimes referred to as 'fish friendly' tide gates, rely on a counter weight or float system to control the opening and closing of the gate based on the water surface elevation outside of the gate (Figure 4-19). In effect, they hold the gate open for a longer period compared to a standard passive gate design. The effectiveness of self-regulating tide gates from a fish passage perspective is highly dependent on their operating range (Bocker 2015), but their use would be considered the minimum standard for all new and replacement tide gates. To optimise fish passage, the objective should be to maximise the duration and aperture that the gate is open, particularly on the incoming tide which some juvenile fish species (e.g., eels and whitebait) use to move upstream (Creutzberg 1961; McCleave & Kleckner 1982; Bocker 2015). This will also facilitate greater hydrological exchange and help to reduce the habitat impacts upstream of the gate.

Figure 4-19: Example of a self-regulating tide gate installed in Canterbury. The counter weight system holds the tide gate open for longer on the incoming tide. The system can be calibrated to manage the magnitude and duration of the opening to best coincide with critical migration periods, e.g., the incoming tide for whitebait and elvers.

4.6 Stormwater management ponds

Stormwater management ponds/wetlands are designed to reduce downstream flooding and erosion in urban and other highly modified catchments. Watercourses are protected from the effects of pollutants and contaminants washed from impervious surfaces during rain events, and the sedimentation of watercourses is controlled by allowing suspended solids to settle out in the ponds or wetlands, improving the quality of the water entering the natural stream network.

There are two types of stormwater management ponds used in urban regions: dry detention ponds and wet ponds (or wetlands). Dry detention ponds are generally dry but intercept and detain stormwater during and immediately after a storm event, gradually releasing this water over time. Dry detention ponds function both in terms of improving water quality and the reduction of flooding and erosion downstream of the pond. Dry detention ponds do not provide suitable permanent habitat for fish, given their ephemeral nature, and fish passage does not need to be considered in these situations.

Wet ponds are the main type of pond used and consist of a permanent pond or a constructed wetland where, except for extreme floods, stormwater flows through at a slow rate. Wet ponds can either be 'on-line' in which the outflow enters the natural stream network or 'off-line' where the outflow enters the stormwater drainage system.

When creating new stormwater management systems, the recommended best practice is to:

- utilise dry detention ponds, or
- develop an 'off-line' wet pond system.

Only in situations where an 'off-line' system is unfeasible should an 'on-line' wet pond be constructed. For 'on-line' systems, good practice is to design a constructed wetland with water levels controlled by a weir at the outlet. The weir should follow the minimum design standards outlined in Section 4.3. Vertical risers are not recommended for water level control as they are prohibitive to both swimming and climbing fish passage.

5 Design requirements for remediation of existing instream structures for fish passage

There are many existing instream structures in New Zealand's waterways that impede fish migrations. Overcoming this legacy offers the potential for rapid and significant gains for native aquatic biodiversity. The following section provides a guide to current good-practice options for remediating fish passage at instream structures. It focuses on highlighting the key design principles necessary for developing site and structure specific remediation solutions.

5.1 Assessing & prioritising structures for remediation

The first step in developing appropriate remediation strategies for existing structures is to evaluate to what extent and why they are not fulfilling the relevant ecological objectives and performance standards (see Section 3.3 for more detail on setting objectives and performance standards). This may be achieved through visual assessments, routine and/or targeted monitoring (see Section 6 for more information on monitoring). Once the extent and cause of the failure is identified (e.g., fish passage success is too low because of high water velocities in the structure), appropriate remediation options can be identified and implemented.

The majority of existing structures may have no documented objectives or performance standards against which to evaluate their effectiveness. The approach typically taken for dealing with this legacy of existing structures is to undertake a census of structures in a given area or catchment, evaluate the likelihood that they present a barrier to fish migrations, and prioritise structures or catchment areas for remediation. Subsequently, appropriate ecological and performance objectives must be set, and remediation options identified and implemented for each structure.

Experience indicates that in the region of 20-40% of existing structures currently impede fish passage due to poor installation or inadequate maintenance. This amounts to many thousands of structures across New Zealand that may require remediation to meet legislative requirements. It is, therefore, generally necessary to prioritise structures or catchment areas for remediation action. There are a range of factors that might influence how structures are prioritised including both ecological criteria and economic or practical considerations. Some potential ecological factors that may influence prioritisation of structures for remediation are described in Table 5.1. This list is not intended to be exhaustive, but provides an indication of the kind of criteria that are valuable to consider from an ecological perspective. They should be used in combination with other relevant factors such as community support for the project, other restoration efforts conducted in the catchment, practicalities (e.g., is the site accessible for the plant required to undertake the work), and the cost of undertaking the remediation.

Once a potential fish migration barrier has been identified and prioritised for remediation, the next stage is to set objectives and performance standards for the structure, confirm consenting and permitting requirements (see Appendix A), and subsequently identify appropriate remediation options for achieving those objectives.

Table 5.1: Examples of some possible ecological prioritisation criteria for fixing instream barriers. Multiple factors may influence the priority of works to restore connectivity. This includes not only ecological criteria, but also economic, social and logistical criteria. Adapted from Franklin et al. (2014).

Criteria	Explanation
Proximity to coast	Barriers that are closer to the coast not only block access to a greater proportion of upstream habitat, but they also generally block a larger number of fish species.
Potential habitat gain	The greater the total length of accessible river upstream of the barrier, the greater the potential habitat gain.
Habitat quality	Restoring access to higher quality instream habitat should be prioritised over providing access to degraded sites.
Proximity to protected areas	Connection with protected area networks may provide added benefits (e.g., constraints on fishing).
Number of species likely to benefit	Some sites are expected to naturally support a greater number of species than others, e.g., sites at low elevation close to the coast. Sites that are expected to support many species may be of higher priority than those expected to support few species.
Conservation status of species	Sites expected to support species with a higher conservation status may be of higher priority for restoration of connectivity.
Preventing spread of exotic and invasive species	Maintaining boundaries on the spread of exotic and invasive species may be a desirable outcome of retaining barriers and should also be considered in prioritising restoration actions.
Protects threatened species	Barriers may protect populations of threatened fish species by preventing access to competing species, e.g., trout. Existence and protection of threatened fish populations should also be considered.

5.2 Setting fish passage objectives for existing structures

Establishing clear objectives and performance standards for existing structures provides greater clarity and focus for the fish passage remediation process. This helps define the design criteria for fish passage remediation at the structure and sets the benchmarks against which the effectiveness of the remediation will be measured.

The objective of retrofitting any culvert or ford should be to achieve unimpeded passage. If this is not feasible (e.g., due to the physical constraints of the existing structure), in the absence of an existing permit, it is necessary to apply to DOC and councils for a permit for exemption or resource consent with a clear justification for any departure from unimpeded access and setting out clearly defined and justified ecological objectives and biological/hydraulic performance standards for the structure (See section 3.3 for more information on setting objectives).

Other instream structures that dam or divert a natural waterway (e.g., weirs, tide gates, pumping stations) are subject to the requirements of Regulations 43-50 of the Freshwater Fisheries Regulations, in addition to relevant regional plan rules. It is an offence under the Freshwater Fisheries Regulations to propose to build such structures without dispensation from DOC nor an approved fish facility. For any such structure that was built post-1983 and has neither dispensation nor an approved fish facility:

- If you were the builder/authoriser, the Department of Conservation can issue you with a dispensation approving the lack of fish facility, or a requirement to build an approved fish facility.
- If you are not the builder/authoriser (i.e., you are a subsequent landowner) you can get a letter of assurance, or a letter stating that the Department of Conservation would like you to build a fish facility.

Performance standards may be specified as part of the requirements for an approved fish facility and will be important in determining the effectiveness of any fish facility. However, such requirements are less prescriptive than those for culverts and fords and thus should be determined with relevance to local setting and ecological objectives. The guidance below, and throughout this document, is suitable for informing the design of fish facilities.

5.3 Good practice remediation design

Structure removal should always be considered as the first option and is the preferred solution for maximising fish passage at existing structures. Alternatively, replacement with a structure that has been designed to meet minimum design standards (see Section 4) will likely offer the most sustainable and effective solution. However, for practical reasons many structures cannot be removed, so the addition of new features to existing structures is a more common strategy for enhancing fish passage. The remediation options available at a site will be dependent on a multitude of factors including the characteristics of the existing structure (Table 5-2), cost, accessibility, the reason(s) for reduced fish passage, and the ecological objectives for the site. Consequently, it is necessary to evaluate the structure characteristics and nature of the fish passage problem at each individual site and develop site-specific solutions.

Table 5-2: Common causes of fish passage problems and some possible mitigation solutions.

Common problems	Possible fixes
Excessive fall height	▪ Removal ▪ Replacement ▪ Backwatering ▪ Addition of ramp fishway
High water velocities	▪ Removal ▪ Replacement ▪ Backwatering ▪ Addition of baffles ▪ Addition of mussel spat ropes
Insufficient water depth	▪ Removal ▪ Replacement ▪ Backwatering ▪ Addition of baffles
Physical blockage	▪ Removal ▪ Replacement ▪ Addition of ramp fishway ▪ Addition of bypass structure ▪ Addition of fish friendly flap gate

5.3.1 Removal or replacement

The most effective fish passage remediation option available for existing structures is removal. There are many structures in our waterways, both small and large, that are now redundant and no longer serve a purpose. Where such structures are identified, strong consideration should be given to their removal and reinstatement of the original waterway. Experience has shown that recovery of fish communities and ecosystem processes can be rapid following removal of migration barriers, including large dams (O'Connor et al. 2015b), and so should be prioritised where feasible.

Where removal is not feasible, replacement with a good-practice design may prove the most cost-effective solution, and will typically result in more reliable outcomes for passage success than mitigation of the existing structure using the methods described below.

5.3.2 Ramp fishways

Overcoming vertical drops at instream structures is a common challenge for restoring fish passage. Ramp fishways have been widely implemented, both in New Zealand and overseas, for overcoming barriers <2 m in height and have also been used for higher barriers. When well designed and maintained they can be a cost-effective means of significantly improving fish passage success. A variety of ramp fishway designs are in use:

- Rock ramp fishways generally consist of a series of pools created by rock ridges, or a continuous ramp of rocks, placed below the barrier and connected by continuous water flow.
- Artificial ramps using novel substrates such as brushes or Miradrain™ have also been used, often at smaller obstructions.

Full-width fishways, which span the full stream width, are most desirable as they provide greater functionality, but partial-width designs can also be effective.

'Nature-like' rock ramps

The objective of 'nature-like' rock ramps is to imitate natural stream conditions in order to disperse the hydraulic head (i.e., vertical drop) over a greater distance, keeping the gradient of the ramp as low as possible. 'Nature-like' rock ramps provide multiple interconnected pathways for fish passage using continuous swimming, or a burst and rest swimming pattern, and typically provide suitable passage conditions and habitat for a variety of species and life-stages over a range of flows.

Full river width rock ramp fishways are the optimal design for overcoming low-head barriers (≤1 m) on many river types and are suitable for downstream of culverts. They are also practical in many situations where the head difference is up to 4 m. The use of 'nature-like' rock ramps has become increasingly common internationally, but uptake of this design in New Zealand has been relatively slow to date. To be effective, rocks must be carefully configured and structured, rather than just being dumped in to the stream. This will ensure greater structural integrity is achieved, reducing the likelihood of future structural failure.

Rock ramp structures typically take the form of a series of transverse rock ridges, with pool sections between the ridges that act as resting areas for migrating fish. Features such as overall gradient, head loss between pools, pool size, minimum water depth and slot width between rocks are all important considerations in the design of these structures. O'Connor et al. (2015a) have provided recommended specifications for rock ramp fishways suitable for small Australian fish species, including inanga, which is widespread in New Zealand. These specifications are summarised in Table 5.3.

Table 5.3: Summary of design specifications for 'nature-like' rock ramp fishways for small-bodied fish. Adapted from O'Connor et al. (2015a).

Design aspect	Specification
Longitudinal gradient	The overall longitudinal slope of the structure should be 1:30 for small-bodied (<200 mm) fish.
Functional range	Maintaining a v-shaped cross-section or sloped lateral (bank-to-bank) channel profile will allow the fishway to operate over a greater range of flows than a fishway with a flat lateral profile.
Pool to pool head loss	A head loss of <75 mm is suitable for small-bodied fish.
Minimum slot width	The width of the gap between lateral ridge rocks should be 100-150 mm.
Pool size	The recommended pool size for a ridge-style rock fishway is 2 m long to allow dissipation of flow and maintain acceptable turbulence levels.
Minimum depth	The minimum recommended water depth is 0.3 m in at least 50% of the pool area in a continuous path ascending through the rock ramp.
Maximum slot water velocity	Maximum water velocity as calculated from the head loss in a vertical slot[3] should be <1.2 m s^{-1}.
Energy dissipation	Turbulence should be minimised, with little 'white' water in the fishway pools. Stream power should be <25 W m^{-3} (calculated as per vertical slot[4]).

With respect to construction, international guidance (DVWK 2002; O'Connor et al. 2015a) suggests that rock size is a site-specific decision. General design principles suggest:

- Large diameter rocks embedded a minimum of 50-60% of their diameter in to the fill rock are recommended for the ridge rocks.
- Ridge rocks should generally protrude 0.3 m above the water surface under normal flows and remain protruding from the water surface within the full design operational range.
- The ridge rocks should extend across the total width of the stream and into the banks, and be keyed in.
- Geo-fabric material may be used on the rock ramp foundation and upstream face of the ridge rocks to trap fine material and decrease permeability.
- It is recommended that several layers of graded rock infill are utilised within the structure.
- Larger infill boulders can be placed to support the protruding ridge rocks.

[3] Calculated as $U = \sqrt{(2g\Delta h)}$, where U = water velocity (m s^{-1}), g = acceleration due to gravity (9.8 m s^{-1}), and Δh = head loss between pools (m).
[4] Calculated as $P = (Q\Delta h\alpha)/V$, where P = Power (W m^{-3}), Q = discharge (m^3 s^{-1}), Δh = head loss between pools (m), α = the weight density of water (9777 N m^{-3} at 25°C), and V = pool volume (m^3).

- Mixed media fill should be augmented with fines to infill interstitial spaces and help ensure the minimum water depth over the ramp is maintained.
- The toe of the ramp should always be secured with rows of large rocks, buried to 1m below bed level and into the banks.

A well-designed ramp should not require grouting (e.g., with concrete) to prevent percolation of water through the structure. This avoids problems associated with subsequent settling of the fishway that can result in grouting cracking and being undermined. Examples of hydraulic design approaches for fish ramps are provided in DVWK (2002). However, it must be recognised that these guidelines were developed for European fishes and thus should be adapted for New Zealand fish species (e.g., Table 5.3).

Figure 5-1: Example of a low gradient nature-like rock ramp fishway on the Patterson River near Melbourne, Australia. Photo: Paul Franklin.

Concrete rock ramps

When space is more constrained, concrete rock ramps may be an appropriate solution for overcoming head drops. This option can be fitted downstream of both culverts and weirs and can be a full- or partial-width design. Ramps can be fitted directly at the culvert or weir base, or at the base of a receiving pool. The need for a receiving pool will vary depending upon the situation; for example, if the flow downstream of the culvert is to be re-directed from its path through the culvert (Figure 5-2). Utilising a receiving pool before the ramp will provide passage at all flows, as in high flow events some water can flow over the edge of the pool away from the ramp, providing a spillway for excess water. This also protects the ramp from damage during flood flows. Any receiving pool should be twice the width of the outlet to the ramp to provide low velocity margins to aid swimming fish passage. Pool depth will depend upon the flows experienced through the culvert, but should be at least 0.3 m. Deeper pools are desirable as they increase energy dissipation and reduce turbulence. In cases where the culvert occurs at a stream confluence and flows out into the main stem perpendicular (or at an angle) to the flow, the ramp should be positioned along the bank and parallel to the main stream channel (Figure 5-2).

Concrete rock ramps generally take one of two forms:

- formal structural designs (e.g., Figure 5-2), or
- grouted rock-ramps (e.g., Figure 5-4).

Formal structural designs typically involve constructing a concrete ramp into which rocks are embedded. Mixed grade irregularly shaped rocks (150-200 mm) should be embedded by 50%, with the longitudinal axis perpendicular to the ramp surface and the widest part of the stone facing in to the flow (Figure 4-11 and Figure 5-2), and arranged haphazardly (as opposed to in uniform lines). Spacing between rocks of 70-90 mm should be suitable for most juvenile fish. On steeper gradient ramps, spacing may have to be closer to maintain lower water velocities, although it is useful to have varying spacings to accommodate different fish species and sizes. Ramps should be angled laterally or created with a V-shaped cross-section to provide a range of water depths that taper to a shallow wetted margin (Figure 5-3). This will provide low water velocities along the margins of the ramp for swimming fish and a wetted margin for climbing species. It is essential that the width of the ramp provides a wetted margin throughout the fish passage design flow range.

Grouted rock ramps take a more natural form where concrete is used as a grouting for a rock-ramp style fishway (Figure 5-4). Geo-fabric material can be used on the foundation of the ramp, with mixed grade rocks and boulders used to create the primary channel form. Concrete is then used as an infill to prevent water seepage between the rocks and to form the desired channel shape in the ramp. This may include the provision of resting pools and should include a low-flow channel. Rocks should remain protruding above the concrete surface to provide the appropriate baffling effect to reduce water velocities and provide low velocity refuge areas. It is also important to ensure the foundations are secure and that water does not seep through the ramp to avoid undermining the structure and flows on the ramp do not dry up. Protection of the toe of the ramp is also important to avoid undermining and maintain the stability of the structure. Installation of large boulders and creation of a receiving pool can be effective ways of providing protection and dissipating energy.

For either design, the slope of the ramp should be less than:

- 1:5 for head differences of ≤0.5 m.
- 1:10 for head differences of ≤1.0 m.
- 1:15 for head differences of 1-4 m.

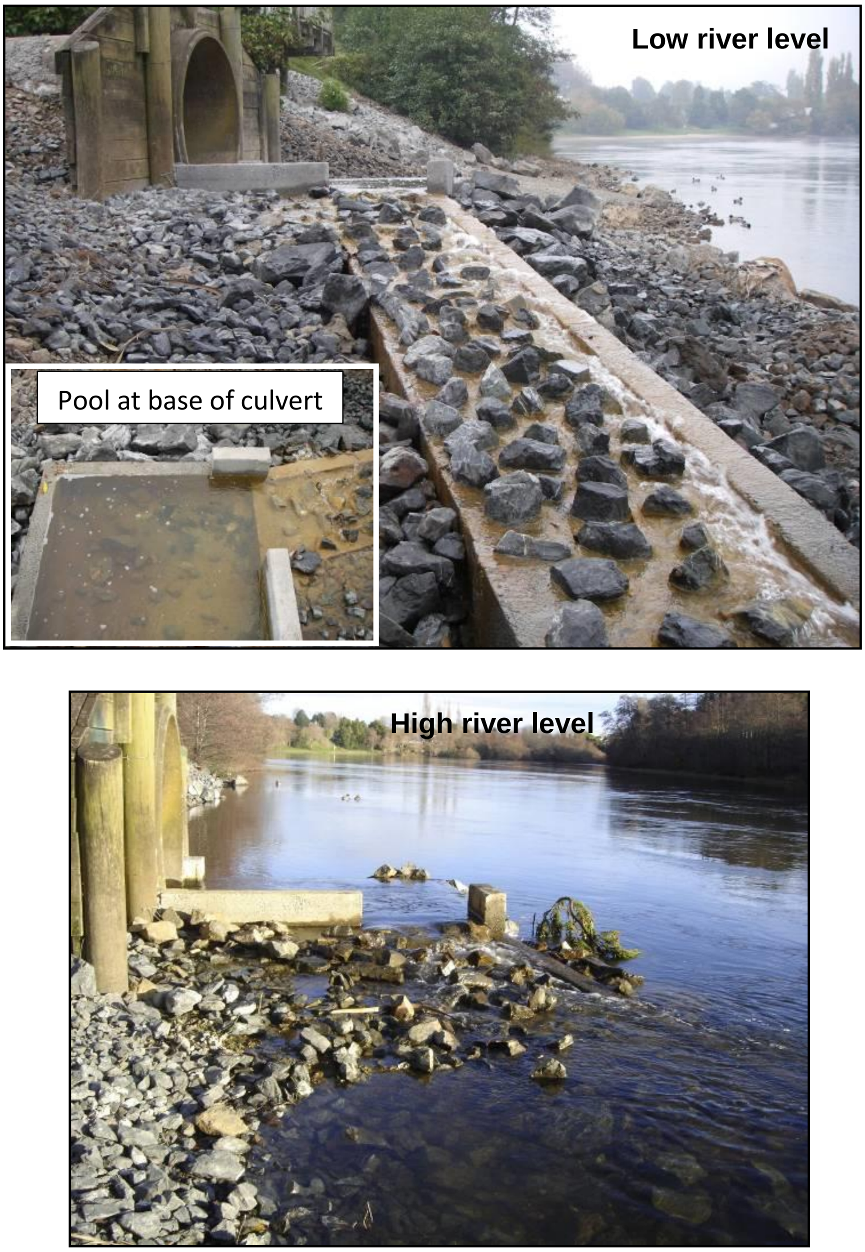

Figure 5-2: Example of a concrete rock ramp below a culvert that is oriented perpendicular to the downstream water body. A receiving pool has been added to the base of the culvert to direct the ramp downstream along the river margin. This provides the foundations for a low gradient sloping ramp.

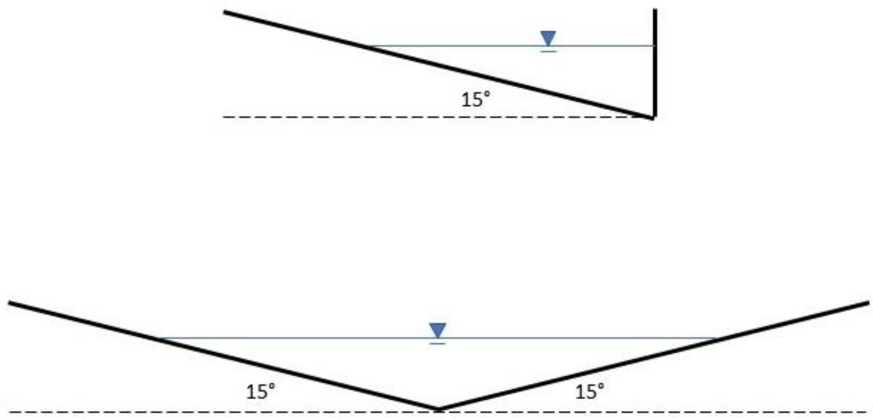

Figure 5-3: Transverse cross-section of a tilted (top) and V-shaped (bottom) ramp showing the lateral tilts that provided a range of water depths tapering to a low velocity wetted margin at the water's edge.

Figure 5-4: An example of a concrete rock ramp below a culvert in the Manawatu-Wanganui region. Concrete is used to prevent water seepage between rocks and is shaped to provide a low flow channel and resting pools to facilitate upstream passage. Photo: Cindy Baker.

Artificial substrate ramps

In New Zealand, a range of artificial substrate ramps have been tested as the basis of designing a cost-effective solution for overcoming low-head vertical drops (c. ≤1 m), for example downstream of perched culverts. Baker and Boubée (2006) evaluated the effects of a range of artificial ramp substrates on the passage of inanga and redfin bullies. For a 1.5 m ramp length, smooth surfaces were insurmountable for both fish species when ramp slope was greater than 15°. Gravel, nylon brush and the plastic cores of two drainage products (Miradrain™ and Cordrain™) resulted in high passage rates for inanga at ramp slopes of 15 and 30°, but only Miradrain™ permitted the passage of any inanga at a slope of 45°.

As redfin bullies use the wetted margin for climbing, surface type had less of an influence on passage success, but overall the Miradrain™ surface provided the highest passage success for both species at a slope of 15°. Subsequently, Baker (2014) showed that passage success over an artificial ramp with a Miradrain™ substrate decreased with increasing ramp length (from 3 to 6 m) and increasing ramp gradient (from 15° to 30°) for inanga and common bully, but that only increasing ramp gradient reduced passage success for redfin bullies. Jellyman et al. (2016) also evaluated the effects of ramp substrate and slope on the passage success of shortfin eel elvers (total length <155 mm). Highest passage success was again provided by the Miradrain™ substrate, but increasing slope (30° to 70°) significantly reduced passage success, particularly for smaller elvers. Ramp length in these trials was limited to 1.5 m. Doehring et al. (2012) tested the effectiveness of artificial ramps 3 m long with a synthetic turf substrate at angles of 5°, 15° and 25°. Inanga passage success decreased significantly with increasing slope, particularly for smaller fish.

Based on the results of these studies, it is clear that ramp substrate, length and slope, and the provision of wetted margins, are all important considerations in artificial ramp designs. High passage success (≥90%) was limited to ramps with a roughened substrate that were 1.5 m long with a slope of 15° (c. 1:4). The Miradrain™ substrate provided the best results across the range of species that have been tested. However, doubling the length of a 15° Miradrain™ ramp to 3 m reduced passage success by approximately 30 and 50% for inanga and redfin bully respectively. Common bully passage success over the 3 m, 15° Miradrain™ ramp was <15%. This indicates that at slopes of 15°, ramp length for a Miradrain™ ramp should generally be limited to ≤1.5 m to optimise passage success. This allows for fall heights of up to 0.4 m to be retrofitted with ramps of this design. For fall heights >0.4 m ramp slope must be reduced, resting pools integrated in to the design, or consideration be given to use of rock-ramp designs instead.

In all cases, ramps should be designed with a roughened surface and a V-shaped cross-section, or tilted laterally to provide a range of water depths that taper to a wetted margin (Figure 5-3). This will provide low water velocities for swimming fish and a wetted margin for climbing species. Ramps should be sized so that a shallow wetted margin is maintained across the fish passage design flow range (Figure 5-5).

A rotational moulded plastic ramp following these design criteria has recently been developed (Figure 5-5). The ramps are 560 mm wide and 2.4 m long and can be cut to length on site. They have a V-shaped cross-sectional profile and include baffles similar in size and configuration to the Miradrain™ substrate. The ramps offer a cost-effective implementation of the artificial ramp design that can be retrospectively installed at the downstream end of culverts or weirs using flexible attachments. Testing of these ramps has indicated passage rates for inanga equivalent to previous ramp experiments (Fake 2018) and initial field testing has demonstrated that the ramps are robust in-situ. These ramps may be a practical solution for overcoming fall heights up to 0.5 m (i.e., where ramp slope is ≤15°). Ramps should be installed so that shallow, low velocity wetted margins are maintained on the ramp across the fish passage design flow range (e.g., Figure 5-5).

Figure 5-5: Example of an artificial fish ramp installed at a perched culvert in Southland. Note that a shallow wetted margin is maintained on both sides of the ramp. Photo: James Dare.

5.3.3 Baffles

A common cause of impeded fish passage at instream structures is water velocities that exceed the swimming capabilities of fish. Baffles have often been used to modify uniform high velocity conditions in culverts or across weirs to improve fish passage success (e.g., MacDonald and Davies 2007; Franklin and Bartels 2012; Forty et al. 2016). Baffles typically comprise plates, blocks or sills that are attached to the culvert base and/or walls, or weir face, in regular patterns with the objective of increasing boundary roughness, reducing water velocity, dissipating energy, developing flow patterns to guide fish, and to create low velocity resting zones for fish.

In New Zealand, most of the research on baffles to date has been focused on facilitating fish passage through culverts. There has been little work on baffling of weirs here, but the research on fish ramps will provide some informative data for developing suitable remediation options.

Culverts

The suitability of a culvert for retrofitting baffling is dependent on its diameter. It will often be impractical to retrofit baffle solutions in culverts <1.2 m diameter, but other media, such as mussel spat ropes (see below), may provide an alternative method for creating a low velocity boundary layer suitable for enhancing passage of juvenile fish in smaller culverts.

A range of baffle types and configurations have been proposed and tested for enhancing fish passage through culverts (e.g., Figure 5-6). From a hydraulic perspective, weir and slotted weir baffle systems have been proposed as the most effective means of reducing water velocities and increasing water depth in culverts (Ead et al. 2002). However, relatively few studies have tested the success of the different baffle designs for providing fish passage.

Laboratory trials undertaken by Feurich et al. (2012) with juvenile inanga (*G. maculatus*) indicated the baffle designs that were most effective at reducing overall water velocities in the culvert (e.g., weir baffles; Figure 5-6a) were not necessarily the best solution for enhancing fish passage. While relative passage efficiency was not evaluated, they observed that for the weir, Alberta fish weir, and slotted weir baffle designs (Figure 5-6a, b, & d), fish tended to get stuck between weirs rather than progressing upstream. In contrast, they found that with spoiler baffles (Figure 5-6c) fish quickly progressed upstream, negotiating the entire length of the test culvert (7 m) with ease. Kapitze (2010) evaluated offset weir baffle designs for small-bodied Australian fish, but found passage rates were lower than should be achievable, and noted that the offset design had lost favour internationally, with spoiler baffles increasingly preferred due to their better performance. Marsden (2015) also evaluated passage of small Australia species through a flume fitted with various configurations of vertical baffles attached to the side wall. Under the conditions evaluated, passage rates were notably increased, but the test flume was only 4 m long and none of the species tested were similar to New Zealand species.

Based on these experimental results, and observations from field trials of spoiler baffles in Australia (MacDonald and Davies 2007) and New Zealand (Franklin and Bartels 2012), spoiler baffle designs (Figure 5-6c; Figure 5-7) are presently recommended as the preferred solution for improving fish passage through culvert barrels. In contrast, weir style baffles are not currently recommended for use where the objective is to optimise fish passage success unless further work is done to establish their performance relative to the preferred spoiler baffle designs.

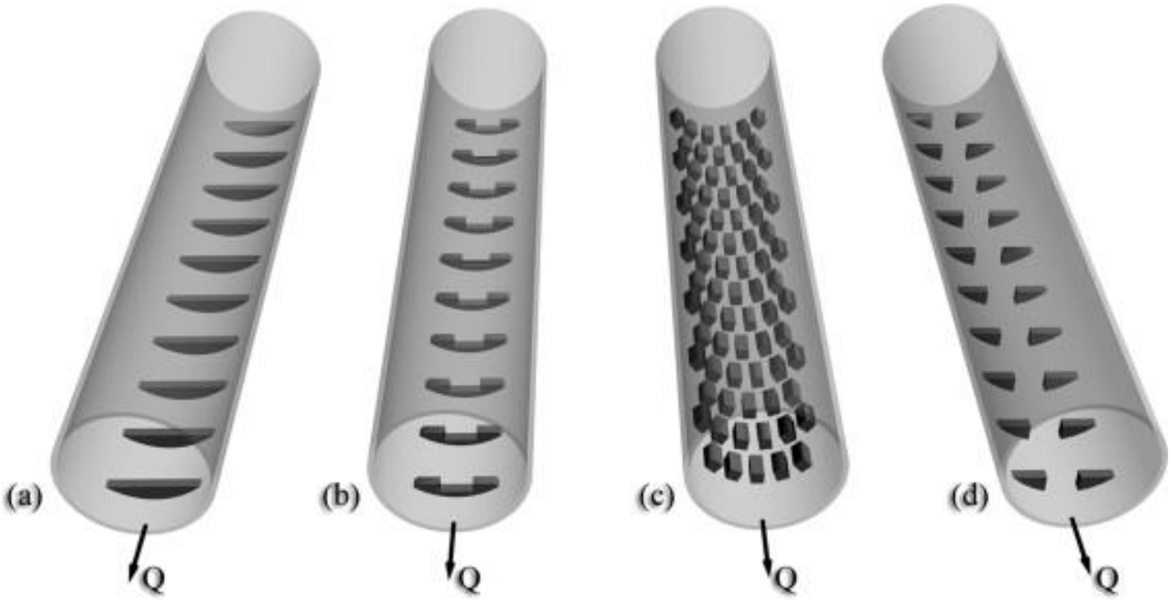

Figure 5-6: Some examples of possible culvert baffle installations that have been proposed to facilitate fish passage. (a) weir baffle; (b) Alberta fish weir; (c) spoiler baffle (recommended); (d) slotted weir baffle. Source: Feurich et al. (2012).

Figure 5-7: Spolier baffle sheets installed inside a culvert.

Stevenson et al. (2008) used a computational fluid dynamics model to investigate the hydraulic consequences of installing different sizes and shapes of off-set spoiler baffles in culverts. The results confirmed the findings of previous studies indicating that baffle sizing should be adjusted to suit the target fish species, culvert size and range of flows over which fish must be passed (Rajaratnam et al. 1991; Ead et al. 2002). However, for culvert slopes up to 2% (1.15°) Stevenson et al. (2008) indicated that rectangular baffles (0.25 m length, 0.12 m width and 0.12 m height) in a staggered configuration with 0.2 m spacing between rows and 0.12 m spacing between blocks within rows (Figure 5-8) created the desired continuous low velocity zone along the base of a 1.35 m diameter culvert and associated resting zones behind baffles that are required by fish (Figure 5-9). The spacing of the baffles is set to help ensure that fish are able to use the resting areas created between rows of baffles. A spacing of 0.20 m between rows of baffles will ensure that migratory fish up to 200 mm in size (which will include most adult native fish) are able to fit between rows. This configuration has subsequently been validated in the field as providing effective passage for inanga and smelt (MacDonald and Davies 2007; Franklin and Bartels 2012).

For culverts with a slope of >2% it may be necessary to adapt the sizing and shape of spoiler baffles to ensure suitable hydraulic conditions are available for fish passage. The work by Stevenson et al. (2008) indicated that smaller baffles (0.12 x 0.12 x 0.12 m) with the same configuration and spacing as the standard baffles may be more effective at creating lower water velocities in the culvert barrel than the standard baffle size at a slope of 3% (1.72°). However, the performance of this configuration is yet to be evaluated with respect to its effectiveness for facilitating fish passage. Consequently, applications outside the standard operating range should be robustly evaluated.

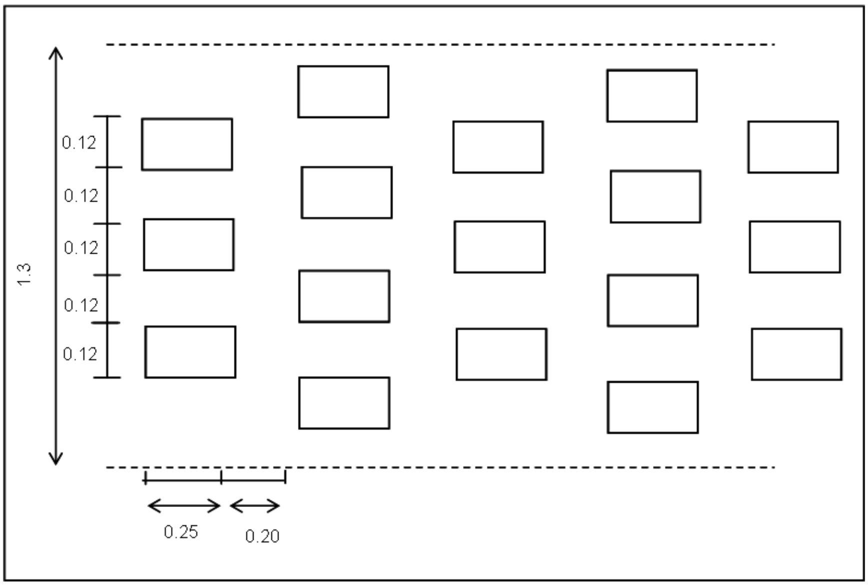

Figure 5-8: Plan view of spoiler baffle arrangement within a 1.3 m diameter culvert. Rectangles represent baffles (0.25 m length, 0.12 m width and 0.12 m height). Dotted lines signify culvert edges, at one third diameter. Rows of baffles are staggered and alternate in rows of three and four baffles. All dimensions are in metres.

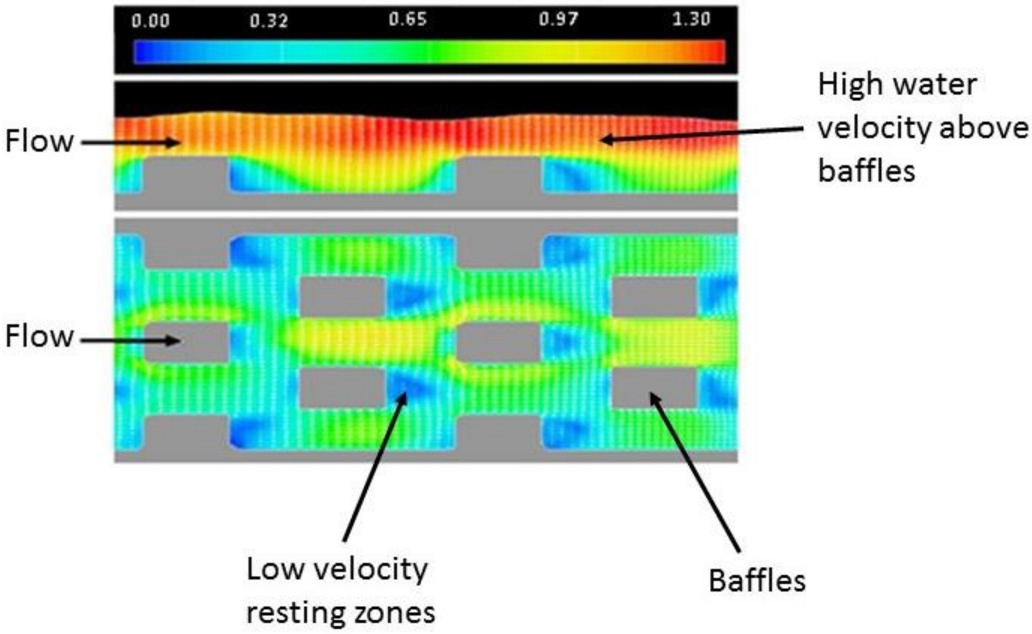

Figure 5-9: Longitudinal view (top section of diagram) and plan view (bottom section of diagram) of modelled water velocity in a culvert with spoiler baffles. The plan view is at 0.075 m depth. Alternating rows of rectangular spoiler blocks (0.25 m length, 0.12 m width and 0.12 m height), spaced 0.20 m apart at a flow of 0.11 $m^3 s^{-1}$. Culvert diameter = 1.35 m. The coloured band at the top of the figure gives the water velocity range (red = 1.30 $m s^{-1}$, blue = 0 $m s^{-1}$).

Although the installation of baffles in culverts has major benefits for fish, they will also decrease culvert capacity, increase roughness and may increase the risk of blockage by debris. The number of spoiler baffles fitted to a culvert will vary with culvert size, but as a general rule Stevenson et al. (2008) suggested baffles should cover approximately one third of the culvert's internal circumference, or the full width of box culverts (Table 5.4).

Table 5.4: Guide to the number of baffles required for different culvert diameters.

Culvert diameter (m)	Number of baffles in alternating rows
1.2	5 and 6
1.5	6 and 7
1.8	7 and 8
2.1	9 and 10
2.4	10 and 11

Numerical modelling has indicated that in a 1.3 m diameter culvert at a slope of 1.2%, culvert fullness is reduced relative to a bare culvert by 8% following the addition of the standard sized spoiler baffles (Feurich et al. 2011). Furthermore, modelling has indicated that the influence of baffles on water depth decreases with increasing flow and with increasing relative culvert size (Ead et al. 2002; Stevenson et al. 2008; Feurich et al. 2011). Table 5.5 summarises the results of the modelling described by Stevenson et al. (2008) that characterised changes in culvert fullness following addition of spoiler baffle arrays of the standard dimensions described above in a range of culvert sizes at a slope of 1.2%.

Rajaratnam et al. (1991) showed that discharge, *Q*, can be related to the relative depth of flow, y_0 / D, where y_0 is a characteristic depth defined as the average depth of flow in the cell (i.e., between rows of baffles in the case of spoiler baffles) and *D* culvert diameter, by the functional equation:

$$Q_* = \frac{Q}{\sqrt{g S_0 D^5}} = f_1\left(\frac{y_0}{D}\right) \tag{7}$$

where Q_* is the dimensionless discharge, *g* is acceleration due to gravity, S_0 is the slope of the culvert, and f_1 denotes a function. They found that for practical purposes the relationship between Q_* and y_0 / D can be expressed approximately by a power law equation of the type:

$$Q_* = C\left(y_0 / D\right)^a \tag{8}$$

where C is a coefficient and a is an exponent. Rajaratnam et al. (1991) used experimental data to characterise the coefficients and exponents for different spoiler baffle arrangements and these results have subsequently been generalised by Ead et al. (2002). They highlighted that across a range of different baffle types, the relationship between Q* and relative depth was affected by the relative baffle height (h/D), where h is baffle height, and their spacing (L/D), where L is the longitudinal distance between baffles. However, for the range of baffle types, flows and slopes tested, for h/D values in the range of 0.07-0.20, where baffle spacing was less than about D, the mean relationship between Q* and y0 /D was generalizable and described by the following equation which can be used for design purposes (Ead et al. 2002):

$$Q_* = \alpha\left(y_0 / D\right)^2 + \beta\left(y_0 / D\right) \tag{9}$$

where α and β are coefficients which vary with *h/D* as described in Table 5.6.

Table 5.5: Changes in culvert capacity at different flows, for bare pipes and for pipes fitted with spoiler baffles. Dimension of spoiler baffles were 0.25 m length x 0.12 m width x 0.12 m height with longitudinal space between baffle of 0.2 m and lateral space 0.12 m. Staggered rows of three and four baffles were modelled for the 1.3 m culvert, rows of six and seven were modelled for the 2 m culvert, rows of 10 and 11 baffles were modelled for the 3 m culvert and rows of 13 and 14 baffles were modelled for the 4 m culvert. Shaded rows indicate that the baffle array was not completely submerged. Reproduced from Stevenson et al. (2008).

Culvert diameter (m)	Discharge ($m^3 s^{-1}$)	Water depth (m)		Fullness of bare culvert	Fullness of culvert with spoilers	Change in culvert fullness
		Bare	With spoiler			
1.3	0.1119	0.146	0.249	11%	19%	8%
1.3	0.2200	0.209	0.314	16%	24%	8%
1.3	0.2750	0.233	0.341	18%	26%	8%
1.3	0.3300	0.26	0.365	20%	28%	8%
2	0.30	0.202	0.326	10%	16%	6%
2	0.55	0.282	0.426	14%	21%	7%
2	1.10	0.410	0.545	20%	27%	7%
2	1.65	0.511	0.655	26%	33%	7%
3	0.75	0.295	0.423	10%	14%	4%
3	1.50	0.442	0.577	14%	19%	5%
3	3.00	0.636	0.763	21%	25%	4%
3	4.50	0.779	0.925	26%	31%	5%
4	2.00	0.468	0.597	12%	15%	3%
4	4.00	0.687	0.83	17%	21%	4%
4	7.50	0.971	1.077	24%	27%	3%
4	11.00	1.302	1.175	30%	33%	3%

Table 5.6: Coefficients for the generalizable relationship between Q_* and y_0/D for culvert baffles. Reproduced from Ead et al. (2002).

h/D	α	β
0.00	15.19	0.02
0.07	8.90	-0.16
0.10	9.39	-1.18
0.15	7.41	-1.44
0.20	5.05	-0.91

Ead et al. (2002) also described a generalised relationship between normalised water velocity and relative depth of flow across a range of baffle types:

$$U_* = 10\left(y_0/D\right) \qquad (10)$$

where $U_* = U/\sqrt{gDS_0}$ and U is the maximum water velocity at the baffles. However, it should be noted that the coefficient will vary under differing baffle configurations and dimensions (Rajaratnam et al. 1991), but has not been characterised for the standardised baffle dimensions proposed by Stevenson et al. (2008).

There are two main options for fitting spoiler baffles to culverts: addition of individual blocks or installation of moulded sheets of baffles. Individual blocks can be relatively low cost to construct, but are time consuming to install in standardised configurations, particularly for larger culverts. The moulded plastic sheets have the advantage of being quicker and easier to install. However, it is important that the sheets are affixed to the culvert base securely to avoid water flowing under the sheets and causing them to lift and fail. The first row of baffles should be attached flush to the end of the pipe at the culvert inlet and it is recommended that the first row of baffles should have the lesser number of baffles (e.g., in a three and four baffle configuration, the first row should only have three baffles). Anka screws, Mushroom Spikes or Dynabolts can be used for fixing baffles to culverts. Regular maintenance checks should be carried out to remove any accumulation of debris, particularly after high flow events.

Use of mussel spat ropes

In smaller culverts (<1.2 m Ø), where access often makes installation of baffles impractical, the use of mussel spat ropes has been proposed for facilitating upstream passage of juvenile fish (David et al. 2014b). Trials with small diameter culverts (0.35 m Ø) up to 6 m long showed that the installation of Super Xmas Tree type mussel spat rope could reduce water velocities by around 75% and improve passage success for inanga, juvenile rainbow trout and a freshwater shrimp (*Paratya curvirostris*). Mussel spat ropes offer a practical low-cost method for promoting passage through long, physically inaccessible culverts. Their effectiveness is, however, dependent on correct installation and limited primarily to improving passage for smaller bodied fish. David et al. (2014a) provided guidance on the appropriate use of mussel spat ropes for facilitating fish passage through culverts. For installation through a culvert they recommend:

- A <u>minimum</u> of two rope lines are used for a 0.5 m diameter culvert, with more necessary for larger culverts.
- Ropes should be installed so that they are tight and flush with the base of the culvert through the entire length of the culvert and not loose at one end or out of the water (Figure 5-10).
- Ropes are set out to provide ‘swimming lanes’ between the ropes (Figure 5-10).
- Knots (half hitches) can be tied along the sections of rope in the culvert barrel to break up the flow and potentially create additional rest areas for fish.

It is recommended that non-looped mussel spat ropes, e.g., Super Xmas Tree, are used within culvert barrels as the loops may be more prone to trapping debris. Used mussel spat ropes are available from some mussel farms, but the durability and effectiveness of these ropes has not been tested. Well-worn used ropes are not recommended for use.

Figure 5-10: Example of good mussel spat rope installation showing fish 'swimming lanes' between ropes. Note that the number of ropes has been scaled up to match the size of the culvert. Photo: Bruno David.

Weirs

Weirs with a sloping downstream face (e.g., crump weirs) often limit upstream fish passage due to high water velocities that exceed the swimming capabilities of fish. Baffling of the weir face can be used to reduce water velocities and facilitate upstream passage. To date there has been no research explicitly addressing the effectiveness of baffling weirs for enhancing passage of New Zealand fish species. However, the research that has been conducted on fish ramps (see section 5.3.2) is relevant and there have been a number of overseas studies that have looked at different baffle types for weirs. The following recommendations are, therefore, based on translating these studies in the context of applications to weirs in New Zealand.

The standard slope of the downstream face of a crump weir is 1:5 (c.11°). The studies on ramp fish passes indicate that, at this slope, if an appropriate substrate and wetted margin are provided, reasonable passage success should be achievable for a range of native fish species including inanga, redfin bullies, common bullies and eels at distances up to 3 m (equivalent to a head difference of c. 0.6 m at a 1:5 slope) (Baker and Boubée 2006; Doehring et al. 2012; Baker 2014; Jellyman et al. 2016). The artificial drainage product Miradrain® has generally been found to perform best for enhancing passage of small bodied native fish species over ramps, but at a ramp slope of 15°, gravel (5-20 mm) also provided similar performance. Addition of substrate material of this size (i.e., with a small roughness height) may not, however, provide for the movement of larger bodied fish species (e.g., adult kōkopu). Where this is the objective, an alternative baffling method will be required.

To also cater for larger bodied fish, a weir could also be retrofitted by embedding rocks (150-200 mm) in to the front face of the weir. The rocks should be haphazardly placed as opposed to uniform lines. To maximise the height of the rock above the concrete ramp, each stone should be embedded longitudinally with the widest part of the stone facing in to the flow (Figure 4-11). The spacing between each rock should be between 70-90 mm. The rocks will not only lower water velocities down the front face of the weir, but also provide small pockets of water on the wetted margins that can act as resting areas for fish such as inanga that must swim over the weir.

5.3.4 Bypass structures

Where fish passage barriers cannot be ameliorated through structural adjustments (e.g., addition of baffles), bypass structures may be the only effective solution for enhancing fish passage. There are two main types of bypass structure:

1. Nature-like fishways mimic natural stream characteristics in a channel that bypasses the barrier. They are suitable for all structure types, but generally require more space than technical fishways. Because they mimic natural stream conditions they are generally suitable for a wide range of fish species and life stages.

2. Technical fishways can take a variety of forms including vertical slot fishways, pool and weir fishways, and Denil passes. To date there are relatively few examples of effective technical fishways in New Zealand, but they have been widely used internationally.

The effectiveness of bypass structures is highly dependent on their design and layout. They must be sited such that fish can find the bypass entrance, and must incorporate conditions that enable fish to successfully traverse the entire length of the bypass channel. It is outside the scope of these guidelines to provide detailed technical design specifications for bypass structures, but some of their key features are summarised below and links to international guidance are provided where available and applicable.

Nature-like fishways

Nature-like fishways have a range of applications and are suitable for all barriers, if there is sufficient space to construct the fishway whilst maintaining an appropriate gradient and shape. Nature-like bypass channels are particularly useful for upgrading existing installations. This type of fishway is generally considerably cheaper to construct than technical fishways (see below). They are negotiable by most fish species and blend into the surrounding landscape. Care must be taken to ensure that the velocity at the channel inlet and outlet can be negotiated by all species. This is particularly important where flow control devices (e.g., gates) are installed.

In general, the channel needs to be well armoured and as diverse as possible and should include pools, riffles, runs and backwaters (Figure 5-11). By including channel diversity, a range of velocities will be provided within the channel but it is essential that these velocities are within the sustained swimming speed of weak swimming fish with only a few areas where burst swimming would be required. It is also important to maintain a low gradient and shape the channel so that at both low and high flows, low velocity wetted margins remain available for fish passage. In catchments prone to extreme water fluctuations, the channel should be able to cater for the range of flows that exist. Wherever possible, different sized material (including woody debris) should be used in the construction. Pool and riffle spacing of six times the channel width and a meander of 12 times the channel width have been recommended (Newbury 1996). The banks should be planted to provide shade as well as maximise flood protection and in-stream cover. DVWK (2002) provides additional detail on the technical design of nature-like bypass channels and refer to O'Connor et al. (2015a) for design criteria relevant to New Zealand species.

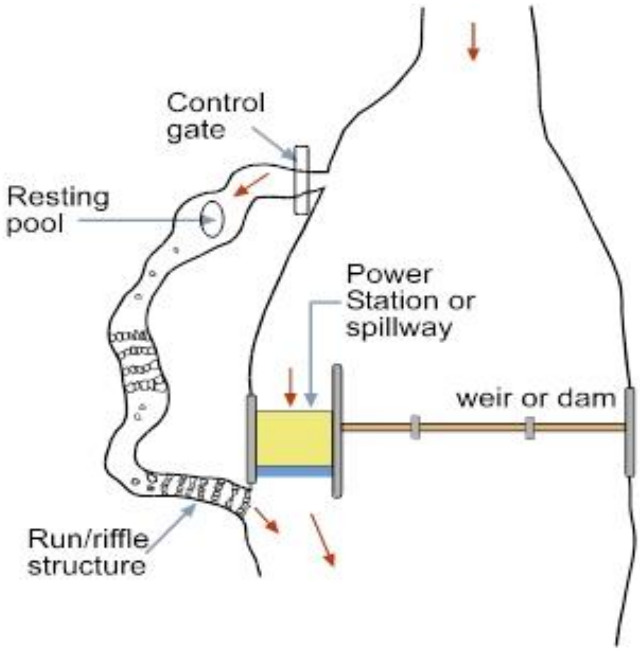

Figure 5-11: Example of a nature-like bypass channel that could be constructed to allow fish passage past a moderate head obstacle. The channel has natural characteristics, such as resting pools and runs/riffles. Modified from DVWK (2002).

As with all solutions, it is important to ensure that the nature-like pass is functioning correctly, and to initiate a regular monitoring programme to ensure objectives are being met. This could include visually inspecting the channel, to ensure that the original channel design has not been moved during floods, and undertaking ecological monitoring and associated hydraulic measurements. A benefit of nature-like fishways is that they also provide habitat for fish and can often support resident fish populations.

Technical fishways

Technical fishways have been widely used internationally for providing fish passage past structures, but have not often been used in New Zealand. This is largely because design guidance specific to New Zealand fish species has not been available. Technical fishways are most effective at facilitating fish passage past low- to medium-head obstructions. They are typically dependent on quite strict hydraulic design criteria in order to provide conditions suitable for the target fish species. Most technical fishway designs originated from efforts to promote the passage of salmonid species meaning there is a general lack of evidence supporting fishway design for species in the temperate south (Wilkes et al. 2017). However, more recently these designs have been adapted to suit a much wider range of fish species, including weaker swimming fish (e.g., inanga).

DVWK (2002) provides a good technical summary of many of the most common designs, e.g., pool and weir, vertical slot, Denil passes and fish locks. However, it must be remembered that the design parameters have not been scaled for New Zealand's native fish species. Low-head, low gradient vertical slot fishways have been shown to successfully pass weakly swimming, small-bodied fish species in Australia, including inanga. O'Connor et al. (2015a) provide design guidance for vertical slot fishways suitable for inanga. Key design features are to ensure the fall height between pools is kept small and that pools are sized to provide adequate energy dissipation.

5.3.5 Fish friendly tide and flood gates

Replacement or modification of existing tide and flood gates with self-regulating mechanisms that delay gate closing can significantly improve the passage of fish at tide and flood gates. Most self-regulating gate systems are built around a counterweight or float system that essentially prolongs the period for which the gate is open (Figure 5-12). Evidence suggests that the key objective should be to maximise the gate aperture when open, and to minimise the duration for which the gate is shut. Particularly important in tidal reaches is to ensure that the gate remains open for at least some part of the incoming tide phase, as this is when most upstream migrating fish are moving (Bocker 2015). The optimum timing and duration of opening will be site specific, and constrained by the specified protection levels (i.e., level of flood protection) of the infrastructure. However, the objective should be to maximise the duration across the full tidal cycle that the gate remains open. This will maximise the opportunities for fish to move, including across the flood, slack and ebb tides. Ensuring greater hydrological exchange across the full tidal range also helps to reduce the negative consequences of tide gates on instream physical habitat (Franklin and Hodges 2015). It is recognised that further work is required to understand optimal operational regimes for tide gates.

There is generally greater flexibility to alter the operating regime of flood gates, as they are most frequently only required to provide protection under more extreme flow conditions (i.e., high flow events). This means that it should be practicable to maintain the gates in an open state such that downstream flow is unimpeded by the gate structure up to the specified design flood protection levels of the gate.

Figure 5-12: A tide gate retrofitted with a fish friendly counter weight system in Christchurch. Credit: Paul Franklin.

5.3.6 Stormwater management ponds – vertical risers

Vertical risers have commonly been used as outlets in existing stormwater retention ponds. These standpipes create a complete barrier to upstream passage of migratory fish and are the least desirable control device for 'on-line' ponds. Where suitable habitat exists upstream of 'on-line' stormwater ponds, existing vertical risers may be remediated to provide passage for climbing fish. In most situations, it would be difficult to retrofit the structure to allow the passage of swimming fish. The use of spat ropes fixed within the internal diameter of the standpipe is not recommended as fish would still be required to climb vertically for several metres. Instead, a spiral fish pass lining the internal diameter of the standpipe is recommend. Due to the lack of existing proven solutions and the need for site-specific design criteria, we recommend engaging a qualified fish ecologist to develop a remediation solution for existing vertical risers. However, general design principles for the fish pass include:

- Use of a baffled substrate (e.g.,, grouted rocks).
- Incorporation of a wetted margin.
- A maximum gradient of 15° (c.1:4).
- Inclusion of resting pools at every metre of vertical gain.

A critical design feature will be creating an inlet that fish can successfully negotiate once reaching the top of the fish pass. In addition, the fish pass and inlet should provide fish passage over the fish passage design flow range during the key migration season for the target species.

6 Built barriers: A special case for protecting native biodiversity

While providing unimpeded fish passage is advantageous for most fish, some of our native freshwater fish, other instream species, and freshwater habitats cannot cope and/or compete with some of the exotic species that have been introduced to New Zealand (e.g., Townsend and Crowl 1991; Townsend 1996; McDowall 2003, 2006a; McIntosh and McDowall 2004; McIntosh et al. 2010; Department of Conservation 2003; Jones and Closs 2015; Jellyman et al. 2017). In these situations, physical barriers, which impede or prevent the upstream and/or downstream movement of unwanted fish species, can help protect key locations by keeping exotic species out and providing a safe refuge area. As such, it may be desirable for these barriers to be retained and monitored to ensure ongoing protection of biodiversity hotspots. Consideration should be given to what species and habitats are present, their distribution and extent, their conservation status, habitat preferences, timing of migration and spawning, life history (e.g., Jones and Closs 2015), and possible impacts of providing or impeding fish passage (e.g., future fragmentation of a species, loss of genetic mixing, hybridising species, restricting some species from available habitats (Allibone 2000; Fausch et al. 2009; Franklin and Bartels 2012; Woodford and McIntosh 2013).

Intentional built barriers are structures that are created with the specific objective of limiting or preventing the movements of certain fish species. Intentional built barriers have been used in New Zealand and internationally to successfully protect native refuges and prevent access for exotic and invasive species (Lintermans, 2000; Lintermans and Raadik 2003; Rowe and Dean-Spiers 2009; Department of Conservation 2012; Ravenscroft 2013; Tobak in prep.). They are generally designed to exceed the target fishes' ability to swim, jump or climb past the structure in order to manage their spread through the river network or into critical habitats. A key motivation for the use of such barriers is that preventing invasion by undesirable species is generally a more efficient management strategy than trying to eliminate a species after introduction (Kates et al. 2012). Design of intentional built barriers is the focus of this section.

While non-physical intentional barriers have been implemented internationally and in a few cases in New Zealand, experience to date suggests results have been somewhat mixed with generally low success (e.g., Bullen and Carlson 2003; Kates et al. 2012; Noatch and Suski 2012; Charters 2013; Ryder 2015). Generally, they can only be relied on when partial exclusion is acceptable and often need to be used in combination with intentional physical barriers to improve their effectiveness (Noatch and Suski 2012). At present there is insufficient evidence available to provide guidance on best practice for the use of non-physical barriers in New Zealand and, thus, they will not be addressed in this edition of the guidelines.

6.1 When must selective fish passage be considered?

The creation of built barriers, and maintenance of known fish passage barriers, should be considered when exotic species are impacting on a location that supports key native fish populations. Consideration should also be given as to whether excluding the exotic species will result in the protection or recovery of at risk species and/or habitats, prevent new fish invasions, and where barriers are viable in the prevailing environment.

The invasive fish species that are present, or have potential to invade a fish community, needs to be considered when making any decision on appropriate fish passage management at a site. Natural barriers to fish passage generally should not be removed or altered, unless conditions have changed and invasive species have gained access to a vulnerable habitat that is subsequently being impacted.

There are also some physical structures, such as culverts and dams, that have become fish passage barriers over time that should be retained in limited locations. The need to maintain or remove such barriers is dependent on what species are currently found in these locations, what species should naturally be present, and whether maintenance or removal is viable. If the barrier is found to be protecting a key native value, then there may be merit in retaining and protecting the existing barrier. Such decisions should be made in consultation with Department of Conservation and local regional council staff.

Of all the freshwater fish found in New Zealand, several introduced and a few native fish have been found to be invasive, impacting on some native fish communities and key freshwater habitats in some locations (e.g., McDowall and Allibone 1994; McDowall 2006a; McIntosh et al. 2010; Department of Conservation 2003). At least 21 species of introduced freshwater fish have established self-sustaining populations in New Zealand waters (Dean 2003) and some of these species pose a threat to the health of native species through predation, competition and/or changes to aquatic habitats (Rowe and Dean-Speirs 2009). Koi carp, perch, brown bullhead catfish, gambusia, orfe, rudd, brown trout and rainbow trout have been identified as of greatest risk and threat to New Zealand's biodiversity (Chadderton et al. 2003; Rowe and Wilding 2012). Tench, goldfish, chinook salmon, sockeye salmon, brook char and grass carp were the next highest risk species that could impact on aquatic environments in certain locations (Chadderton et al. 2003; Rowe and Wilding 2012). Atlantic salmon and Mackinaw could have potential to be invasive, but no impacts are known to date due to restricted distribution and information available (Wilding and Rowe 2008).

Salmon and trout species are implicated in the decline of some native fish populations via competition and predation in some locations (Dean 2003), and there is little habitat where galaxias species are free from predation from salmonids (McDowall 2006a). Trout predation has caused local extinctions and impacts on many of our threatened non-migratory galaxiids (Townsend 1996; Allibone and McDowall 1997; Allibone and McIntosh 1999; McDowall 2006a; McIntosh et al. (2010); Ravenscroft 2013; Woodford and McIntosh 2013). Trout colonisation is not static and the process continues today, causing the long term security of all galaxias species to be of increasing conservation concern (McDowall 2003; McDowall 2006b). In recent times there has also been observations of lower numbers of galaxiids in areas where brook char have moved into (Allibone and McDowall 1997; McDowall 2006a).

Other introduced species such as rudd (*Scardinius erythrophthalmus*), catfish (*Ameiurus nebulosus*), gambusia (*Gambusia affinis*) and orfe (*Leuciscus idus*) are known to compete for food with native species. Catfish, gambusia and perch are also known to directly predate native fish species, and rudd are known to eat macrophytes, especially preferring native species (Allibone and McIntosh 1999; Ludgate and Closs 2003; Rowe and Smith 2003; Collier and Grainger 2015). Koi carp, rudd and catfish are known to disturb the ecology and freshwater communities that they invade (Collier and Grainger 2015).

Longfin eel, shortfin eel, Australian longfin eel, smelt, kōaro and non-migratory galaxiids were identified by Chadderton et al. (2003) as the native fish species with potential to be invasive, though none were assessed as high risk compared to the introduced species. Both kōaro and eels have been found to impact directly on other native fish populations, predominately non-migratory galaxias and Canterbury mudfish (McDowall and Allibone 1994; Allibone and McDowall 1997; O'Brien and Dunn 2007; Allibone 2000). It should, however, be noted that risks from native fish species arise primarily from when they are introduced or their abundance increased outside of their natural range.

This has occurred, for example, where land-locked populations of galaxiids have become established upstream of large dams resulting in the proliferation of a native species, but in areas of the catchment where they would not normally exist in such high abundance.

6.2 Which native fish may benefit from built barriers?

Of our native fish, non-migratory galaxias and mudfish are the key groups where populations could benefit most from a natural or full exclusion built barrier (see Table 6-1). These species have fragmented distributions, occur in or are restricted to habitats that are conducive to built barriers being established, do not require access to and from the sea to complete their lifecycles, can maintain a self-sustaining population upstream of barriers, and are vulnerable to direct predation and/or competition by invasive species (see Section 6.1). They are also vulnerable to the adverse changes to aquatic habitats caused by these introduced species (Rowe and Dean-Speirs 2009; Salant et al. 2012).

For some of these species, such as lowland longjaw galaxias, dusky galaxias, Eldon's galaxias, Clutha flathead galaxias, Nevis galaxias and Teviot galaxias, it has been found that without natural waterfall barriers and/or built barriers, or conservation management intervention (including invasive species removal and barrier installation to prevent reinvasion), these populations would have or have been lost, and could now be extinct (Allibone and McDowall 1997; Department of Conservation 2004; Ravenscroft 2013; Bowie et al. 2013). If the current rate of documented losses continues at present levels for some of these species, then we may see extinctions within the next century (Goodman et al. 2004; Bowie et al. 2013).

Migratory native fish species can also benefit from natural or built barriers, and in some situations a selective barrier that provides access for climbing species over a natural or built barrier (e.g., kōaro, banded and giant kōkopu), while preventing other non-climbing species (e.g., trout, perch, koi carp) from moving upstream could be advantageous. For example, waterfalls maintain good native fish refuge from introduced species. By preventing invasive fish access, these selective barriers provide access for young native fish to protected upstream habitats, and protect spawning habitats of adult fish. Whether migratory species, such as the large galaxiids and smelt (McDowall 2000), have developed facultative non-migratory lifecycles, which allow them to maintain a self-sustaining population if they were to be isolated, is another key consideration in determining if species may benefit from a selective barrier.

Table 6-1: List of key non-migratory galaxias that could have increased protection from a natural or built barrier to exclude invasive fish. (Original source; Charters 2013, with additional information added). Those ranked high are likely to require barriers to persist, while those of medium priority would likely continue to exist without barriers, albeit with a smaller range.

Common Name	Scientific Name	Built or natural barriers would be advantageous to prevent extinction (High (H), Medium (M))
Central Otago roundhead galaxias	*G. anomalus*	M
Lowland longjaw galaxias	*G. cobitinis**except for Kauru and Kakanui	H
Taieri Flathead galaxias	*G. depressiceps*	M
Dwarf galaxias	*G. divergens*	M
Eldon's galaxias	*G. eldoni*	H
Gollum galaxias	*G. gollumoides*	M
Bignose galaxias	*G. macronasus*	M
Alpine galaxias	*G. paucispondylus*	M
Upland longjaw galaxias	*G. prognathus*	M
Dusky galaxias	*G. pullus*	H
Clutha flathead galaxias	*G. 'species D'*	H
Northern flathead galaxias	*G. 'species N'*	M
Canterbury galaxias	*G. vulgaris*	M
Dune lake galaxias	*G. sp.*	M
Southland flathead galaxias	*G. Southern sp.*	M
Teviot flathead galaxias	*G. Teviot sp.*	H
Nevis galaxias	*G. aff gollumoides Nevis sp.*	H
Canterbury mudfish	*N. burrowsius*	M
Brown mudfish	*N. apoda*	M
Black mudfish	*N. diversus*	M
Northland mudfish	*N. heleios*	M

6.3 Biological factors to consider in creating and maintaining a built barrier

To effectively manage fish passage, and understand what makes a barrier to protect native areas from invasive species, we need to understand the characteristics and behaviours of the fish we are trying to protect and exclude. Different freshwater fish have different abilities and characteristics (e.g., Appendix D). These differences in abilities can be exploited to identify key design parameters to limit or prevent invasive species movements, while allowing some species to navigate the structure and/or protection of the upstream habitat and native fish population (Table 6-2). For example, trout can jump, while some natives can climb so in these situations grates or overhangs or a lack of depth downstream can be used to prevent trout jumping upstream, while still allowing climbing native species access. In addition to fishes' abilities, their behaviour should also be considered, as not all will be affected equally by a barrier. For example, an eel may be able to navigate around an instream structure via land in a way that cannot be achieved by whitebait or trout, or an aquatic insect with a flighted adult stage may be unaffected by a land separation.

Table 6-2: Factors influencing fishes' ability and likelihood of successfully negotiating barrier(s). Adapted from Charters (2013) with consideration of water temperature and hydraulic wave added from Holthe et al. (2005) and Stuart (1962) respectively. Originally adapted from Rowe and Dean-Speirs (2009) and Noatch and Suski (2012).

Fishes Ability/Response	Influencing Factors
Jumping	Height of barrier.
	Longitudinal distance from downstream pool to top of barrier.
	Area of downstream pool.
	Depth of downstream pool.
	Fish species.
	Age and size of fish (i.e., juvenile versus adult).
	Water temperature.
Upstream swimming	Fish species.
	Size of fish (i.e., juvenile versus adult).
	Water velocity/ hydraulic wave.
	High flow conditions (i.e., floods).
	Maximum swimming speed of fish.
	Water depth in stream channel (e.g., juvenile fish can move upstream in less water than adult of same species).
Climbing	Fish species.
	Availability of wetted surface (for adhesion).
Avoidance response	Sensitivity range of fish species to environmental conditions such as sound, light and water pollutants.

6.4 Setting objectives for built barriers

In addition to setting general objectives and performance standards (e.g., Section 3.3), a key consideration in the design of any built barrier is whether it should operate as a full exclusion barrier or a partial barrier that enables some fish passage. This will depend on the situation, requirements of the species present or using the area, and/or the habitat being protected from invasive species. In each situation, consideration needs to be given to the possible impacts of providing or impeding fish passage. This includes restricting some species from reaching available natural habitats, potential fragmentation of a species, the possibility of creating sink populations, isolating populations in a way that could lead to speciation, mixing new populations that could lead to hybridisation, risk of localised extinction, ensuring adequate habitat quantity and quality for sustaining populations, the loss or restriction of the ability to carry out full lifecycles within the barrier area, and loss of genetic mixing, that could affect the long-term resilience of the species (Allibone 2000; Eikaas and McIntosh, 2006; Fausch et al. 2009; Franklin and Bartels 2012, Woodford and McIntosh 2013). Built barriers may also be considered as a means to simply prevent access for invasive species to aid recovery of important freshwater habitats that they have impacted (Gumbley and Daniel 2015), rather than solely to protect an individual species or population. It should be noted that intentional screened barriers (e.g., water intakes) are the exception, and should generally exclude all species (Jamieson et al. 2007), as otherwise these fish are lost to the fishery, especially diadromous species.

If diadromous species strongholds are present and are proposed to be protected from an invasive species, a partial barrier will likely be required to ensure the diadromous species can negotiate the barrier to maintain their migratory lifecycle or ensure life stages can still migrate or disperse. There could be exceptions to this in limited situations, including where diadromous species have formed landlocked populations and can complete their lifecycle within the barrier area. Under this circumstance, some consideration should be given to the potential impacts on other native species of the development of landlocked populations potentially altering the distribution and abundance of competing species outside of their normal range.

Full exclusion barriers are likely predominately required in situations where highly threatened non-migratory galaxias are restricted to fragmented headwater locations, and where without a barrier these populations are likely to become extinct over time. Fortunately, the distance inland to these headwaters sites means diadromous fish species are effectively absent from many non-migratory galaxiid sites and, therefore, passage past the barrier for diadromous species is not required. Once an initial barrier has been installed, additional barriers and invasive species removal can be established over time further downstream to extend the range and protected area for the non-migratory galaxiid species (Lintermans 2000).

6.5 Best practice design criteria and installation of built barriers

The use of built barriers (<4 m in height) as a management tool to protect key species' locations and habitats has increased in recent times. Several successful built barriers have now been designed, installed and maintained in several locations in New Zealand (Bowie et al. 2013; Charters 2013; Ravenscroft 2013; Ravenscroft et al. in prep; Gumbley and Daniel 2015; Tobak in prep) (Figure 6-1 to Figure 6-6). Most of these physical built barriers have been weirs over 1 m in height designed to prevent the movement of salmonids, and have successfully resulted in the protection of key non-migratory galaxiid locations, when combined with invasive species removal operations (Figure 6-1 to Figure 6-6). Information and lessons learnt from these and overseas experience can now provide some good guidance for future built barrier use in New Zealand. However, it should be noted that there are still gaps in knowledge, and further outcome monitoring over time is needed to improve guidance, management and future design.

The design of a built barrier is directed by the objectives of the barrier. Considerations will include whether the barrier is to provide full or partial exclusion, whether the goal is to lower the abundance of or prevent access for invasive species, whether it should allow for migratory native fish, and if the aim is to prevent upstream movement and/or downstream movement. Objectives should be determined in collaboration with DOC staff. There is no one design that fits all, however, with knowledge of the objectives, key design features can be identified. It should be noted that for a physical barrier to be successful it often cannot be the sole method of control and has to be implemented along with physical removal of the invasive species.

Figure 6-1: Swinburn Creek barrier in Otago. A built barrier has been installed onto a natural waterfall to protect Central Otago roundhead galaxias populations, after brown trout gained access upstream when stream conditions changed. Credit: Daniel Jack (DOC).

Figure 6-2: Akatore Creek barrier in Otago . A built barrier has been installed onto a natural waterfall to protect Taieri flathead galaxias, after brown trout gained access upstream when conditions changed. Credit: Sjaan Bowie (DOC).

Figure 6-3: Built barrier installed in Cabbage Tree Gully, Canterbury. The barrier was built to prevent trout accessing a key lowland longjaw galaxias stronghold in the lower Waitaki River, Canterbury. Credit: Peter Ravenscroft.

Figure 6-4: Built barrier installed in an unnamed spring of the Ahuriri. The objective was to prevent trout accessing a key lowland longjaw galaxias stronghold in the MacKenzie Basin, Canterbury. Credit: Dean Nelson (DOC).

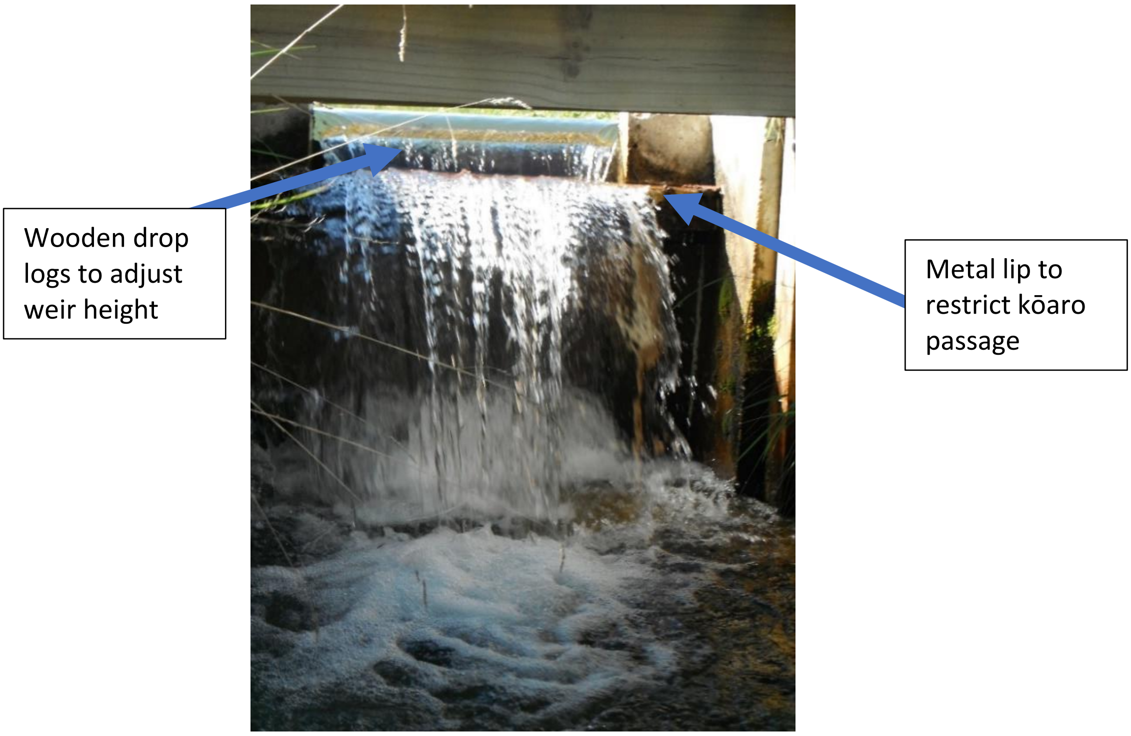

Figure 6-5: Built barrier installed in an unnamed spring of the Fraser River. The objective of this built barrier was to prevent trout and kōaro accessing a key lowland longjaw galaxias and bignose galaxias stronghold in the MacKenzie Basin, Canterbury. Key features of the barrier were the height to prevent trout access, the metal lip to prevent kōaro passage, and the wooden drop logs to allow for flushing of flows and maintenance of flows and habitat upstream. Credit: Sjaan Bowie (DOC).

Figure 6-6: Built barrier installed in an un-named tributary of Upper Waipori River. The objective was to prevent trout and kōaro access to a key dusky galaxias stronghold in Otago. Inset shows a close-up view of the successful kōaro lip barrier. Credit: Josh Tobak.

Costs for planning and construction of built barriers in New Zealand range depending on site and barrier type and can vary between $5000, to around $100,000 for isolated or large and complicated barriers.

There are many natural, and physical intentional and unintentional fish passage barrier features that can be used to aid design for future successful built barriers. Waterfalls, overhangs, swamps, dry stream beds, low water levels and uninhabitable zones are key features of natural barriers to fish passage, while dams, chutes (high water velocity), falls/weirs, screens and overhanging lips are key features of physical barriers to fish passage (Table 6-3) (Charters 2013). Built barriers, therefore, provide the common physical characteristics of known fish passage barriers that are proven to create conditions unfavourable to invasive fish passage. This includes features such as large fall heights, high water velocities, perched structures, low water depths, and the presence of physical structures that block waterways e.g., dams, grills or screens (see Appendix E for further discussion of these features). All these barrier features have advantages, limitations and factors that control their effectiveness, which need to be considered when they are being used as a management tool to protect native values (Table 6-4).

Built barriers can generally be categorised into ‘high head’ (>1.0 m) or ‘low head’ (<1.0 m) barriers. The inability of many invasive species, such as trout, to negotiate >1 m high vertical barrier makes high-head barriers ideal for invasive fish exclusion in most parts of New Zealand. However, achieving head drops of >1 m requires relatively steep stream gradients if significant impacts on upstream habitats (e.g., backwatering) are to be avoided. If partial exclusion is required in these situations, then the climbing ability of some the diadromous native fish can be relied on, or selective fish passes can be provided to facilitate native passage.

Charters (2013) collated information from over 30 known built barriers (weir, screened barriers, culverts and other) case studies from New Zealand, Australia, Canada and USA, that could apply to the New Zealand situation. It was found that weir barriers were the most common successful type of built barrier. Barrier location, height, profile, flow, and downstream zone are the key design features that are important for successful vertical weir built barriers (Table 6-4) (Charters 2013).

Table 6-3: Barrier types that have been found to protect native values. Adapted from Charters (2013).

Type of Barrier	Type	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Swamp	Natural	Vegetated channels with lack of surface flow and/or ephemeral flows prevent or limit fish access.	▪ Hydraulic and environmental conditions. ▪ Permanence of conditions establishing a barrier. ▪ Species-specific - what one species can tolerate, another may thrive.	▪ Can be an effective partial barrier.	▪ Changes in natural conditions can result in changes in barrier effectiveness.
Dry stream bed	Natural	Prevents swimming/access to habitat.	▪ Hydraulic and environmental conditions. ▪ Permanence of conditions establishing a barrier. ▪ Species-specific - what one species can tolerate, another may thrive.	▪ Can be an effective partial barrier, especially as these environments can favour some native fish being sustained over invasive fish.	▪ Changes in natural conditions can result in changes in barrier effectiveness.
Low water levels	Natural	Prevent swimming, also known to cause stress for fish.	▪ Hydraulic and environmental conditions. ▪ Permanence of conditions establishing a barrier. ▪ Species-specific - what one species can tolerate, another may thrive.	▪ Can be an effective partial barrier, especially as these environments can favour some native fish being sustained over invasive fish.	▪ Changes in natural conditions can result in changes in barrier effectiveness.
Uninhabitable zone	Natural	Species-specific – what one species cannot tolerate, another may be perfectly healthy in.	▪ Hydraulic and environmental conditions. ▪ Permeance of conditions.	▪ Can be an effective partial barrier, especially as these environments can favour some native fish being sustained over invasive fish.	▪ Changes in natural conditions can result in changes in barrier effectiveness.

Type of Barrier	Type	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Dams/ Waterfalls	Built & natural	The dam/ waterfall height creates a full or partial exclusion barrier in the waterway (preventing swimming, jumping or climbing) depending on fish community.	▪ Height of barrier. ▪ Surface of barrier – specific species abilities to negotiate dam structure. Such as if wetted margins or form on dam face allows native fish to climb face. ▪ Presence of spillway (weir), fish pass or fish trap and transfer facilities.	▪ Can be full or partial exclusion barriers dependent on species present. ▪ Dams may have been installed for another purpose or waterfalls formed, but exclusion of invasive species results.	▪ Dams can result in significant alteration of stream hydrology, sediment transportation and consequently, in-stream habitats. ▪ Dams create large amount of infrastructure and are high cost.
Chutes (Velocity)	Built & natural	High water velocity fatigues fish before they can fully negotiate a barrier (i.e., it exceeds their maximum swimming ability (see section 2.3)). Increased velocities can be achieved in natural cascades in waterways or through placement of a culvert or chute that constricts the water flow. Shallow water depth in or downstream of these barriers can prevent larger fish from swimming as well as inhibit their ability to jump.	▪ Flow velocity and depth of water in and/or downstream of chute. ▪ Hydraulics during differing flow conditions. ▪ Fishes' swimming ability and behavior.	▪ Less hydrological effect than weirs or dams. ▪ Can function as selective barriers (i.e., they exclude one species while allow another species passage, particularly for weak swimming species).	▪ Different fish species have different swimming performances and so their ability to negotiate a velocity barrier varies. ▪ Salmonids and trout species are strong swimmers, and therefore velocity barriers may be insufficient to prevent them passing upstream. ▪ Changes in natural conditions can result in changes in barrier effectiveness.

Type of Barrier	Type	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Falls/weirs	Built	A weir can be used to create a full or partial exclusion barrier by various mechanisms, including a vertical barrier exceeding or preventing invasive fish access e.g., jumping, or creating a concentrated zone of fast flow over its crest.	▪ Height of structure crest. ▪ Downstream pool that prevent jumping ability. ▪ Presence of an upstream pool that alters habitat upstream. ▪ Flow velocity. ▪ Hydraulics during high flow conditions.	▪ Less hydrological effects than dam. ▪ Precast components available.	▪ Change in hydraulics under high flow conditions may reduce barrier effectiveness (e.g., raised tailwater depth (pooling at base)). ▪ Instream structures have been known to degrade and deform over time, adversely affecting their performance as a barrier. ▪ Instream structures can be a high cost dependent on design required, planning processes and accessibility of site.

Type of Barrier	Type	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Screens/grills	Built	Screens physically block biota (including adult and juvenile fish, and fish eggs) over certain sizes from passing through, while allowing water to continue flowing. This could be gabion basket weirs, that are established to try and let small/ climbing fish but exclude large upstream migrating fish, or water intakes, that are established to take water from waterways and prevent entrainment or impingement of fish otherwise they are lost to the fishery, or structures with screens, protruding grills or bars sized and spaced appropriately to prevent access.	▪ Hydraulics during high flows (e.g., overtopping a gabion basket weir may occur). ▪ Permanence of barrier. ▪ Water intake design parameters are maintained over time (e.g., approach & sweep velocity, screen material opening gap). ▪ Screens, grills and bars are maintained on structures to prevent invasive access.	▪ Can be an effective full or partial barrier to selectively prevent or allow access to particular species. ▪ Gabion basket weirs and screens can allow stream flow to continue through barrier, with minimal impact on hydraulics. ▪ Barrier to prevent downstream or upstream movement.	▪ Screen, grills and other structures (e.g., gabion baskets) have been known to degrade and deform over time, adversely affecting their performance as a barrier. ▪ High velocities and conditions at screen and water intake interfaces may trap or harm fish if not designed appropriate for the location and species, and maintained. ▪ Instream structures can be a high cost dependent on design required, planning processes and accessibility of site.

Type of Barrier	Type	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Overhanging lips	Built & natural	Overhangs can be created by waterfalls, built solid structures (e.g., culverts) or grated or solid lips hanging out from the downstream face of a barrier.	▪ Height of the overhang. ▪ Width, length (protrusion), spacing (if not solid) and angle of overhang from downstream face. ▪ Grate spacing, if not solid overhang.	▪ Provides additional barrier against jumping. ▪ Exclusion barrier for climbing species.	▪ Can block native climbing species. ▪ Instream structures have been known to degrade and deform over time, adversely affecting their performance as a barrier. ▪ Instream structures can be a high cost dependent on design required, planning processes and accessibility of site.

Table 6-4: Design considerations for built (weir) barriers. Adapted from Charters (2013). Further additions added from learnings from recent installations.

Design Feature	Design Criteria	Design Considerations
Barrier location	▪ Barrier placed in a stable section of streambed, with a moderate slope and small floodplain area.	▪ Minimise upstream backwater effects including loss of riffle zones and flooding by placing barrier in section of reasonable gradient.
Barrier height	▪ Drops ≥1- 1.5 m are effective exclusion barriers. Smaller drops should be used in combination with other barrier types, such as a shallow, high velocity chute, screens, or overhanging lips.	▪ Minimising upstream backwater effects by minimising barrier height while still achieving barrier effectiveness. ▪ Change in sediment transport within stream.
Barrier profile	▪ Existing weir barriers can use V-notch profiles or perched culverts to maintain a concentrated, high-velocity body of flow under low flow conditions. ▪ Existing barriers have used ≥500 mm overhangs to inhibit jumping. ▪ Drop log features can be added to the barrier face to help manage flow and allow sediment flushing.	▪ Minimise upstream backwater effects by using a shallower upstream face profile, or locating in a moderate slope area. ▪ If a pool upstream is formed it should be eliminated where possible to increase stability of the structure and removing the habitat for invasive fish to access. ▪ Scour protection downstream and side (wingwalls sloped) of the apron. ▪ Grated overhangs have been used to allow climbers and certain size swimmers to pass up through barrier.
Design flow	▪ Existing barriers (in the US) have used 1:100-year flood flows as the maximum design flow for full exclusion.	▪ Hydraulic profile over weir crest under varying flows. ▪ Anchoring of weir structure to prevent overturning, sliding and scour. ▪ Protection of abutments. ▪ Minimise favourable conditions for invasive macrophytes establishment upstream.
Downstream zone	▪ Downstream apron (>2 m length) to eliminate pooling and create a high velocity and shallow water zone that inhibits jumping and swimming.	▪ Scour protection on sides and downstream of apron to ensure integrity of structure maintained long term and eliminate any opportunity for bypass around structure. ▪ Rocks may need to be removed from the downstream area to reduce areas of slow water and ponding (e.g., increase water flow away from downstream side of barrier, eliminate back eddies off the rocks).

In situations where fall heights of only <1m can be achieved, built barrier designs will have to strengthen and focus on the design features other than barrier height, for example providing a shallow water zone downstream and adding bars or screens that will prevent access (see Table 6-3). One-way barriers (Figure 6-7 and Figure 6-8) (Gumbley and Daniel 2015), good water intake screen designs (Jamieson et al. 2007), or non-physical barriers could also be considered in these situations, but proven designs are still relatively limited in New Zealand and outcome monitoring is critical to ensure future success.

Most built barriers are needed to prevent upstream movement, as the invasive species of concern establishes in the lower reaches, and for many at risk species, headwater areas are the only remaining strongholds. However, at times there could be a need to control downstream movement. For instance, where invasive species has been introduced into a lake environment, a barrier to prevent the invasive species establishing in a downstream location may be desired, or a barrier may be established to collect invasive species as they move downstream and prevent any upstream passage back into an area where restoration is being attempted.

There has been varying success in the use of physical barriers to exclude koi carp from localised areas overseas (Lougheed et al. 2004; Hillyard 2011). In New Zealand, a one-way barrier located at the outlet of Lake Ohinewai was trialled as a koi carp control measure with limited success. A screened gate (Figure 6-7 and Figure 6-8) was installed in 2011 to prevent large koi carp from migrating upstream into the lake, while allowing juvenile native species to move upstream, and all fish to move downstream to exit the lake. In addition to the one-way gate, an invasive species removal programme was undertaken in Lake Ohinewai to reduce the koi carp population from its 2011 estimate of 374 kg/ha to below 100 kg/h (Tempero and Hicks 2017). Through a combination of the one-way gate and fish removals, by 2014, koi carp biomass was estimated to be 14 kg/ha (Tempero and Hicks 2017). However, reductions in koi carp biomass were short lived, and a follow up survey in 2016 found koi carp had more than quadrupled to an estimated biomass of 94 kg/ha (Tempero and Hicks 2017). In addition, increases in the biomass of catfish and goldfish also occurred between 2014 and 2016 (Tempero and Hicks 2017). Although the one-way gate was effective in preventing adult carp access to the lake it still allowed passage of juveniles, which quickly develop into spawning stock. In addition, regular maintenance was required as the horizontal bar spacing of 30 mm clogged with debris (Tempero and Hicks 2017). Any future installations of this type of barrier should consider vertical bar placement to try and improve debris clearance (John Gumbley, pers. com). Overall it appears that the exclusion barrier will function most effectively in conjunction with other control measures.

Other New Zealand examples of built barriers preventing access of unwanted exotics are in the Lake Waahi catchment (Figure 6-9 and Figure 6-10). These built barriers protect habitat for lacustrine banded and giant kōkopu, as well as for longfin and shortfin eels, from the adverse impacts of koi carp, goldfish, perch, rudd, gambusia and catfish. Within the Waahi catchment, the lacustrine banded and giant kōkopu populations are of considerable conservation value because recent otolith analyses have determined that juveniles of these lacustrine stocks are augmenting diadromous populations of these kōkopu species in the wider Waikato catchment (B. David, WRC, pers. comm.).

Figure 6-7: One-way gate fitted to Lake Ohinewai outlet drain, Waikato. The gate is designed to prevent adult koi carp from accessing the lake, while still providing small and other fish access to and from the lake. Credit: Adam Daniel.

Figure 6-8: One-way gate structure prior to installation showing screen that can be lifted for inspection and clearing of debris. Credit: Adam Daniel.

Figure 6-9: A weir built on top of a natural waterfall in Waitawhara Stream, Waikato. Although not designed as a selective barrier, the weir and waterfall prevent koi carp, goldfish, perch, rudd, gambusia and catfish from accessing headwater habitats whilst allowing the passage of banded and giant kōkopu and shortfin and longfin eels. Credit: Cindy Baker.

Figure 6-10: Baffled concrete weir in the lower reaches of Puketirini Stream, Waikato. A degraded weir (inset top left) was successfully preventing koi carp, goldfish, perch, rudd and gambusia from accessing upstream habitats whilst allowing the passage of banded and giant kōkopu, and shortfin and longfin eels. To continue protecting native fish populations the weir was remediated in 2018. Credit: Cindy Baker.

Many locations where built barriers will be considered in New Zealand, are likely to have the objective of excluding salmonids. As detailed in Appendix E, brown trout and other salmonids, such as brook char, have good jumping ability compared to our native fish, with some able to jump greater than 74 cm fall height, depending on fish size, condition and surrounding waterway conditions (e.g., downstream pool size and depth) (Holthe et al. 2005; Kondratieff and Myrick 2006; Aaserude and Orsborn 1985). Some invasive carp species are also able to jump and this will need consideration in any built barrier design aiming to exclude carp (Hofstra et al. 2014). This difference in abilities between native fish and many invasive fish is the key design criteria that has resulted in several successful built barriers to date (Figure 6-1 to Figure 6-6), and is the key reason for requiring a minimum of 1 m fall height and a shallow downstream zone that inhibits jumping where possible.

Gabion basket weir barriers have been trialled as a partial exclusion barrier in two locations (Orokonui, Otago and West Coast in small streams (Figure 6-11 and Figure 6-12). Both did limit some fish access, but failed to consistently provide partial exclusion long-term due to silt accumulation causing infilling of the gaps in the gabion baskets intended to provide passage for juveniles, and invasive macrophytes establishing on the structure. These factors resulted in the need for regular cleaning of the structure, and it was found that the physical structure degraded and changed shape over time. These barriers could be useful as a temporary barrier. Any future consideration of installation of gabion basket weirs will need to consider these limitations.

Figure 6-11: An unsuccessful gabion basket weir installed to allow migratory native fish access, while preventing trout access in Orokonui Creek, Otago. Credit: Sjaan Bowie.

Figure 6-12: An unsuccessful gabion basket weir installed to protect a dwarf galaxias stronghold from trout in an unnamed tributary of the Maruia River, West Coast. Credit: Sjaan Bowie.

Another key consideration in built barrier design is minimising any upstream effects on stream hydrology and habitat of the vulnerable species or habitat you are trying to protect. Salant et al. (2012) and Birnie-Gauvin et al. (2017) found because of weir installation, riffles and gravel substrate were lost, silt settled and built up against the upstream face of the weir as the water is slowed, deeper pool habitat was established upstream of the weir face and, if weirs were installed in a shallow gradient area, an extensive area of backwater could establish. These changes may enhance or reduce the available habitat of the vulnerable species upstream, may cause flooding beyond areas previously flooded, and change availability of habitat and the balance of the aquatic community (Salant et al. 2012).

Crowder (2009) proposed a formula for estimating backwater length for typical vertical weirs that could be a useful starting point for approximating the potential upstream effects of weir construction:

$$L_{bw} = 0.7d/S \quad (11)$$

Where L_{bw} = backwater length (km), d = water depth (m) and S = stream gradient (m/km).

Where silt and water build up is expected upstream of the structure, a v-notch profile, drop log structure allows modification of upstream water levels and flushing of the system (Figure 8-3). A perched culvert or a culvert pipe with stopper within the weir (Figure 6-4) could also be considered to provide a mechanism for flushing and/or maintaining a concentrated high water velocity under low flow conditions if required.

Key considerations associated with the design flow are the hydraulic profile over the weir crest under varying flows, anchoring of the weir structure to prevent overturning, sliding, or scour during high flows, and protection of abutments (Charters 2013). Existing US barriers have used 1:100 year flood flows as the maximum design flow for full exclusion (Charters 2013), but there is currently no widely accepted design flow.

Figure 6-13: Wooden slots on the Fraser Spring built barrier. Credit: Sjaan Bowie.

A variety of overhangs have been used in built barriers to exclude invasive jumping fish and/or climbing fish species (Figure 6-6; Figure 6-13). Grated or bar structures added to physical structures provide the opportunity for allowing climbing diadromous native fish and/or limiting certain sized fish or species. If possible, a ≥500 mm overhang is thought ideal to inhibit jumping. There have been many failed attempts to create a kōaro barrier, however, a solid plate has been used successfully in Waipori tributary in Otago where the invasive climbing native fish kōaro is impacting on dusky galaxias and need to be excluded (Figure 6-6) (Tobak in prep). This has been the third attempt to design a kōaro barrier at this site. This successful lip has a number of design aspects that have aided its success including:

- It is made of aluminium as it resists corrosion, is cheaper, easy to work with, is light and transportable while still being strong.
- The perched lip was designed to:

- Be as wide as possible to prevent any water tracking along the lip and any wetted margin forming under any flow conditions. Topside panels on either end of the lip were added as an additional feature to stop water if it did track along the top during rain or splashing events.
- Be deep enough to keep a strip of concrete beneath it dry (either side of the main flow) under all flow conditions, but not too deep that water and any debris coming down stream could damage the barrier or get stuck.
- Be placed as high above the water surface level downstream as possible to stop algae or other things bridging the barrier and to stop any possible jumping opportunities.
- Have a 90-degree angle and additional thin downward facing lip with a drastic change in angle to discourage kōaro climbing.
- Have support struts on the topside of the barrier to keep the underside as flat as possible.
- Ensure a tight seal against the concrete and stop water passing behind the barrier.

6.6 Conclusion

Experience to date has indicated that full and partial exclusion built barriers can be effective, particularly when the follow features are included:

- Drops >1-1.5 m. However, if this fall height is not possible, increased focus must be placed on incorporating other features such as overhangs, screens or non-physical barriers (e.g., shallow, high water velocity) to compensate for lower fall heights.
- Downstream apron >2 m length that creates an area of fast water velocity and low water depth to inhibit invasive species jumping.
- Upstream backwater effects are minimized by setting the barrier within a stream reach with reasonable slope. Substrate or other structures could also be added to establish and maintain shallow habitat (e.g., add large rocks or a concrete pad).
- Scour protection downstream and to the sides of the apron to cater for any hydraulic jump that may form, protection in high flows, and generally ensure the structure's integrity will be maintained over time.
- The barrier should be located where the channel is stable with a moderate slope. Waterways in highly erodible soils, steep stream beds and/or made up of very mobile substrates should be avoided where possible due to high erodibility and likelihood of barrier integrity being compromised over time.

Additional criteria that are worthwhile considering include:

- If silt and water build up upstream is of concern then a v-notch profile, drop log structure, a perched culvert, or a culvert pipe with stopper within the weir could be considered to provide for flushing and/or maintain a concentrated high water velocity under low flow conditions if required.
- Overhangs could be added to physical structures to inhibit jumpers and or climbers (> 500 mm).

The importance of these different design criteria varies depending on species being excluded, species and habitat being protected and the general environment. Thus, it is important to understand the objective of the barrier before finalising any design and to obtain input from relevant experts on appropriate designs.

7 Monitoring fish passage success

Fish passage monitoring requirements will vary depending on site characteristics and the structure or remediation design implemented at a site. At sites where proven best practice designs have been implemented, or at low value or low priority sites, the monitoring needs may be relatively low. At high value or high priority sites, or sites where unproven designs are used, more robust monitoring is recommended.

Even when best practice guidelines are followed, a well-designed monitoring and maintenance programme will help to ensure the structure remains fit-for-purpose, and meets the project objectives and performance standards. Furthermore, evaluating the performance of a structure or fish pass can inform the level of mitigation that might be required to overcome poor passage efficiency at a structure. Well-designed monitoring programmes also help to increase knowledge of the function of different fish passage solutions and inform future improvements in design. Following the installation of an instream structure it is valuable to implement an appropriate monitoring and maintenance regime, whether it is a new structure or an existing structure that has been remediated.

Monitoring is the only way to understand how well a structure is working and to ensure that any reduction in fish passage caused by a structure is not adversely impacting upstream communities. It is particularly important to understand these things under situations such as:

- High value fish communities or ecosystems are present upstream of the structure.
- Unproven designs are being used.
- Proven designs are being used in novel situations.
- Retrofit solutions form only one component of an instream structure.
- Multiple structures exist within a waterway causing cumulative effects.
- Selective barriers are being used to manage the movement of undesirable species.

The appropriate type of monitoring programme in any situation will be contingent on the design of the structure, ecological objectives and legislative requirements. A range of options are available, but the two approaches recommended for evaluating fish passage success at an instream structure are: a before-after-control-impact (BACI) survey, and an in-situ mark and recapture study. Other methods such as biotelemetry studies and fish counters can also be utilised, but they generally require a higher investment in resources and have severe limitations in monitoring small bodied fish with a slim morphology (i.e., juvenile galaxiids). Simpler methods such as visual checks can also be used, but can be subject to observer bias and a lack of reproducibility. As such, this section focuses on BACI surveys and mark and recapture studies, which have the widest applicability for monitoring upstream fish passage with New Zealand species. The main benefits and drawbacks of a range of approaches are outlined in Table 7.1. Pairing BACI surveys with mark and recapture trials will provide the most robust assessment of passage efficacy for an instream structure, and would be the recommended approach for initially ensuring any new instream structure or remediation is fit-for-purpose. Once sufficient evidence is available to have confidence in the effectiveness of particular solutions and the circumstances under which they are suitable, the need for comprehensive monitoring may be reduced.

Table 7.1: The main benefits and drawbacks of various monitoring approaches.

Monitoring	Benefits	Drawbacks
BACI survey (e.g., electric fishing or spot lighting surveys).	Documents changes to fish communities upstream of the remediated structure following intervention (e.g., structure removal or installation).	Can take several years to determine if the remediation is effective.
	Minimises handling and stress to fish species.	If the retrofit is unsuccessful in promoting fish passage no information is provided on which component of the remediated structure is still problematic.
Mark & recapture study (e.g., stain and release).	Can be used to test different components of an instream structure independently and collectively.	Fish are subjected to handling and stress, which may affect passage success.
	Immediate results on the effectiveness of the solution.	Does not document changes in upstream fish communities.
		May require permits from MPI or DOC for the transfer and release of fish.
Biotelemetry (e.g., PIT, acoustic and radio tagging).	Timing and location of fish movements and behaviour can be captured.	Tags too big for some species and/or life stages and may alter behaviour.
	Remote data capture possible.	Battery life of tags may not be sufficient.
		Tags and antennae can be relatively expensive.
Fish counters	Minimises handling of fish.	Does not document passage failure.
	Can be low cost.	Does not document changes in upstream communities.
Video and acoustic cameras	Avoids handling of fish.	Video processing can be laborious.
	Can be relatively low cost.	Ineffective in water with poor visibility.
	Can provide semi-automated monitoring of target species.	Generally restricted to enclosed areas and does not document changes in upstream communities.
Visual checks	Quick and cost-effective means of identifying potential problems.	Ineffective at quantifying passage success rates.
		Does not document changes in upstream communities.

7.1 BACI survey

Where the objective is to evaluate the effects of improved connectivity on upstream fish communities, the recommended long-term approach to monitoring is to utilise a before-after-control-impact (BACI) survey design. This is where fish surveys are undertaken both downstream (control) and upstream (impact) of the structure (assuming the focus is on upstream migration), before and after remediation is carried out. Before and After sampling will determine how the installation of a structure or structure remediation changed the fish community through time relative to its historical condition. Control and Impact sampling will allow effects of the structure to be discerned from natural variability, stochastic events, and underlying trends in fish populations in the wider area. The BACI survey design is widely used for environmental impact assessment.

7.1.1 BACI methodology

A minimum of one survey reach upstream and one survey reach downstream of the structure is required for a BACI survey. As far as practicable, the two survey reaches should have similar habitat types and be of a similar size. This helps to minimise the potential influence of habitat availability and stream size on differences in fish communities between the control and impact sites. Consideration should also be given to locating the downstream survey reach slightly away from the immediate vicinity of the structure. Upstream migrant fish may aggregate immediately downstream of a barrier as they attempt to move upstream, so if the downstream survey reach includes these aggregations, fish population estimates can be biased and over-exaggerate the relative differences in fish community composition.

A range of sampling methods can be utilised for BACI surveys including electric fishing, netting and trapping, or spot lighting. The most appropriate method will depend on the characteristics of the site and the objectives of the monitoring. Electric fishing is typically considered the least biased sampling method for capturing the full range of species present and is, therefore, recommended for assessing changes in fish community composition where practicable.

When undertaking sampling as part of a BACI survey, regardless of what method is used it is critical to ensure that data are collected in a consistent, standardised and reproducible way. This means that for both the control and impact reaches, and before and after remediation:

- sampling is carried out using the same method at each survey,
- the same sites are used each survey,
- sampling effort is equivalent between reaches and surveys (i.e., the same area is fished), and
- sampling is carried out under similar conditions (e.g., similar flows) and at the same time of year at each reach and survey.

The National Freshwater Fish Sampling Protocols (Joy et al. 2013) provide a suitable sampling methodology for identifying changes in species composition over time. Guidance is provided on standardised approaches for electric fishing, netting and spot lighting. However, there are two caveats to utilising the protocols suggested by Joy et al. (2013):

Stop nets. The standardised electric-fishing protocol does not utilise stop nets at the start and end of the survey reach. Recent works by Crow and Jellyman (2014) have indicated that population estimates generated without stop net catches will underestimate fish abundance by 12-25%

depending on the time of year. Consequently, utilising stop nets will provide a more accurate representation of the fish community at the survey sites. This is particularly important where shoaling fish such as inanga are key target species.

Fish density assessment. The Joy et al. (2013) standardised electric-fishing protocol utilises a single pass, which is a semi-quantitative method. Consequently, the results generated are the relative abundance of fish species, which is not equivalent to fish density and can only be used for a relative comparison at a site over time. If the objective is to quantify changes in fish numbers over time in response to changes to a structure, multi-pass depletion fishing is required to generate population estimates and true estimates of fish density. This allows a quantitative comparison of fish communities before and after remediation of the passage barrier within and between sites, and improved detection of population trends over time. Should multi-pass depletion fishing be carried out, the recommended protocol is as follows:

- Utilise a 50 m reach at each site.
- Set stop nets at the top and bottom of each reach.
- Carry out multiple electric-fishing passes until there is at least a 50% reduction in the catch of the main fish species compared with the previous pass. Generally, three passes are the minimum necessary.
- Fish and habitat information (e.g., fish lengths, wetted stream widths) should still be collected as detailed in Joy et al. (2013), but with five 10 m sub-reaches assessed instead of ten reaches.

For three pass depletion fishing, population estimates for each species in the reach can then be calculated using the explicit approximation of the maximum likelihood formulae from Cowx (1983):

$$N_o = \left(6X^2 - 3XY - Y^2 + \left(Y \times \sqrt{\left(Y^2 + 6XY - 3X^2\right)}\right)\right) / \left(18 \times \left(X - Y\right)\right) \quad (12)$$

Where N_0 = population estimate, X = $2c_1 + c_2$ and Y = $c_1 + c_2 + c_3$ and c_n = the number of fish captured in pass *n*. Population estimates for multiple pass fishing surveys can also be calculated using the method of Zippin (1958) as executed in the removal function (http://www.rforge.net/FSA/) in R (http://www.R-project.org).

The density of each fish species in each section can then be calculated by dividing the population estimate by either the length of stream fished, to give the number of fish per linear metre of stream, or the stream area, to give the number of fish per metre square.

7.1.2 Frequency and timing

As recruitment of diadromous fish species can show annual variation, and migrations of juveniles tend to be seasonal, it can take several years of monitoring to detect any change in biodiversity and fish abundance attributable to changes in a structure. At any given site, there is also considerable temporal variation in most fish species' abundances. To help account for this, we recommend annual surveys in the same month each year until results are clear. Where possible it is recommended that surveys should be carried out between December and April inclusive (Joy et al. 2013).

The ability to statistically detect differences between the control and impact reaches in BACI surveys is influenced by the number of samples overall, and the balance of the study design, amongst other factors (Smokorowski and Randall 2017). Having the same number of samples both before and after the impact is preferable, with a minimum of three surveys prior to and after the impact recommended. Regular monitoring (i.e., every year) is also recommended over periodic or irregular monitoring (e.g., 1, 3 and 5 years post-impact) (Smokorowski and Randall 2017). It is recognised that practicalities and budget limitations restrict the opportunity to undertake comprehensive monitoring at all sites, and efforts should be prioritised towards sites of significant value or for proving novel designs. Use of quantitative multi-pass survey methods will enhance the ability to detect real changes in fish numbers over time compared to single-pass survey methods. Consideration should, therefore, be given to this when deciding on an appropriate sampling strategy for a BACI study.

7.2 Mark and recapture study

Mark and recapture studies allow quantification of the proportion of fish that pass a structure (i.e., passage efficiency). This information is valuable as it allows the relative performance of different structure types or fish passage solutions in a given situation to be established. This is essential to optimising fish passage outcomes at a site because the best solution for optimising fish passage can be more readily identified.

A mark and recapture study is recommended to:

- establish the performance and operating range of a fish passage solution that is to be installed across a range of sites,
- quantify the effectiveness of a solution that has not been demonstrated in practice, or
- to evaluate the relative influence of different components of a structure on overall fish passage success. For example, remediation of perched culverts commonly entails retrofitting a fish pass to the culvert outlet, yet the culvert barrel or transition from the fish pass to inside the culvert may still represent an impediment or barrier to certain fish species.

Because this type of study requires the stream to be barricaded at the top and bottom of the test reach, it is difficult to carry out in large non-wadable rivers and streams, or streams with high discharges and water velocities. For larger, high flow systems a BACI survey using nets and traps would be more applicable.

7.2.1 Target species

To ensure the fish pass is effective for all target species, mark and recapture trials should focus on the weakest species that requires passage. If passage of swimming fish is desirable, juvenile inanga are the benchmark species to use if present in the catchment. If passage of climbing fish is the objective, then juvenile redfin bullies are considered the least adept climbing species. If redfin bullies are not present in the catchment, then utilise juveniles of the weakest climbing galaxiid(s) present. Of the four diadromous galaxiids capable of climbing, their ability to surmount instream obstacles in ascending order would be: giant kōkopu, shortjaw kōkopu, banded kōkopu, and kōaro. As obtaining large numbers of identifiable shortjaw and giant kōkopu whitebait is difficult and/or costly, either banded kōkopu or kōaro juveniles are recommended.

7.2.2 Fish capture and maintenance

It is important to test the life-stage of the target species that is expected to be present at the instream obstacle. For example, the perched culvert on Kara Stream, Upper Kingston Road, Manawatu (described in the case study in Appendix I), is more than 30 km from the sea. Consequently, inanga reaching these culverts will be pigmented, feeding fish (post-whitebait/juvenile) with stronger swimming abilities than fresh-run whitebait. In this regard, the site of capture for test fish should be representative of the test location.

It is desirable to capture test fish using nets and traps rather than electric-fishing. This is to minimise the physiological damage to fish that is likely to influence passage performance.

To reduce stress and increase performance of the test fish, it is recommended to hold all fish in the stream they are to be tested in. This is because previous trials carried out by NIWA have indicated that fish held in a different water supply to that of the test system, display reduced upstream movement. This loss of motivation could relate to detectable changes in water quality. We recommend holding fish in purpose built live-bins that provide an adequate transfer of fresh aerated stream water (Figure 7-1). Bins should be secured in a pool that provides deep water without excessive water velocities (Figure 7-1). Ensure the lids are cable tied onto the bins otherwise whitebait can push their way out. Test fish should be held for at least 24 hours to habituate and recover from capture and handling prior to colouring in the dye solution. Although experimental releases should be timed with appropriate weather and flow conditions, it is advisable to not hold fish for longer than a week before using in trials.

Figure 7-1: Live-bins deployed in Kara Stream to maintain inanga for fish passage trials. Inset shows close up of live-bin.

7.2.3 Fish marking procedure

Mark test fish by immersion in a solution of Rhodamine B[5] or Bismarck Brown[6]. By colouring fish in both dyes, it provides two replicates of test fish that can be trialled simultaneously, under the same environmental conditions. In the case study of the Upper Kingston culvert (Appendix I), where no inanga could be captured in Kara Stream at the time of carrying out the mark and recapture trials, unmarked inanga could also be released as a third replicate. These fish also act as a control for the marked fish as they have not had the additional stress of staining, and are less visible to predators. Unmarked fish should only be used as test fish in situations where these fish are not naturally occurring in high numbers and, therefore, cannot infiltrate the test reach and confound results.

In a trial evaluating fish passage through a standard single culvert in a wadeable stream, between 100 and 200 fish per replicate would typically be used. However, if only low numbers of test fish are available (e.g., such as banded kōkopu whitebait) then using 30-50 fish per replicate will suffice. At more complex structures, or structures in larger streams (e.g., a weir across a stream), it may be necessary to increase the number of fish used per replicate in order to increase the probability of capture during the trial.

[5] http://www.sigmaaldrich.com/catalog/product/sigma/r6626?lang=en&region=NZ&gclid=Cj0KEQiAwPCjBRDZp9LWno3p7rEBEiQAGj3KJgIsyxGXuruPdLVT5O5k7MEP9-rFYmNe--7qRJcTBOIaAkMt8P8HAQ

[6] http://www.sigmaaldrich.com/catalog/product/sigma/15000?lang=en&region=NZ

To stain fish:

- In the shade adjacent to the stream, set up a separate bin containing 50 litres of stream water (to stain up to 500 fish) for each dye solution.
- To increase survival and buffer the solution, add aquarium salts (sold in pet shops to make salt water) to produce a salinity of c. 15‰.
- Add 10 g of Rhodamine B (0.2 g/L) or 2.5 g Bismarck Brown (0.05g/L). Wear gloves when handling both dyes. Refer to the MSDS for each compound to ensure safe practices are adhered to. Rhodamine B colours fish pink, and Bismarck brown colours fish orange (Figure 7-2).

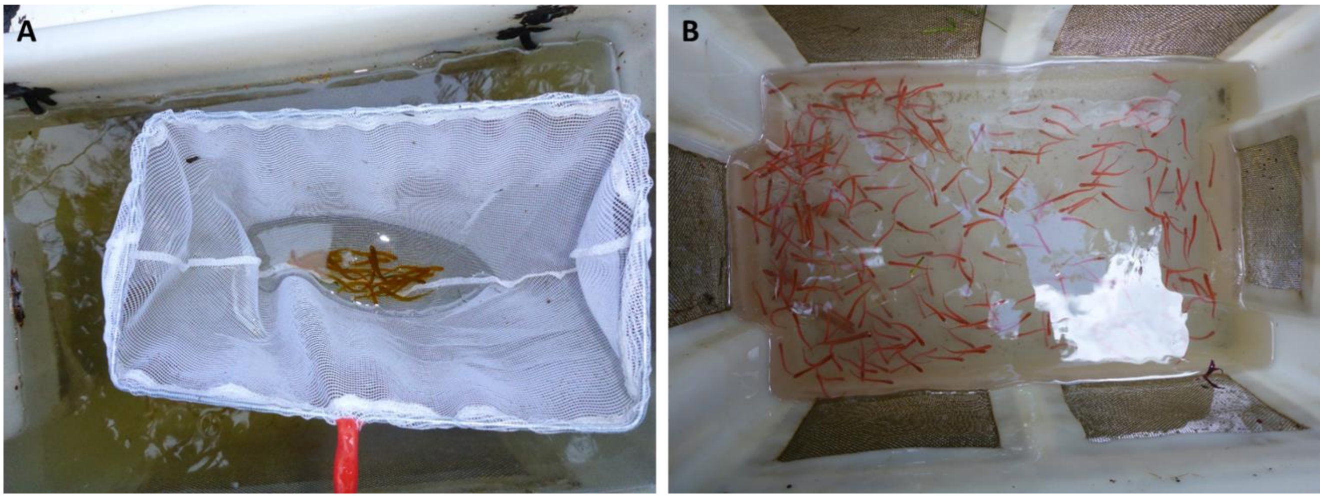

Figure 7-2: Fish coloured orange with Bismarck Brown (A) and pink with Rhodamine B (B).

- Aerate the solution well with a portable air supply system. A dive cylinder and adapted regulator or portable 12 volt air compressor unit would be suitable.
- Determine the stream water temperature and add ice as necessary to the dye solutions to maintain the water at ambient stream temperature.
- For fish in Rhodamine B, remove after 2 hours, and for fish in Bismarck Brown, remove after 1 to 1.5 hours. Hold coloured fish overnight in live bins to recover before trials. After removing the fish, discard the waste solution onto the bank. Do not pour it into the stream.
- Wear gloves whilst removing fish, discarding waste solutions and cleaning bins and dip nets.

For each experimental trial, it is advisable to hold 10% of the marked fish in a live-bin as ‘control’ fish to verify mortality attributable to the colouring procedure.

7.2.4 Timing

A critical aspect of mark and recapture trials is timing. That is, carrying out the trials during base flow in the study stream, under a high pressure front that will limit rainfall and subsequent rises in stream discharge over the trial period. This is not only because the barricades and trap can get washed out, but also because fish species such as inanga may alter their behaviour during changing flow conditions, which will disrupt trial results.

7.2.5 Trial design

The trial design is dependent on the structure type and layout, and the objectives of the monitoring. In some cases, the objective will be to determine overall passage rates for the structure, while in others it may be to evaluate fish passage rates across individual components of the structure (e.g., up a fish ramp and through a culvert). The overall passage rate for a structure is most relevant for evaluating the potential impact on upstream fish abundance. However, assessing passage rates across individual components of the structure provides greater insight in to the main constraints on fish movements across the structure and can be used to evaluate the effectiveness of specific mitigation actions that may target individual components of the structure.

When evaluating overall passage efficiency for a structure, a relatively simple trial design is required with the marked fish to be released on one side of the structure (downstream for looking at upstream migrants) and traps set on the other side of the structure to recapture the fish that successfully traverse the structure (see Section 7.2.6 for more detail on setting traps).

Trials targeting evaluation of individual structure components will require more complex study designs depending on local site layout and the nature of the different components to be evaluated. A common example application would be to evaluate the success of retrofitting a perched culvert with a rock ramp at the culvert outlet (e.g., see Appendix I). In this situation, it would be beneficial to firstly determine the proportion of fish successfully ascending the rock ramp and, secondly, to establish the proportion of those fish that subsequently successfully pass through the culvert barrel. If a resting pool is present between the rock ramp and the culvert outlet, this provides a means of easily separating the different components of the structure to evaluate them independently (i.e., fish can be trapped in the pool and/or at the culvert inlet). For structures lacking a resting pool separating the components, the recommended approach would be to:

- examine fish passage through the culvert only, and
- examine fish passage over the entire structure (e.g., rock ramp and culvert).

This will enable the relative influence of the culvert on overall passage success to be controlled for, allowing the effectiveness of the remediation to be determined. In a similar way, where multiple culvert barrels are present the trial design must also be adapted. The recommended approach is to test all the culverts and any associated retrofits collectively to determine what proportion of fish select, and successfully pass, each culvert barrel. For these tests, a trap must be deployed at the inlet (upstream end) of each culvert barrel.

7.2.6 Stop nets and trap

Install a stop net barricade at the bottom of the test site to prevent fish escaping downstream or stream fish moving upstream. A seine net or whitebait mesh form suitable barriers (Figure 7-3). It is important to dig the bottom of the mesh into the substrate and cover with boulders to try and create a secure barrier. If possible, the top of the mesh can be secured to trees on the stream banks (Figure

7-3B), otherwise waratahs or stakes will need to be used (Figure 7-3C). Installing a second net downstream as a back-up is also advisable (Figure 7-3). The barrier should be installed below a pool at the base of the structure to provide fish with a low velocity area to rest before ascent. Note: it is desirable to create a pool at the base of any remediated fish migration barrier (Figure 7-3B & C) to dissipate energy and prevent erosion.

At the top end of the test site, a whitebait trap and barrier net also needs to be installed (Figure 7-4). Ensure the trap is weighted down to avoid any movement with increases in water flow. For structures with multiple culverts, a separate trap and whitebait mesh should be used at the inlet of each culvert. Once nets and traps are set it is preferable to minimise disturbance of the stream bed within the barricaded area to reduce the likelihood of debris being mobilised and clogging the nets.

Figure 7-3: Downstream barricades installed in Kara Stream during the inanga passage trial. A - C Barrier nets deployed during the rock-ramp trial. D, Barrier nets deployed for testing inanga passage through the culvert independently of the rock-ramp.

Figure 7-4: Whitebait trap installed at the culvert inlet in Kara Stream.

7.2.7 Measurements

Flow

It is important to record the flow at the time of the trials. If the study stream does not have a water level recorder installed, a flow gauging can be carried out on each day the trials are being undertaken.

Water velocity

It is also advisable to measure the average water velocity over each section of the instream structure (e.g., culvert and rock-ramp). This will help inform or predict potential problem areas for fish passage, as well as provide some comparative information between sites. The most commonly used method to calculate average water velocity is to time how long a float takes to travel a set distance. A mandarin or orange makes an excellent float as it is easy to see, can withstand knocking into rocks, and it floats almost submerged so the wind does not influence its movement. It is advisable to measure the average water velocity on each of the trial days.

Trial length

As each instream structure and stream system is different, the appropriate trial length will be determined during the monitoring, but based on results from previous studies, it is recommended that fish are given 24 hours to pass an instream structure. The trap can be inspected after 12 and 24 hours to determine if extending the trial to 36 hours is warranted.

7.2.8 Sampling protocol

- Initiate trials in the early morning. This may require the barricades to be installed the previous day.

- Prior to releasing the marked fish, electric-fish the test reach to remove any resident fish that could confound trial results. Utilise multi-pass fishing until no fish are captured.
- Release the marked fish at the base of the structure inside the barricade (Figure 7-5).
- Check barrier nets periodically throughout the trial to ensure they remain functional. However, do not walk adjacent to the stream edge to prevent spooking the fish.
- If testing passage over a structure with multiple components, i.e., a culvert and rock-ramp, at the conclusion of the trial install a temporary stop net at the base of the culvert to prevent both upstream and downstream fish movement between each section of the structure.
- Empty the upstream trap into a bucket or fish bin to hold fish for processing.
- Electric-fish each component of the structure separately, in a downstream direction to collect fish that failed to pass. Use multi-pass fishing until no fish are collected over several passes. Keep fish collected from each section of the structure in a separate bucket.
- Anaesthetise fish in each bucket and record their length and colour. If time allows, record the length of every recaptured fish, otherwise ensure lengths are measured for at least 50 successful and 50 unsuccessful fish from each replicate (e.g., pink, orange and unmarked). This will determine if fish size influenced passage success over the instream structure. Carry out counts of the remaining fish where lengths are not measured.

Figure 7-5: Releasing marked inanga below the rock-ramp in Kara Stream, at Upper Kingston Road.

7.3 Defining success

The performance of any fish pass will vary with the type of pass and target species, as well as specific site conditions. As highlighted with the case study at Bankwood Stream (see Appendix I), fish passage performance can vary according to the size and condition of the fish as well as with environmental variables such as flow. The relationship between passage performance and flow will likely change both throughout the migration season and between years, and this needs to be considered when interpreting passage success. Although the efficiency of a fish pass is a quantitative measure of its performance, it needs to be considered in the context of the efficiency required to maintain upstream communities. In general, for any site and species, the two main factors influencing the required efficacy of passage past the structure will be the carrying capacity of the upstream habitats and the number of recruits reaching the base of the structure. In Bankwood Stream, approximately 30% passage efficiency of inanga past the culvert is maintaining species such as smelt and inanga in the upstream habitats. However, because of an additional migration barrier to non-climbing fish species, only around 160 m of linear stream is currently accessible to swimming fish species, meaning that carrying capacity is limited.

The results should also be considered in a catchment context. The cumulative effect of individual fish passes or structures can have a multiplicative impact on the proportion of successful fish recruits reaching upstream habitats. This is illustrated in Figure 7-6 for several hypothetical examples of multiple structures with passage efficiencies of 10% – 90%. For example, if upstream migrants are required to pass a series of five culverts, where passage efficacy at each culvert is 50%, then only 3.1% of fish will successfully reach upriver habitats. Consequently, passage efficiency at each individual structure may need to be higher to account for the cumulative effects of multiple structures on the fish community composition as a whole.

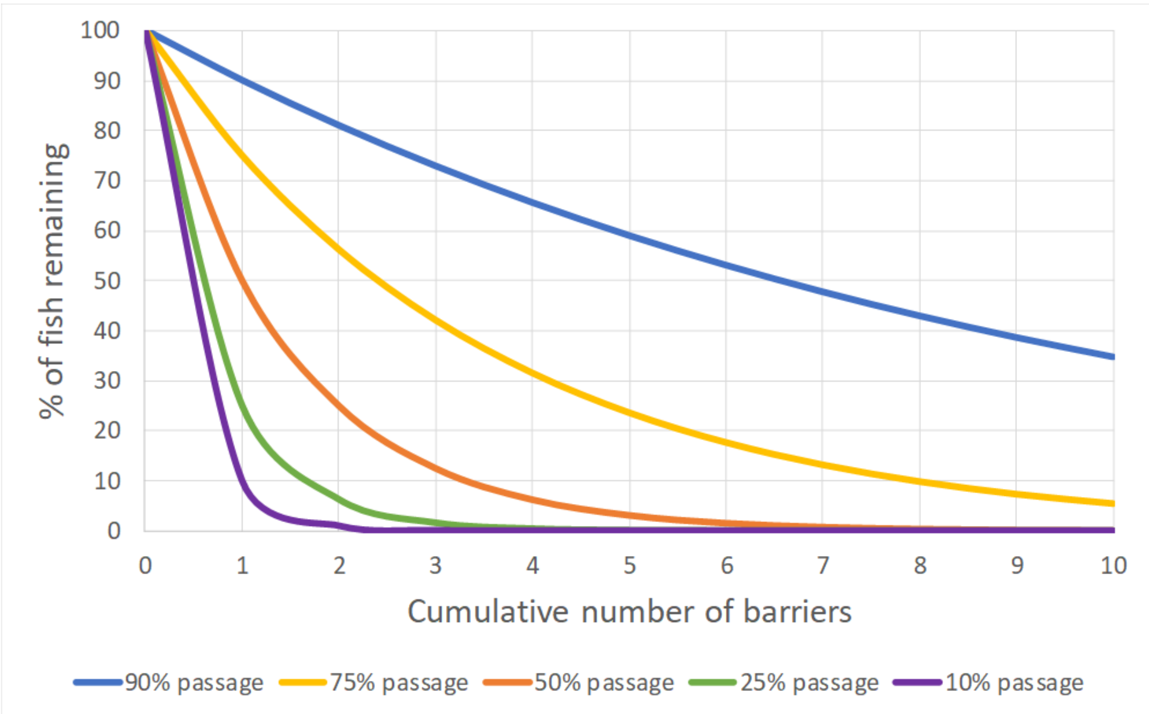

Figure 7-6: Illustration of hypothetical cumulative effects of multiple instream barriers with varying passage rates.

Too few fish pass solutions have been monitored at present to provide guidance on the required passage efficiency necessary to maintain upstream fish communities relative to distance inland and carrying capacity of different sized catchments. Consequently, moving forward it will be important to carry out a robust monitoring programme (i.e., pairing BACI surveys with mark and recapture trials) for new or remediated instream structures to improve determination of the efficiency required to define successful passage across a range of structures and situations. The appropriate threshold will likely vary depending on life stage, stream habitat availability, location in the catchment and the species present.

8 Knowledge gaps & research needs

The information in these guidelines is based on current state-of-the-art knowledge regarding fish passage needs in New Zealand. However, it must be recognised that this knowledge is incomplete and constantly evolving. The following section highlights some of the key knowledge gaps and technical challenges associated with advancing fish passage outcomes in New Zealand.

To design structures that provide effective fish passage, there is a need to understand the life-cycles, habitat preferences, behaviours and swimming abilities of the fish species to be provided for. For many of New Zealand's native fish species there are still notable knowledge gaps regarding basic ecology and the capabilities of even some of the most common species. Furthermore, in contrast to the salmonid species that have historically been the focus of much of the fish passage research in the Northern Hemisphere, there is a significant number of species in New Zealand that undertake their main upstream migrations as weak-swimming juveniles. Consequently, many of the traditional fish passage designs and state-of-the-art research methodologies that have been developed in the Northern Hemisphere are largely ineffective for our native species due to their differing biological characteristics and ecology. This presents challenges for developing robust and scientifically informed guidance for supporting fish passage management in New Zealand.

8.1 State-of-the-art in fish passage research methods

A variety of experimental and field-based approaches have evolved in the field of fish passage research. Much of this innovation was originally driven by the need to develop fish passage criteria for large-bodied salmonids and is consequently orientated towards characterizing their movements and behaviour. More recently, interest has increased in understanding the requirements of other fish taxa, such as cyprinids and anguillids, which has resulted in further methodological developments. However, many of the approaches remain most suited to large-bodied fish.

Biotelemetry methods have been fundamental to enhancing our understanding of fish behaviour in and around instream structures and fishways. Passive Integrated Transponder (PIT) tags have been widely used due to their relatively low cost and suitability for a wide range of species. The small 8-12 mm PIT tags have further boosted the scope of this technology for tracking smaller fish, but for small-bodied fish <60 mm in length, the size of the tags still limits their applicability (Baker et al. 2017). Acoustic and radio tagging offer the opportunity to actively track individual fish behaviour, providing more detailed information on the response of fish to different stimuli, but the battery life and physical size still limits the size of fish able to be tracked (Jellyman 2009). For large-bodied fish, the combination of high resolution acoustic tracking with hydraulic modelling is proving to offer valuable insights into fish behaviour at and around barriers and fishways (Piper et al. 2015). New techniques such as accelerometery and electromyogram telemetry offer the opportunity for greater insight into swimming behaviour and the energetics of fish in fishways (Silva et al. 2015).

Advances in technology for measuring the physical characteristics of flow within and around structures and fishways offer the opportunity to better understand fish behaviour under different hydraulic stimuli. Acoustic Doppler velocimetry (ADV) and particle imaging velocimetry (PIV) offer the ability to characterize hydraulics at higher spatial and temporal resolutions than ever before. When combined with videography or biotelemetry, this has helped to gain greater insight in to the significance of turbulence and three-dimensional flow characteristics for understanding fish behaviour and their ability to pass different structures (Liao et al. 2003b; Silva et al. 2012).

Greater computational capabilities have also opened up options for improved modelling studies to help inform the design of instream structures and fishways. Computational fluid dynamics (CFD) offer the ability to simulate hydraulic dynamics in two and three dimensions, helping to understand the evolution of flow fields under different flows and structure designs. The capability to link this to fish behaviour through bioenergetic and agent based modelling allows an improved mechanistic understanding of fish responses to hydraulic and physical stimuli, and therefore in how instream structures can be improved to enhance their passage efficiency (Weber et al. 2006; Gao et al. 2016).

What is clear is that there is a need to adopt multiple complementary approaches for studying the biological requirements that define the design requirements of instream structures for providing fish passage. There is a need to integrate both field and laboratory based experimental work with in-situ empirical observations of fish behaviour. Furthermore, an integrated ecohydraulic approach that combines both biological and engineering techniques is required to optimize outcomes (Silva et al. 2018). To date, much of the development in this field has occurred in the Northern Hemisphere, with a focus on large-bodied, strong swimming fish species such as salmon. There has been recent progress in adapting some of these methodologies to weaker swimming and smaller fish, but the contrasting biological characteristics of many of New Zealand's fish species presents significant challenges for transferring these methods and advancing the science of fish passage research here.

8.2 Challenges for fish passage research and management in New Zealand

Franklin and Baker (2016) summarised some of key challenges for advancing fish passage research in New Zealand. For our most common and widespread fish species, we generally have a good basic understanding of their life-histories and key migration periods. However, we still lack information on key life-stages of many of our species, we have poor understanding of the dynamics of migration, and we are still discovering new species. For example, the spawning habitat of the pouched lamprey (*Geotria australis*) and the largest of the galaxiid species, the giant kōkopu (*Galaxias argenteus*), have only been discovered in the last five years (Franklin et al. 2015; Baker et al. 2017). There were also fourteen taxonomically indeterminate fish taxa (i.e., still to be officially described) included in the most recent national threat rankings that we know very little about (Goodman et al. 2014). These gaps in knowledge of the fundamental ecology of key species makes it difficult to set well targeted objectives and performance standards for instream structures, and subsequently to develop appropriate design criteria for providing effective fish passage.

The main upstream migration for many of our native fish species most frequently occurs during the juvenile life-stage, when fish are small-bodied and 15-60 mm total length (McDowall 2000). This presents two particular challenges for fish passage research. Firstly, due to the small size and weak swimming ability of these fish at the time of migration, seemingly small obstructions in waterways can significantly impede upstream passage. Baker (2003), for example, showed that fall heights of as little as 100 mm restricted migrations of juvenile common bully (*Gobiomorphus cotidianus*) and inanga (*Galaxias maculatus*). Finding solutions for overcoming low head barriers, therefore, becomes extremely important. Secondly, the small body size of fish at the time of migration means that biotelemetry methods that have been widely used to advance fish passage research in the Northern Hemisphere are largely excluded as an option for studying fish behaviour during migration for many species (Jellyman 2009). The advent of smaller tags has increased the scope for adopting biotelemetry methods for investigating smaller fish species (Baker et al. 2017). However, alternative methods are still required for understanding in-situ behaviours of juvenile migrants.

A significant challenge in developing these guidelines has been the limited knowledge of swimming capabilities and behavioural responses to hydrodynamic stimuli for native fish. Variation in swimming performance between fish species and life-stages is high and, therefore, presents one of the main challenges in catering for passage of multi-species assemblages. There are few published studies of swimming performance for New Zealand fish species (Mitchell 1989; Nikora et al. 2003; Plew et al. 2007), and these are limited with respect to the number of species, life-stages and environmental conditions tested. There is even less information regarding how fish respond to different hydraulic conditions (e.g., turbulence, accelerating or decelerating flow) and how they behave when faced with different environmental cues. The limitations of these data constrain our ability to define robust design criteria for instream structures suitable for effectively passing native fish species and increases reliance on interpretation of expert knowledge. Furthermore, it limits our ability to develop mechanistic models of fish performance and utilise bioenergetics approaches that can help improve understanding of fish behaviour.

A relatively unique characteristic that has evolved in some of our fish species is the ability to climb wet surfaces during the juvenile life-stage. New Zealand's waterways are often characterized as being relatively short and steep, and it is thought that the development of the capability to climb may be related to the need to overcome the challenges of migrating inland to adult habitats in the middle to upper reaches of these streams. The utilization of this alternative form of locomotion presents a challenge in terms of understanding and characterizing the different climbing strategies. It also requires a different way of thinking about optimizing fish passage, with different features required to take advantage of this strategy that may not be consistent with traditional approaches focused on designing for fish swimming capabilities.

Another critical challenge is how to manage the process of reconnecting waterways in New Zealand, while also limiting the dispersal of exotic species that compete with or predate protected native fish. Trout are known to negatively impact native galaxiid fish species (McIntosh et al. 2010). There are numerous examples where natural migration barriers (e.g., waterfalls) are fundamental to protecting threatened native fish populations from the impacts of trout. There are also an increasing number of situations where artificial barriers are being used to prevent the invasion of trout to important habitats for threatened fish species. Developing selective barriers that allow passage of native fish, but limit movements of exotic species, is critical to protecting some of New Zealand's unique endemic biodiversity. However, this presents a real test given that trout and other exotics are generally more capable swimmers and jumpers than our native fish species.

8.3 Critical knowledge gaps

There are still many things for us to learn that will improve our ability to provide evidence-based solutions for maximising fish passage at instream structures in New Zealand. In a review of research needs carried out by members of the New Zealand Fish Passage Advisory Group, a number of key themes and associated knowledge gaps emerged. Those considered most critical to advancing fish passage management in New Zealand are summarised below.

8.3.1 Fish ecology, behaviour and capabilities

Improving our knowledge of the ecology, behaviour and capabilities of our native fish species is absolutely fundamental to achieving better fish passage outcomes. At the highest level, the key question is what are the ecological consequences of restricted and/or delayed fish passage? In the case where a structure is a complete barrier to fish migration, the consequences are simple to understand – fish are absent upstream of the barrier. However, where a structure is a partial barrier (i.e., it lets some fish through) or fish migrations are delayed by a structure, but not prevented, what are the implications for upstream fish populations? How many fish need to be able to pass to maintain sustainable upstream fish communities? If migration is delayed, what are the flow on effects in terms of fitness of the fish and their ability to successfully complete their life-cycle? While these are challenging questions to answer, they are important when trying to determine an appropriate balance between avoiding impeding fish passage and developing cost-effective instream infrastructure.

At the next level, our most critical challenge is trying to better understand the migration ecology of fish. What is the timing (seasonal or circadian) of key migrations (both upstream and downstream) for different life-stages of different fish species? What are the primary factors motivating fish to migrate (e.g., flow, habitat, pheromones, temperature) and that determine their behaviour during migration? Understanding these factors helps to set appropriate objectives and performance standards, and subsequently to design structures that create conditions that match those that fish are seeking out and responding to.

The other main research gap addresses the ability of fish to negotiate the conditions they experience as they approach and pass an instream structure. This includes improving understanding of both the physical capabilities of fish (e.g., how fast they can swim, how far they can climb, how high they can jump) and the factors that influence their behaviour as they approach and attempt to pass instream structures (e.g., attraction flows, water velocity gradients, turbulence).

8.3.2 Passage success at existing structures

Understanding how fish passage success varies at different structure types under different conditions is important for establishing the primary design features that influence fish passage. There are few studies that have attempted to evaluate this for New Zealand's main fish species. Improving our understanding of how different structure characteristics (e.g., length, slope, substrate, roughness) will help improve our ability to identify existing structures that impede fish passage and to better target efforts to develop structure designs that are less likely to restrict fish migrations.

A range of different solutions (e.g., baffles and fish ramps) are currently marketed in New Zealand as being effective for restoring fish passage. However, in the vast majority of cases they have received little to no biological testing, and there has been negligible post-installation monitoring to validate their effectiveness for passing fish. There is an urgent need to address this knowledge gap to avoid ineffective solutions being installed. The research effort should be focused on evaluating the passage efficiency under different conditions. These results can then be used to identify the key design features of different structures that either enhance or limit passage success.

8.3.3 Key design parameters for instream structures

As knowledge of fishes' capabilities and behaviour improves, it will enhance our ability to determine the primary design features of different structures that are most important in determining fish passage success. This information must then be translated in to a form that is consistent with methods used by engineers to design instream structures. This should include consideration of technical fish pass designs (e.g., vertical slot fishways) and how they can be adapted to make them suitable for New Zealand's native fish species.

8.3.4 Selective barrier designs

There is a need to balance restoration of connectivity with controlling the spread of undesirable invasive and exotic species. This requires that structure designs be developed that facilitate the passage of native fish species, while limiting or preventing the movement of the exotic species. This involves developing designs that exploit the differences in capabilities and behaviour that exist between native and exotic species. Research is required to determine these key differences and to translate them in to effective structure designs.

8.3.5 Downstream fish passage

This version of the fish passage guidelines has given relatively little consideration of the requirements for downstream fish passage. This is largely because the biggest impacts on downstream migrations of fish result from the development of large dams and intakes. However, particularly for eels, there is a significant gap in our ability to provide safe downstream migratory pathways at instream structures. The large size of our eel species when they begin their downstream migration means that they are suitable for studying with state-of-the-art biotelemetry methods. There is potential to make significant progress towards better understanding their behaviour by coupling these tracking techniques with high resolution hydrodynamic and individual based modelling techniques. Given the ongoing large scale trap and transfer of juvenile eels (elvers) above large dams and concerns over the future of eel populations, there is an urgent need to develop effective methods for enhancing the number of adults that are able to return downstream and contribute to the breeding population. Large numbers of eel fatalities have also been observed at some flood pumping stations due to inadequate screening, poor operation or lack of alternate safe migration pathways. Research is, therefore, required to improve outcomes at these sites.

8.4 The need for novel solutions and innovative approaches

In the face of continued development of waterways in New Zealand, there is a need for rapid progress towards developing robust and effective fish passage design criteria that cater specifically for the unique characteristics of diverse native fish communities. Due to some of the features identified above, direct transfer of existing state-of-the-art fish passage research methods will not always be possible. Consequently, there is a need to seek out novel and innovative approaches for advancing fish passage knowledge. Developing techniques for studying and characterizing the behaviour of small-bodied fish is a key priority and is fundamental to progressing fish passage research in New Zealand. Finding ways of capturing and exploiting the climbing capabilities of some species also offers the opportunity for new avenues of research. Taking advantage of this capability has been the basis of several studies in New Zealand that have resulted in novel solutions for enhancing passage of these fish species at instream barriers (Baker and Boubée 2006; David and Hamer 2012).

The development of innovative solutions to enhancing fish passage at instream structures is encouraged. However, it is important that the effectiveness of new solutions is evaluated and their operating range defined prior to widespread application. David et al. (2014b), for example, demonstrated the efficiency of using mussel spat ropes inside culverts to enhance passage of fish and shrimp, and subsequently provided guidance on the appropriate use of this solution (David et al. 2014a). There are a number of novel fish passage solutions currently in use in New Zealand that have not yet been robustly evaluated (e.g., Figure 8-1). Anecdotal evidence suggests that some of these solutions may provide some passage for some species and/or life stages where previously fish movements were completely blocked. Currently, there are no data that quantify their efficiency (i.e., the proportion of fish that pass) under different environmental settings (e.g., fall height, flow etc.,) in a way that can robustly inform their application.

Figure 8-1: Examples of novel fish passage remediation solutions for perched culverts. Left: An example of a novel fish ladder design. Right: Conveyor belt rubber being used as a fish ramp alongside mussel spat ropes.

We strongly recommend that the development of new solutions be well founded in sound ecological and hydraulic design principles. Investing in solutions that do not adhere to good-practice and reflect state-of-the-art knowledge can prove to be false economy because they fail to provide the right conditions for optimising fish passage outcomes. Consequently, there is a critical need to increase efforts to robustly evaluate the effectiveness of different solutions and to understand the circumstances under which they operate successfully. Once the effectiveness of a solution has been demonstrated (e.g., using the monitoring techniques described in Section 6), recommendations can be provided on suitable applications.

9 Glossary of abbreviations and terms

Amphidromous	Amphidromous fish are born in freshwater/estuaries, then drift into the ocean as larvae before migrating back into freshwater to grow into adults and spawn, e.g., banded kokopu.
Anadromous	Anadromous fish are born in freshwater, migrate to the ocean as juveniles where they grow in to adults before migrating back into freshwater to spawn, e.g., lamprey.
Ancillary structure	Ancillary structures include additional features such as headwalls, wingwalls and aprons that may be required to complete the construction of a primary structures such as a culvert or weir.
Apron	A hardened surface (usually concrete) placed at the inlet and/or outlet of a structure to protect the structure from erosion.
Attraction flows	The flow of water required to direct moving fish towards a fish pass or bypass channel.
Backwatering	The effect of backing up water in its course by an obstruction.
Baffles	A device used to modify and restrain the flow of water.
Bankfull discharge	The river flow that just fills the stream channel without overtopping the banks. This is generally considered the dominant channel forming flow.
Bankfull elevation	The water level at bankfull discharge.
Bankfull width	The wetted width at the bankfull discharge.
Broad-crested weir	A weir with a crest of significant thickness measured in the direction of flow.
Built barrier	An instream structure built with the explicit intent of restricting or preventing the movement of aquatic organisms.
Bypass structure	A structure used to facilitate fish movements around instream obstructions. They are often known as fish passes or fishways.
Catadromous	Catadromous fish are born in saltwater, then migrate into freshwater as juveniles where they grow into adults before migrating back into the ocean to spawn, e.g., longfin eel.
Critical shear stress	The minimum amount of shear stress exerted by stream flow that is required to initiate movement of substrate particles.
Culvert	A connection between two water bodies or parts of a waterbody, typically a pre-formed concrete tube located below roads or other constructions.
Denil fishway	A type of technical fishway consisting of a linear channel in which baffles are arranged at regular and relatively short intervals, angled against the direction of flow.
Diadromous	A category describing fish that spend part of their lives in freshwater and part in saltwater. Anadromous, amphidromous and catadromous are all sub-categories of diadromous.

Fish passage	The movement of fish and other aquatic organisms between all habitats necessary to complete their life cycle.
Fish passage design flow	The range of flows over which fish passage is required.
Ford	A shallow place in a river or a stream allowing one to walk or drive across.
Head drop	The difference between water levels upstream and downstream of a structure.
Hypoxia	Oxygen deficiency in the environment.
Impede	Delay or prevent by obstructing them; hinder.
Nappe flow	The term nappe refers to the sheet of water flowing over a weir crest. Nappe flow occurs when the sheet of water is not in contact with the weir structure (i.e., there is an air gap between the underside of the nappe and the downstream weir face).
Nature-like fishway	A bypass structure that mimics natural stream characteristics in a channel that bypasses a barrier.
Open channel design	A design process using the principles of open channel hydraulics. Open channel hydraulics is a branch of fluid mechanics dealing with the conveyance of water through conduits with a free surface (i.e., the surface of the water is in contact with the air and not under pressure).
Overshot weir	A weir where water flows over the top of the weir.
Peak design flow	The highest flow that a structure is designed to convey.
Pool and weir fishway	A type of fish pass consisting of a series of small dams and pools of regular length to facilitate the movement of fish around or over an obstruction.
Rheotaxis	An innate behaviour in fish that leads them to orientate themselves into the flow.
Rock-ramp fishway	A type of fish pass consisting of rock ridges and pools that mimics natural stream conditions to facilitate movements of aquatic organisms around or over an obstruction.
Shear stress	A measure of the force of friction from a fluid acting on a body in the path of that fluid.
Subcritical flow	Flow with a velocity lower than the wave velocity (i.e., surface ripples progress upstream as well as downstream). Downstream influences can cause upstream effects. Flow is typically deep and slow.
Supercritical flow	Flow with a velocity higher than the wave velocity (i.e., surface ripples do not progress upstream). Downstream influences do not cause upstream effects. Flow is typically fast and shallow.

Technical fishway	A category of fish pass generally characterised by a relatively formal structure typically dependent on quite strict hydraulic design criteria in order to provide conditions suitable for passage of the target fish species. Examples include vertical slot and denil fishways.
Undershot weir	A weir where water flows underneath a weir gate. These are sometimes referred to as sluice gates.
Vertical slot fishway	A type of fish pass consisting of a series of pools separated by walls with a narrow vertical gap allowing fish to pass between pools.
Weir	A barrier across the cross-sectional width of a river that alters the flow characteristics of the water and usually results in a change in the height of the river level.
Weir crest	The top edge of a weir that water overflows.
Weir face	The downstream sloping face of a weir.
Wetted margin	A shallow, low velocity area along the edges of the water.
Wetted width	The width of the river channel at the water surface.
Wingwall	A wall on a structure that ties the structure to the river bank.

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Appendix A Legislative context – who manages fish passage?

Note: This section was published prior to gazetting of the National Policy Statement for Freshwater Management 2020 and the Resource Management (National Environmental Standards for Freshwater) Regulations 2020. This section will be revised in a future update of the Guidelines. For information on the fish passage provisions in the National Policy Statement for Freshwater Management 2020 and the Resource Management (National Environmental Standards for Freshwater) Regulations 2020 please refer to the Ministry for the Environment factsheet.

All fisheries in New Zealand are generally governed by the Conservation Act 1987 (CA87), which includes the Freshwater Fisheries Regulations 1983 (FFR83) (subsidiary legislation administered under section 48(a) of the CA87), the Fisheries Act 1983, and specific responsibilities including protecting freshwater habitats (section 6(ab) of the CA87), and advocating for aquatic life and freshwater fisheries generally (section 53(3)(d) of the CA87). These functions are managed by a number of organisations including the Department of Conservation, Ministry for Primary Industries, and Fish and Game New Zealand. The Ministry for the Environment (e.g., National Policy Statements and National Environmental Standards) and Regional Councils also have freshwater management responsibilities under the Resource Management Act 1991 (RMA91).

Department of Conservation (DOC) and regional councils have specific responsibilities to manage fish passage in New Zealand waterways under the FFR83 and RMA91 respectively (see Appendix B). In the past, there was some confusion regarding potential duplication in these statutory requirements, however, an Environment Court decision (Re Auckland Regional Council [2002] NZRMA 241) identified no conflict between the general sustainable management provisions of the RMA91 and the more specific fish passage protection mechanisms of the FFR83. The decision identified they contained different purposes and, therefore, one did not take precedent over the other. This means that DOC's authorisations for fish passage under the FFR83 are required, regardless of any other consent (e.g., RMA91, Building Act) or landowner approvals which may be required.

In addition to specific fish passage requirements it should be noted that there are other statutory requirements that need to be considered in any proposals for development and management of physical structures. These include:

- Design integrity for intended purpose and on-going management of structures and assets (e.g., Building Act 2004, Railways Act 2005, RMA91, Local Government Act 2002).
- Land status (such as landowner approval for any works on their property and on special status areas, e.g., Reserves Act 1977).
- Protection of species and habitat, for instance section 26ZJ of the CA87 which provides that it is an offence if any works (e.g., installing a structure into a waterway) disturb or damage spawning grounds of any freshwater fish; or regulation 70 of the FFR83, which makes it an offence to intentionally kill or destroy indigenous fish (refer Appendix B).
- Fish salvage, which can often be required in construction projects within waterways. If, during any fish salvage or translocation, someone wishes to transfer and release fish into any freshwater, they are likely to require approval under section 26ZM of the CA87 and/or regulation 59 of the FFR83 (refer Appendix B).

- The requirement to manage for ecosystem health under the National Policy Statement for Freshwater Management (NPS-FM).

The purpose of the RMA91 is to promote sustainable management of natural and physical resources, while safeguarding the life-supporting capacity of air, water, soil and ecosystems, and avoiding, remedying and mitigating any adverse effects of activities on the environment. No person may undertake an activity that contravenes a national environmental standard or a regional rule unless the activity is allowed by a resource consent, or the activity is allowed for under other parts of the RMA91 (e.g., when water is required to be taken or used for individual's reasonable domestic needs, an individual's animal's drinking water, or for firefighting purposes). Under section 13 and 14 of the RMA, regional councils control effects relating to the use of water and waterways by placing restrictions on certain uses of beds of lakes and rivers (e.g., the use, construction and/or removal of structures in rivers and stream beds and/or avoiding, damaging or removing habitats of animals in, on or under the bed of a lake or river), and restrictions relating to water (e.g., the take, use, damming or diversion of water). Environmental effects relating to structures in river and stream beds are, therefore, controlled under the RMA91, and these include consideration of the habitat of aquatic and terrestrial flora and fauna, and fish passage (by implication).

Regional councils are responsible for implementing the requirements of the RMA91. This is primarily undertaken by developing regional policy statements, regional plans and the issuing of consents under the RMA91. Their fish passage responsibilities include managing and controlling the environmental effects of using freshwater, and managing waterways and flood control.

Regional policy statements provide an overview of the resource management issues of a region, and objectives, policies and methods to achieve integrated management of the natural and physical resources of that region.

Regional plans set rules governing the use of resources within the region, and no person may use land, water, air or the coastal marine area in a manner that contravenes a regional rule (for a permitted activity) without holding a resource consent. Rules implemented in regional plans can include the consideration of fish passage (e.g., requiring new and existing structures in waterways to provide fish passage), and protection of areas of significant habitats for indigenous fauna. Some regional plans required this for all structures, including those that existed before the plan was introduced.

Regional rules regarding fish passage currently vary across the country, so it is essential to refer to local regional plan policies and rules to understand local legislative requirements and responsibilities.

The National Policy Statement for Freshwater Management (NPSFM) is also implemented through the regional planning framework. Ecosystem health has been established as a compulsory national value under the NPSFM. The NPSFM sets out a requirement to maintain or improve ecosystem health (and other values) in freshwater ecosystems. Instream structures are a pressure on ecosystem health, disrupting the state of river connectivity, and impacting the status of fish and other aquatic communities (Ministry for the Environment and Stats NZ 2017). Consequently, as the requirements of the NPSFM are progressively implemented by national and regional government agencies, maintaining connectivity of waterways is likely to receive increasing focus.

Under the FFR83 (Part 6, Regulations 41-50), DOC has specific fish passage responsibilities that apply to all natural rivers, streams or other freshwater bodies, but are limited to physical barriers, i.e., dams, diversion structures, culverts and fords. These include:

- Culverts and fords may not be built in such a way as to impede fish passage without a permit (regulation 42(1)).
- Culverts and fords have to be maintained by the occupier[7] to prevent the development of fish passage barriers, unless removed or exempted (regulation 42(2)).
- DOC may require that any dam or diversion structure to be built has a fish facility included, and set conditions on their design and performance[8] (regulations 43 & 44).
- If a fish facility is required:
  - Every manager of a dam or diversion structure shall ensure the structure maintains adequate flow through or past so it functions as specified at all times or periods specified within their control (regulation 45).
  - DOC may require maintenance or repair of any fish facility (regulation 46).
- That it is an offence for anyone to injure or damage a fish facility (regulation 47).
- Approval is required for any person to make a structural change to a fish facility (regulation 48).

Definitions of some technical terms such as dam, diversion structure, fish facility and fish pass are provided within FFR83 that help with interpretation of when these fish passage statutory requirements apply (Refer Appendix C). Culverts, fords, impede and fish passage have not been defined in the regulations, but international fish passage guidelines and common dictionary definitions appear to fit the apparent intention of the legislation:

Culvert – “a connection between two water bodies, typically a pre-formed concrete tube located below roads or other constructions” (Gough et al. 2012).

Ford – “a shallow place in a river or a stream allowing one to walk or drive across.”

Passage – “the action or process of moving through or past somewhere on the way from one place to another.”

Impede – “delay or prevent by obstructing them; hinder.”

Based on these definitions, any instream structures (e.g., floodgates, tide gates, pumping stations, water intakes) that meet the definition of a dam, diversion structure, culvert and/or ford are also subject to the statutory requirements of Part 6 of the FFR83. For example, a floodgate usually has a gate that can be opened or closed to admit or exclude water, so this gate could be a diversion structure if it diverts water, and a dam as it controls water.

The FFR83 regulations came into force on 1 January 1984, so generally apply to all structures built after 1 January 1984. However, regulation 42(2) (i.e., the requirement for culverts and fords to be maintained to prevent the development of fish passage barriers) applies to all culverts or fords built before and after 1984. These regulations apply to all dams or diversion structures in any natural river, stream or water, but exclude:

[7] The term occupier includes the owner of any land when there is no apparent occupier; and also includes any person doing any work by contract for the occupier.
[8] Subject to the RMA91 and any determination under that Act

- Any net, trap, or structure erected and used solely for the purpose of taking or holding fish.
- Any dam constructed on dry or swampy land or ephemeral water courses for the express purpose of watering domestic stock or providing habitat for water birds.
- Any water diversion not being incorporated into or with a dam, that is solely and reasonably required for domestic needs or for the purposes of watering domestic stock and that empties, without dead ends, into any viable fish habitat.
- Any dam or diversion structure subject to a water right issued under the provisions of the Water and Soil Conservation Act 1967 (prior to 1 January 1983) or any structure authorised by a Regional Water Board not requiring a water right that in no way impedes the passage of fish. This Act was the primary legislation governing the use of water resources prior to the enactment of the RMA91.

The regulations do not seek to prevent all effects on fish movement, but rather to ensure that structures do not have undue effects on fish passage and fisheries. In recent years, focus has been on ensuring that best practice design is developed and implemented to allow structures such as culverts to be put in place without significant effects on fisheries; barriers to be installed or enhanced to protect key threatened fish populations; and water intake structures to be designed with the aim of preventing entrainment and impingement of fish.

In summary, approval from both the Regional Council and DOC could be required as a minimum for the installation, maintenance or alteration of instream structures in New Zealand waterways. It is, however, best to contact the relevant authorities to check legislative responsibilities, as legislation and interpretation of legislation can change over time. If you plan to install a dam or diversion or have a culvert and/or ford that could impede fish passage, then you must contact your closest DOC permissions team[9] for more information and to apply.

[9] http://www.doc.govt.nz/get-involved/apply-for-permits/contacts/

Appendix B Legislation

The following sections provide excerpts of relevant legislation referred to in the text of the guidelines. The wording was taken directly from the relevant legislation available at http://www.legislation.govt.nz and was correct as of 22 January 2018. Legislation is updated over time and so legislation should be checked for updates on a regular basis.

Resource Management Act 1991

13 Restriction on certain uses of beds of lakes and rivers

(1) No person may, in relation to the bed of any lake or river—

- (a) use, erect, reconstruct, place, alter, extend, remove, or demolish any structure or part of any structure in, on, under, or over the bed, or
- (b) excavate, drill, tunnel, or otherwise disturb the bed, or
- (c) introduce or plant any plant or any part of any plant (whether exotic or indigenous) in, on, or under the bed, or
- (d) deposit any substance in, on, or under the bed, or
- (e) reclaim or drain the bed -

unless expressly allowed by a national environmental standard, a rule in a regional plan as well as a rule in a proposed regional plan for the same region (if there is one), or a resource consent.

(2) No person may do an activity described in subsection (2A) in a manner that contravenes a national environmental standard or a regional rule unless the activity -

- (a) is expressly allowed by a resource consent, or
- (b) is an activity allowed by section 20A.

(2A) The activities are -

- (a) to enter onto or pass across the bed of a lake or river
- (b) to damage, destroy, disturb, or remove a plant or a part of a plant, whether exotic or indigenous, in, on, or under the bed of a lake or river
- (c) to damage, destroy, disturb, or remove the habitats of plants or parts of plants, whether exotic or indigenous, in, on, or under the bed of a lake or river
- (d) to damage, destroy, disturb, or remove the habitats of animals in, on, or under the bed of a lake or river.

(3) This section does not apply to any use of land in the coastal marine area.

(4) Nothing in this section limits section 9.

14 Restrictions relating to water

(1) No person may take, use, dam, or divert any open coastal water, or take or use any heat or energy from any open coastal water, in a manner that contravenes a national environmental standard or a regional rule unless the activity -

(a) is expressly allowed by a resource consent, or

(b) is an activity allowed by section 20A.

(2) No person may take, use, dam, or divert any of the following, unless the taking, using, damming, or diverting is allowed by subsection (3):

(a) water other than open coastal water, or

(b) heat or energy from water other than open coastal water, or

(c) heat or energy from the material surrounding geothermal water.

(3) A person is not prohibited by subsection (2) from taking, using, damming, or diverting any water, heat, or energy if -

(a) the taking, using, damming, or diverting is expressly allowed by a national environmental standard, a rule in a regional plan as well as a rule in a proposed regional plan for the same region (if there is one), or a resource consent, or

(b) in the case of fresh water, the water, heat, or energy is required to be taken or used for -

(i) an individual's reasonable domestic needs, or

(ii) the reasonable needs of a person's animals for drinking water -

and the taking or use does not, or is not likely to, have an adverse effect on the environment, or

(c) in the case of geothermal water, the water, heat, or energy is taken or used in accordance with tikanga Māori for the communal benefit of the tangata whenua of the area and does not have an adverse effect on the environment, or

(d) in the case of coastal water (other than open coastal water), the water, heat, or energy is required for an individual's reasonable domestic or recreational needs and the taking, use, or diversion does not, or is not likely to, have an adverse effect on the environment, or

(e) the water is required to be taken or used for emergency or training purposes in accordance with section 48 of the Fire and Emergency New Zealand Act 2017.

Conservation Act 1987

6 Functions of Department

The functions of the Department are to administer this Act and the enactments specified in Schedule 1, and, subject to this Act and those enactments and to the directions (if any) of the Minister -

(a) to manage for conservation purposes, all land, and all other natural and historic resources, for the time being held under this Act, and all other land and natural and historic resources whose owner agrees with the Minister that they should be managed by the Department:

(ab) to preserve so far as is practicable all indigenous freshwater fisheries, and protect recreational freshwater fisheries and freshwater fish habitats:

…

26ZJ Offences relating to spawning fish

(1) Every person commits an offence who -

- (a) disturbs or damages the spawning ground of any freshwater fish
- (b) disturbs or injures the eggs or larvae of any freshwater fish
- (c) is in possession of the eggs or larvae of any freshwater fish
- (d) with any spear, gaff, spear gun, net, trap, or similar device takes any sports fish from any river or stream where sports fish are congregating or have congregated for spawning
- (e) while in the vicinity of any river or stream where sports fish are congregating or have congregated for spawning, has possession or control of any spear, gaff, spear gun, trap, or similar device or material suitable for the taking of any sports fish, in circumstances likely to result in the taking of sports fish.

(2) Nothing in subsection (1) shall apply to -

- (a) the taking of freshwater fish or the eggs or larvae of such fish for the purposes of scientific investigation or data collection, under a permit or authority under this Act, and in accordance with any conditions imposed by such permit or authority
- (b) the taking of freshwater fish subsequently found to contain eggs or larvae.

26ZM Transfer or release of live aquatic life

(1) No person shall transfer live aquatic life or release live aquatic life into any freshwater, except in accordance with this section.

(2) The prior approval of the Minister of Fisheries shall be required for the following:

(a) the movement of live aquatic life between sites where the species already exists

(b) the movement of live aquatic life between the islands of New Zealand.

(3) The prior approval of the Minister of Conservation shall be required for the following:

(a) the transfer of live aquatic life to or the release of live aquatic life in a new location where the species does not already exist (including the transfer of a new species to or the release of a new species in an existing or a new fish farm)

(b) the transfer of a species of live aquatic life to any land or water managed or administered under this Act or any other Act specified in Schedule 1.

(4) The following provisions shall apply where the approval of the Minister of Conservation is required under subsection (3):

(a) the applicant shall advertise, on at least 2 consecutive Saturdays in at least 1 newspaper circulating in the area concerned, the intention to transfer or release live aquatic life

(b) every advertisement under paragraph (a) shall state that submissions or objections in respect of its subject matter should be sent to the Director-General within 20 working days after the date specified in the advertisement for that purpose (being a date that is not earlier than the date on which the advertisement is first published)

(c) the Director-General may require an applicant to provide an environmental impact assessment report before granting approval.

(5) Every person commits an offence and is liable to a fine not exceeding $5,000 who contravenes or fails to comply with subsection (1).

(5A) Nothing in this section applies to the transfer of any live aquatic life to an existing fish farm where the species is already present.

(6) Except where the Director-General or the Director-General of Agriculture and Fisheries requires it to comply with this section, nothing in this section shall apply to the transfer by a Fish and Game Council of sports fish to another location within the same island in New Zealand where the species is already present.

(7) Except as provided in subsections (5A) and (6), this section applies to all persons.

48A Special regulations relating to freshwater fisheries

(1) Without limiting section 48, the Governor-General may from time to time, by Order in Council, make regulations for all or any of the following purposes:

…

(n) requiring and authorising the provision of devices and facilities to permit or control the passage of freshwater fish or sports fish through or around any dam or other structure impeding the natural movement of fish upstream or downstream,

…

Freshwater Fisheries Regulations 1983

Part 6 Fish Passage

41 Scope

(1) This Part shall apply to every dam or diversion structure in any natural river, stream, or water.

(2) For the purposes of these regulations dam or diversion structure shall not include -

(a) any net, trap, or structure erected and used solely for the purpose of taking or holding fish in accordance with the provisions of the Act, or of these regulations

(b) any dam constructed on dry or swampy land or ephemeral water courses for the express purpose of watering domestic stock or providing habitat for water birds

(c) any water diversion not being incorporated into or with a dam, that is solely and reasonably required for domestic needs or for the purposes of watering domestic stock and that empties, without dead ends, into any viable fish habitat

(d) any structure authorised by a Regional Water Board not requiring a water right that in no way impedes the passage of fish.

(3) For the purposes of this Part, the term occupier includes the owner of any land when there is no apparent occupier; and also includes any person doing any work by contract for the occupier.

42 Culverts and fords

(1) Notwithstanding regulation 41(2)(d), no person shall construct any culvert or ford in any natural river, stream, or water in such a way that the passage of fish would be impeded, without the written approval of the Director-General incorporating such conditions as the Director-General thinks appropriate.

(2) The occupier of any land shall maintain any culvert or ford in any natural river, stream, or water (including the bed of any such natural river, stream, or water in the vicinity of the culvert or ford) in such a way as to allow the free passage of fish,

provided that this requirement shall cease if the culvert or ford is completely removed or a written exemption has been given by the Director-General.

43 Dams and diversion structures

(1) The Director-General may require that any dam or diversion structure proposed to be built include a fish facility:

provided that this requirement shall not apply to any dam or diversion structure subject to a water right issued under the provisions of the Water and Soil Conservation Act 1967 prior to 1 January 1984.

(2) Any person proposing to build such a dam or diversion structure shall notify the Director-General and forward a submission seeking the Director-General's approval or dispensation from the requirements of these regulations, shall supply to the Director-General such information as is reasonably required by the Director-General to assist him in deciding his requirements (including plans and specifications of the proposed structure and any proposed fish facility).

(3) Should the Director-General consider that the information supplied is inadequate, he shall, within 28 days, advise the applicant as to what further information is required.

44 Requirement for a fish facility

(1) If, in the opinion of the Director-General, a fish facility is required or dispensation from such a requirement is acceptable, the Director-General shall as soon as practical but in no case longer than 6 months if a fish facility is required from the date of receiving all information required, or 3 months where a fish facility is not required from the date of receiving all information required, forward his written requirement or dispensation to whomsoever made the submission.

(2) Where in the opinion of the Director-General a fish facility is required he shall specify what is required to enable fish to pass or stop the passage of fish, and while not limiting this general requirement may specify -

(a) the type, general dimensions, and general design of any fish pass to be utilised,

(b) the type, general dimensions, general design, and placement of any fish screen utilised.

(3) Subject to the Resource Management Act 1991 and any determination under that Act, the Director-General may specify -

(a) the type and placement of any water intake to be utilised where fish screens are not required

(b) the flow of water through any fish pass and the periods of the day and year when the pass must be operational

(c) the volume, velocity, and placement of additional water to attract migrating fish to any fish pass

(d) the type and scope of any remedial works in connection with any fish screen or fish pass to enable fish to approach the structure or to be returned to the normal course of the water channel

(e) the volume or relative proportion of water that shall remain downstream of any dam or diversion structure and the period of day or year that such water flows shall be provided.

(4) Every approval given by the Director-General shall expire 3 years from the date of issue if the construction of the dam or diversion structure is not completed, or such longer time as he may allow.

(5) The manager of every dam or diversion structure in connection with which a fish facility is provided shall at all times keep such fish facility in good and satisfactory repair and order, so that fish may freely pass and return at all times or are prevented from passing as specified under these regulations.

45 Adequate water

The manager of every dam or diversion structure in connection with which a fish facility is provided shall, subject to the Resource Management Act 1991 and any relevant determination under that Act, maintain a flow of water through or past such fish facility sufficient in quantity to allow the facility to function as specified at all times or periods specified; but no person shall be liable for a breach of this regulation due to drought, flood, or other sources beyond his control if the default is made good as soon as reasonably possible.

46 Required maintenance or repair

The Director-General may serve notice in writing to the manager of any fish facility notifying him of any defects or want of repair in such fish facility and requiring him within a reasonable time to be therein prescribed to remove any defect or make such repairs as may be required:

provided that nothing in this regulation shall affect the liability of a manager under regulation 44.

47 Damage

No person shall wilfully injure or damage any fish facility.

48 Alterations

No person shall, without the written consent of the Director-General, make a structural alteration in any fish facility.

49 Inspection of fish facilities

Any officer may at all reasonable times enter upon any fish facility and upon any remedial works or upon the land bordering such fish facility or remedial works for the purpose of their inspection.

50 Protection of fish

No person, other than an officer acting in his official capacity, shall take or attempt to take any fish on its passage through a fish facility, or place any obstruction therein or within a radius of 50 m of any point of a fish facility, or shall within a radius of 50 m of any point of a fish facility use any contrivance whereby fish may be impeded in any way in freely entering or passing through or passing by a fish facility except as may be provided by the Director-General in writing to the manager of the fish facility.

Part 8 Management

59 Restricted authority to liberate fish or ova

No person shall liberate any fish or fish ova of any description whatever in the waters of any lake, river, or stream within any area of jurisdiction of the Fish and Game Council for that area without the prior written consent of the Fish and Game Council within the meaning of the Conservation Act 1987 of that area.

Appendix C Legal definitions

The following definitions should be considered when interpreting the requirements of the Freshwater Fisheries Regulations 1983. Legislation does change so please check http://www.legislation.govt.nz/ for current requirements and interpretation.

Freshwater Fisheries Regulations 1983

- **Dam** means any structure designed to confine, direct, or control water, whether permanent or temporary; and includes weirs.
- **Diversion structure** means any structure designed to divert or abstract natural water from its natural channel or bed whether permanent or temporary.
- **Fish facility** means any structure or device, including any fish pass or fish screen inserted in or by any water course or lake, to stop, permit, or control the passage of fish through, around, or past any dam or other structure impeding the natural movement of fish upstream or downstream.
- **Fish pass** means any structure providing passage through or over any barrier to their passage.
- **Fish screen** means any device whether moving or stationary designed to impede or stop the passage of fish.
- **Remedial works** means any structures, channel modifications, or water flow provided to offset the effect of a dam or diversion structure.

Conservation Act 1987

- **Bed** means -

  (a) in relation to any river, the space of land which the waters of the river cover at its fullest flow without overtopping the bank, and

  (b) in relation to a lake, the space of land which the waters of the lake cover at its highest level without exceeding its physical margin.

- **Department** means the Department of Conservation.
- **Deputy Director-General** means a Deputy Director-General of Conservation.
- **Fishery** means 1 or more stocks or parts of stocks or 1 or more species of freshwater fish or aquatic life that can be treated as a unit for the purposes of conservation or management.
- **Freshwater** means -

  (a) all waters of rivers, streams, lakes, ponds, lagoons, wetlands, impoundments, canals, channels, watercourses, or other bodies of water whether naturally occurring or artificially made

  (b) all waters of estuaries or coastal lagoons

(c) all other fresh or estuarine waters where freshwater fish indigenous to or introduced into New Zealand are found

(d) all waters in the mouth of every river or stream, and the mouth of every river and stream shall be deemed to include every outlet thereof and the seashore between those outlets and the waters of the sea or lying within a distance of 500 metres from any place where at low tide the waters of a river or stream meet the waters of the sea.

- **Freshwater fish** includes all species of finfish of the Classes Agnatha and Osteichthyes, and all shellfish of the Classes Mollusca and Crustacea, that must, at any time in the life history of the species, inhabit fresh water; and includes any part thereof and such finfish and shellfish that seasonally migrate into or out of freshwater.

Appendix D Ecological considerations for instream structure design

Barriers to fish migration at road crossings and other instream structures can adversely affect fish populations, reducing fish numbers and altering fish species diversity within catchments by obstructing migration to critical habitats. This section explains the importance of freely accessible and connected freshwater habitats for sustaining our valued freshwater fish communities, and highlights some of the key characteristics of instream structures that can impede fish movements.

Linking habitats and fish movement

Why do fish and other aquatic organisms need to move?

Many of our native fish species have to travel between marine and freshwater environments to complete their life-cycle, i.e., they are diadromous. The majority of the most widespread native fish species that occur in New Zealand's waterways have larvae that rear in the sea and then migrate back into freshwater as juveniles. Their adult populations are, therefore, dependent on the success of the annual upstream migrations of juveniles. Some of the main life-cycles used by New Zealand fish species are explained below.

Inanga (*Galaxias maculatus*) are the most common of the five whitebait species and are found throughout New Zealand. Inanga have a catadromous life-cycle because their adults migrate from rivers and streams to estuaries to spawn (Figure D-1). The eggs are laid during high spring tides in the intertidal vegetation, and develop out of water. After hatching, larvae migrate to the sea to feed and grow. Inanga migrate back into freshwater as juveniles in search of habitat suitable for growing into adults. This is when people catch them as whitebait. Both longfin (*Anguilla dieffenbachii*) and shortfin (*Anguilla australis*) eels are also catadromous, but their adults migrate all the way to the ocean to spawn.

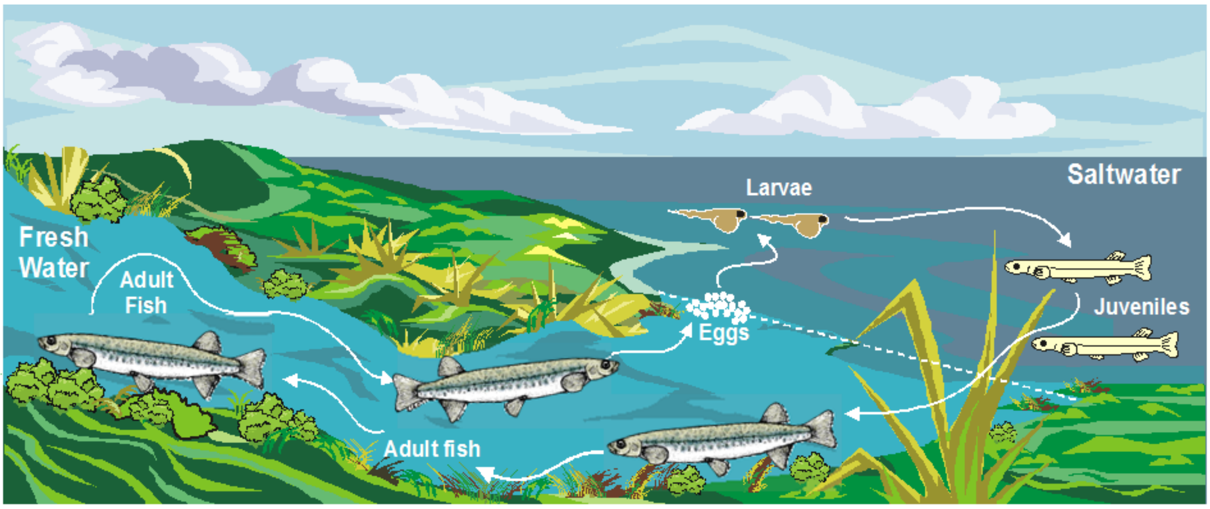


Figure D-1: Life-cycle of inanga. Adults migrate down to estuaries to spawn, upon hatching larvae move out to sea and rear into juveniles before returning to freshwater for growth to adulthood.

The other four galaxiid fish species that make up the whitebait catch in New Zealand, banded kōkopu (*Galaxias fasciatus*), giant kōkopu (*G. argenteus*), shortjaw kōkopu (*G. postvectis*) and kōaro (*G. brevipinnis*), all have an amphidromous life-cycle (Figure D-2). This means the adults do not migrate to marine waters to breed and, instead, spawning occurs in freshwater rivers and streams. The eggs are laid in riparian vegetation on the banks during flood flows and, similar to inanga, subsequently develop out of water. Upon re-inundation, the larvae hatch and migrate out to sea to feed and rear. They then migrate back into freshwater as juveniles in search of habitat for growth to adulthood. This type of life-cycle is also seen in many of our bully species (*Gobiomorphus spp.*) and torrentfish (*Cheimarrichthys fosteri*).

Figure D-2: Life-cycle of banded kōkopu, giant kōkopu, shortjaw kōkopu and kōaro. Adults spawn in rivers and streams. Larvae migrate to the sea upon hatching, where they feed and grow into juveniles before returning to freshwater for growth to adulthood.

Some of the species with an amphidromous life-cycle also have populations in New Zealand that undertake their entire life-cycle in freshwater (e.g., banded kōkopu and common bully). These populations are known as lacustrine (i.e., lake-based) or landlocked (i.e., they can't access the sea). After the larvae hatch in tributary streams, rather than moving out to sea, they move to downstream lakes and rear there. As juveniles they move out of the lakes again and into nearby streams where they then grow in to adults. Despite not undertaking a migration to sea and back, these fish still require connectivity between larval rearing habitats in the lakes and adult rearing and spawning areas in streams.

The lamprey (*Geotria australis*) has an anadromous life-cycle. This means that their larvae rear in freshwater and migrate to the ocean as juveniles. They feed and grow to adulthood in the ocean and then migrate back to freshwater to spawn and die. Naturally, most salmon and trout species also have an anadromous life-cycle. However, in New Zealand the majority of salmonids are non-diadromous and complete their entire life-cycle in freshwater. Typically salmonids spawn in streams, where the larvae hatch and rear. As juveniles they migrate downstream to adult rearing habitats, either in larger rivers or lake systems. In New Zealand, anadromous populations of brown trout and chinook salmon exist in some river systems, but the other salmonid species are not know to have sea-run populations here.

Several native fish species are resident in freshwater, e.g., non-migratory galaxiids, some bullies and mudfish. They complete their whole lifecycle in freshwater streams and rivers. These fish still need to move within waterways to varying degrees to access different habitats, e.g., downstream dispersal of larvae, so effective fish passage management remains important.

This diversity of life-history strategies means it is important to understand what fish are present in any location before devising appropriate strategies for providing effective fish passage. This must account for differences in species, life-stage, direction and timing of movements. For example, some species, e.g., giant bullies, rarely move far from the coast, but species such as longfin eel and kōaro regularly penetrate a long way inland. Information on what species are present at a site may be available from the New Zealand Freshwater Fish Database (NZFFD)[10]. However, consideration must be given to the timing and methods used for the surveys included in the NZFFD, and the best way to find out what fish are present (or should be present in the absence of barriers) is to undertake a fish survey. There are also many locations where no data are available and in this case modelled information on expected fish occurrence may be of use, e.g., Crow et al. (2014).

The need for open waterways is not only limited to freshwater fish, but also many of our aquatic invertebrates. The loss of physical habitat caused by installation of instream structures impacts on the abundance of aquatic invertebrates. There is also evidence demonstrating impacts on adult flight paths, with the presence of culverts being associated with significant reductions in some species upstream of culverts (Blakely et al. 2006). Furthermore, a recent study has shown that recolonization of freshwater mussels was enhanced following the installation of a fishway at a weir (Benson et al. 2017). Mussels have an obligate larval stage that parasitizes fish hosts. If fish movements are limited by a barrier, the potential dispersal of the mussels at that larval stage is also limited.

Timing of fish movements

The timing of fish migrations vary both within and between species. However, the main migrations are typically associated with key stages in fishes' life-histories, e.g., spawning, hatching and rearing. Many of New Zealand's native fish species undertake their main upstream migrations as relatively weak swimming, small-bodied juveniles. This contrasts with many of our sports fish (e.g., trout and salmon), which undertake their main upstream migration as large, strong swimming adults. The migration times of some of the main freshwater fish species found in New Zealand are summarised in Figure D-3. It is important to consider both upstream and downstream movements. This information can be used to inform expectations on what species and life-stages of fish you might expect to be migrating at any given time and, therefore, inform design criteria for instream structures and timing of installations. However, it should be noted that there are regional variations in the timing of migrations and it is important to confirm this information locally.

Fish swimming behaviours

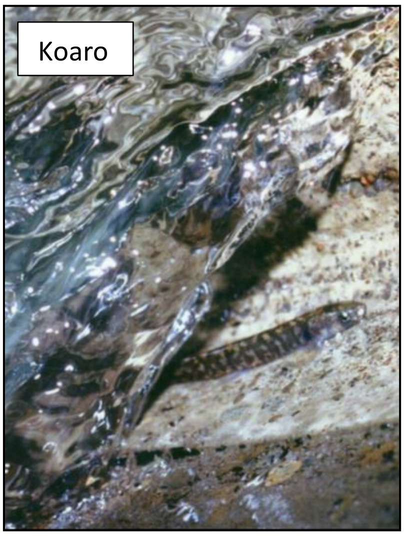
The ability of fish to migrate upstream is influenced by a number of factors including swimming ability, behaviour and environmental factors, such as water temperature. There are four main modes of movement utilised by fish (Figure D-4). Swimming is the primary mode of movement, however, some species have developed additional modes to help them overcome natural obstructions such as waterfalls and rapids. In New Zealand, several of our native fish species, e.g., eel, banded kōkopu and kōaro, are excellent climbers as juveniles. This allows them to negotiate some obstacles, such as waterfalls, as long as a continuous wetted margin is available for them to climb and access habitats far inland and at relatively high elevations.

[10] https://www.niwa.co.nz/our-services/online-services/freshwater-fish-database

Functional group	Species	Conservation status	Direction	Life stage	Summer			Autumn			Winter			Spring		
					D	J	F	M	A	M	J	J	A	S	O	N
Bullies (fast flow) & torrentfish	Bluegill bully	●	↑	J												
			↓	L												
	Redfin bully	●	↑	J												
			↓	L												
	Torrentfish	●	↑	J												
			↓	L												
Bullies (slow flow)	Common bully	○	↑	J												
			↓	L												
	Giant bully	○	↑	J												
			↓	L*												
Eels	Longfin eel	●	↑	L*												
			↑	J												
			↓	A												
	Shortfin eel	○	↑	L*												
			↑	J												
			↓	A												
Inanga & smelt	Inanga	●	↑	J												
			↓	A												
			↓	L*												
	Common smelt	○	↑	J												
			↓	L												
Lamprey	Lamprey	+	↑	A												
			↓	J												
Large galaxiids	Banded kōkopu	○	↑	J												
			↓	L												
	Giant kōkopu	●	↑	J												
			↓	L												
	Kōaro	●	↑	J												
			↓	L												
	Shortjaw kōkopu	+	↑	J												
			↓	L												
Salmonid sports fish	Atlantic salmon	Δ	↑	A												
			↓	J												
	Brook char	Δ	↑	A												
			↓	J												
	Brown trout	Δ	↑	A												
			↓	J												
	Chinook salmon	Δ	↑	A												
			↓	J												
	Rainbow trout	Δ	↑	A												
			↓	J												
	Sockeye salmon	Δ	↑	A												
			↓	J												

Figure D-3: Freshwater fish migration calendar for key New Zealand fish species. Showing migration range (light blue) and peak periods (dark blue ■), migration direction and life stage at the time of migration. ○ Not threatened; ● At risk declining; + Threatened nationally vulnerable; Δ Introduced sports fish. Life stages: L = larval, J = juvenile, A = adult. * indicates the life-stages that are present only within the lower reaches of rivers and streams. Modified from Smith (2014).

Figure D-4: Locomotory classification of some New Zealand freshwater fish species. Modified from Mitchell and Boubée (1989). Lamprey photo: Jane Kitson.

Mode of swimming	Species
Swimmers: Species that usually swim around obstacles. They rely on areas of low water velocity to rest and reduce lactic acid build-up with intermittent “burst” type anaerobic movements to get past high water velocity areas.	Inanga, smelt, grey mullet and common bullies. 
Anguilliforms: These fish are able to worm their way through small spaces between stones or vegetation either in or out of the water. They are able to breathe atmospheric oxygen if their skin remains damp.	Shortfin and longfin eels 
Climbers: These species climb the wetted margins of waterfalls, rapids and spillways. They ‘stick’ to the substrate using surface tension and can have roughened “sucker like” pectoral and pelvic fins or even a sucking mouth (like lamprey).	Lamprey, elvers (juvenile eels), juvenile kōkopu and kōaro. Juvenile and adult redfin bullies and, to a limited extent, torrentfish. 
Jumpers: These species are able to leap using the waves at waterfalls and rapids. As water velocity increases it becomes energy saving for these fish to jump over the obstacle.	Trout and salmon. 

Swimming performance is a critical factor determining the ability of fish to migrate and overcome barriers to migration. Swimming abilities can be used to determine water velocity conditions that need to be meet for fish to pass over or through an instream structure. It is typically defined in terms of the duration of swimming and the intensity (i.e., speed) at which the fish swims. There are three dominant swimming modes accepted by most researchers: (1) sustained swimming, (2) prolonged swimming, and (3) burst swimming (Beamish 1978; Hammer 1995; Kieffer 2010). Sustained swimming is aerobic, can be maintained for extended periods of time (typically >200 min) and does not involve fatigue. The prolonged swimming mode lasts between twenty seconds and 200 minutes and, depending on the swimming speed, ends in exhaustion. Burst swimming represents a form of high intensity, short duration (<20 secs), anaerobic activity (Beamish 1978). While the endurance thresholds between swimming modes have been widely cited, they are somewhat arbitrary and there is evidence to suggest these thresholds vary between fish species and possibly individuals (e.g., Nikora et al. 2003).

Knowledge of swimming speeds in fish has advanced significantly over the last 50 years (Kieffer 2010; Katopodis and Gervais 2012). Critical swimming speed (Brett 1964) is the most frequently used and easiest method to measure swimming performance (Plaut 2001). It is essentially a measure of the prolonged swimming mode, with fish incrementally exposed to higher water velocities for a set period of time until they reach fatigue. Critical swimming speeds have frequently been used to inform the development of water velocity design criteria for providing fish passage at instream structures (Katopodis and Gervais 2012), although not without criticism (Peake 2004). Another commonly used measure of swimming performance is endurance, which provides information on how far and/or how long a fish can swim against a given water velocity (Brett 1964; Beamish 1978; Katopodis and Gervais 2012). These data have also been used to help inform design criteria for fish passage (e.g., Peake et al. 1997; Laborde et al. 2016).

More recently, research has begun to focus on assessments of voluntary fish swimming performance in open channels, e.g., streams (Katopodis and Gervais 2012; Vowles et al. 2013). This has been facilitated by the emergence of biotelemetry methods that allow real-time tracking of fish movements and upstream progress allowing an assessment of swimming performance in real-world instream conditions (e.g., Haro et al. 2004; Goerig et al. 2015). Unfortunately, the utility of these techniques for many New Zealand species are limited by their small body size at migration (Franklin and Baker 2016). There is increasing evidence emerging that volitional swimming performance can be significantly different to that assessed under some controlled laboratory conditions (e.g., Peake 2004; Castro-Santos 2005; Mahlum et al. 2014; Goerig et al. 2015), likely reflecting the influence of natural environmental heterogeneity (e.g., turbulence and boundary layer conditions) and the impacts of fish motivation and behaviour on overall fish swimming performance.

A number of studies have demonstrated the influence of environmental factors on fish swimming performance, including water temperature (Beamish 1978; Rodgers et al. 2014), dissolved oxygen (Farrell et al. 1998; Landman et al. 2005) and turbulence (Enders et al. 2003; Nikora et al. 2003; Liao 2007; Silva et al. 2012), but understanding of these influences is still relatively poor in most cases, especially for New Zealand's native fish species. Physiological (e.g., age and fatigue) and behavioural (e.g., learning) factors are also thought to have an impact on fish swimming performance (e.g., Farrell et al. 1998; Liao 2007), but remain relatively poorly studied (Kieffer 2010; Katopodis and Gervais 2012; Vowles et al. 2013).

Fish swimming ability increases with size (Bainbridge 1958; Nikora et al. 2003). Given that the majority of New Zealand's native fish species migrate upstream at a small size, they require more conservative design criteria for ensuring fish passage compared to salmonids (which migrate upstream as adults) and many of the other species that have been more widely studied in the Northern hemisphere. Table D-1 summarises the main published data available regarding swimming performance for New Zealand fish species. Inanga and shortfin eel are the only species for which standardised, reproducible measures of swimming performance (i.e., critical swimming speed or fixed velocity endurance tests) are available (Langdon and Collins 2000; Nikora et al. 2003; Bannon 2006; Plew et al. 2007; Tudorache et al. 2015). Mitchell (1989) evaluated the swimming performance of six native New Zealand fish species, including inanga and shortfin eel, in a flume using a non-standard experimental methodology. While there are some inconsistencies between the results of Mitchell (1989) and results from some of the more standard test procedures, the results are valuable for providing a sense of the relative swimming performance of some of the more common native fish species in New Zealand. The study by Bannon (2006) is the only one to evaluate the impacts of environmental conditions, in this case water temperature and dissolved oxygen, on fish swimming performance. That study showed that critical swimming speeds are temperature dependent, with inanga swimming performance reduced at lower and higher temperatures. Furthermore, a negative effect of mild hypoxia on fish swimming performance was demonstrated at higher water temperatures. While there are significant gaps in the swimming performance data for native fish species, the available data provide a valuable guide for developing design criteria for maximum allowable water velocities. If water velocities exceed the swimming capabilities of a fish, it will not be able to pass. The translation of swimming speeds in to design criteria is discussed in Section 4.2.2.

While there is little published data on the climbing abilities of New Zealand freshwater fishes, certain species of New Zealand freshwater fishes have well developed climbing skills. Amongst the galaxiids, banded kōkopu and kōaro are both extraordinarily skilled climbers, and can pass significant falls (McDowall 2000). The galaxiids climb by unilateral pectoral fin movement, leading to a wiggling motion from side to side as they ascend. By contrast, the bullies that can climb use a bilateral motion of both pectoral fins simultaneously to detach and re-attach to the wetted surface, climbing by little hops upwards. While common bullies are not known to be climbers, redfin bullies can surmount significant barriers by climbing, and bluegill bullies can pass moderate barriers (McDowall 2000). Shortfin and longfin elvers are also skilled climbers, longfins reputedly more-so than shortfins (McDowall 2000). Elvers climb by attaching themselves to the substrate using friction and surface tension, and undulating their bodies in an anguilliform motion as when swimming, but with their bodies adpressed closely to the substrate (Jellyman 1977). They often take advantage of rough substrate by wiggling between raised areas to provide greater surface area for adhesion. However, their ability to climb vertical surfaces is largely limited to when they are <120 mm (Jellyman 1977).

Table D-1: Summary of fish swimming data for NZ species. Where possible equations are given for fish swimming speed (U or U_{crit} for critical swimming speed) in terms of fish length (L for total length or L_f for fork length) and swimming time (t for swimming time or t_f for specifically time-to-fatigue). Comments are given on the mode of fish swimming, and the level of standardisation of the experimental methods. It is important to note that the values given in the table are relative to water velocity, and are not fish velocity over the ground. Design velocities must consider that a fish must first exceed the water velocity before it can make any headway upstream.

Species	Size (mm)	Swimming speed (m s^{-1})	Comments	Source
Inanga	52-73	0.19	Non-standard method. “Sustained” swimming.	Mitchell (1989)
Inanga	52-73	0.36	Non-standard method. “Prolonged” swimming.	Mitchell (1989)
Inanga	52-73	0.47	Non-standard method. “Burst” swimming.	Mitchell (1989)
Inanga	50	1.09 @ 5s 0.60 @ 20s	$U=14.4L^{0.63}.t^{-0.43}$ Non-standard method. Burst swimming.	Boubée et al. (1999)
Inanga	72	1.37 @ 5s 0.76 @ 20s	$U=14.4L^{0.63}.t^{-0.43}$ Non-standard method. Burst swimming.	Boubée et al. (1999)
Inanga	48 ± 2.5 (SD)	0.62 @ 5s 0.46 @ 20s 0.36 @ 1min 0.25 @ 5min	$U=8.86L_F^{0.76}.t_f^{-0.22}$ for t_f 1 to 400 s. Fixed velocity tests. Burst to prolonged swimming. Temperatures 16-22°C.	Nikora et al. (2003)
Inanga	62 ± 6.5 (SD)	0.75 @ 5s 0.55 @ 20s 0.43 @ 1min 0.31 @ 5min	$U=8.86L_F^{0.76}.t_f^{-0.22}$ for t_f 1 to 400 s. Fixed velocity tests. Burst to prolonged swimming.	Nikora et al. (2003)
Inanga	92 ± 10.3 (SD)	1.01 @ 5s 0.75 @ 20s 0.59 @ 1min 0.41 @ 5min	$U=8.86L_F^{0.76}.t_f^{-0.22}$ for t_f 1 to 400 s. Fixed velocity tests. Burst to prolonged swimming.	Nikora et al. (2003)

Species	Size (mm)	Swimming speed ($m\ s^{-1}$)	Comments	Source
Inanga	84 ± 8.5 (SD)	0.48 @ 37s (SD 40) 0.60 @ 21s (SD 13)	Time to fatigue fixed velocity test. Prolonged swimming mode.	Plew et al. (2007)
Inanga	47-50	0.25	Critical swimming speed. $U_{crit\ max}$ @ 17.7°C. 0.5 BL s^{-1} increments every 15 min. Decreased U_{crit} at higher and lower temperatures. Hypoxia reduced U_{crit} at temperatures > 15°C.	Bannon (2006)
Inanga	39-40	0.22	Critical swimming speed. $U_{crit\ max}$ @ 9.4°C Decreased U_{crit} at higher and lower temperatures.	Bannon (2006)
Inanga	55-68	0.25	Critical swimming speed. $U_{crit\ max}$ @ 18.3°C Decreased U_{crit} at higher and lower temperatures.	Bannon (2006)
Common bully	30-42	0.24	Non-standard method. “Sustained” swimming.	Mitchell (1989)
Common bully	30-42	0.28	Non-standard method. “Prolonged” swimming.	Mitchell (1989)
Common bully	30-42	0.60	Non-standard method. “Burst” swimming.	Mitchell (1989)
Banded kōkopu	44-55	0.19	Non-standard method. “Sustained” swimming.	Mitchell (1989)
Banded kōkopu	44-55	0.29	Non-standard method. “Prolonged” swimming.	Mitchell (1989)
Banded kōkopu	44-55	0.43	Non-standard method. “Burst” swimming.	Mitchell (1989)
Smelt	56-67	0.19	Non-standard method. “Sustained” swimming.	Mitchell (1989)
Smelt	56-67	0.27	Non-standard method. “Prolonged” swimming.	Mitchell (1989)
Smelt	56-67	0.50	Non-standard method. “Burst” swimming.	Mitchell (1989)
Smelt	70	1.35 @ 5s 0.74 @ 20s	Non-standard method. $U=14.4L^{0.63}.t^{-0.43}$ “Burst” swimming.	Boubée et al. (1999)
Shortfin eel	55-80	0.20	Non-standard method. “Sustained” swimming.	Mitchell (1989)

Species	Size (mm)	Swimming speed (m s^{-1})	Comments	Source
Shortfin eel	55-80	0.34	Non-standard method. “Prolonged” swimming.	Mitchell (1989)
Shortfin eel	55-80	0.57	Non-standard method. “Burst” swimming.	Mitchell (1989)
Shortfin eel	54	0.29	Max “sustained swimming” speed. 30 min.	Langdon and Collins (2000)
Shortfin eel	54	0.29-0.35	“Steady prolonged”. 3 - 30 min.	Langdon and Collins (2000)
Shortfin eel	54	0.35-0.64	“Rapid prolonged”. 24 - 180 s.	Langdon and Collins (2000)
Shortfin eel	54	0.64-0.79	“Burst swimming” speed. 3 – 2.4 s.	Langdon and Collins (2000)
Shortfin eel	746 ± 25 (SE)	0.74 ± 0.03 (SE)	Critical swimming speed. 0.1 m s^{-1} increments at 20 min intervals.	Tudorache et al. (2015)
Shortfin eel	746 ± 25 (SE)	0.51 ± 0.02 (SE)	Swimming speed with minimum energy consumption (U_{opt}).	Tudorache et al. (2015)
Koaro	50-100	0.40-0.64	“Critical swimming speed”, non-standard method. 12hr fixed velocity tests. U_{crit} defined as water velocity with 60% mortality. 14°C.	Moffat and Davison (1986)
Grey mullet	25-45	0.12	Non-standard method. “Sustained” swimming.	Mitchell (1989)
Grey mullet	25-45	0.2	Non-standard method. “Prolonged” swimming.	Mitchell (1989)
Grey mullet	25-45	0.35	Non-standard method. “Burst” swimming.	Mitchell (1989)
Rainbow trout	70 ± 5 (SE)	0.41	$U_{crit\ max}$ @ 15.1C. U_{crit} declines with increasing or decreasing temperature & hypoxia at 20°C.	Bannon (2006)
Roundhead galaxias	5.5-7.5	0.037 ± 0.010 (SE)	Critical swimming speed. 0.02 m s^{-1} increments at 2 min intervals.	Jones and Closs (2016)
Taieri flathead galaxias	7-8	0.068 ± 0.013 (SE)	Critical swimming speed. 0.02 m s^{-1} increments at 2 min intervals.	Jones and Closs (2016)
Eldon’s galaxias	8-10	0.057 ± 0.005 (SE)	Critical swimming speed. 0.02 m s^{-1} increments at 2 min intervals.	Jones and Closs (2016)
Dusky galaxias	8-11	0.068 ± 0.024 (SE)	Critical swimming speed. 0.02 m s^{-1} increments at 2 min intervals.	Jones and Closs (2016)

Species	Size (mm)	Swimming speed (m s^{-1})	Comments	Source
Canterbury galaxias	64-77	1.08 ± 0.065 (SE)	Non-standard method. Burst swimming. n=4. t=5-20 s.	NIWA unpublished data
Canterbury galaxias	62-69	0.88 ± 0.034 (SE)	Non-standard method. Prolonged swimming. n=14. t=25-600 s.	NIWA unpublished data
Bluegill bully	53-63	0.78 ± 0.065 (SE)	Non-standard method. Burst swimming. n=4. t=10-15 s.	NIWA unpublished data
Bluegill bully	38-64	0.37 ± 0.040 (SE)	Non-standard method. Prolonged swimming. n=10. t=30-600 s.	NIWA unpublished data
Upland bully	55-60	0.32 ± 0.037 (SE)	Non-standard method. Prolonged swimming. n=4. t=40-165 s.	NIWA unpublished data
Common bully	51-67	0.64 ± 0.107 (SE)	Non-standard method. Burst swimming. n=5. t=10-20 s.	NIWA unpublished data
Common bully	51-66	0.43 ± 0.065 (SE)	Non-standard method. Prolonged swimming. n=5. t=29-508 s.	NIWA unpublished data

Appendix E What creates a barrier to fish movements?

Barriers to fish movements can be caused by both natural and artificial features in streams (Franklin et al. 2014). Artificial structures, such as dams, culverts, weirs and fords, can obstruct fish movements if adequate consideration is not given to catering for these movements during structure design, installation and maintenance. While these structures impede the movements of fish, this result is generally an unintended consequence of the design and they have been termed unintentional barriers (Charters 2013). Avoiding the creation of new, and improving the mitigation of existing, unintentional artificial barriers is one of the primary objectives of this guidance (see Sections 4 and 5 respectively).

Features such as waterfalls, cascades or naturally intermittently dry stream reaches can impede or prevent the movement of fish. However, as naturally occurring features, the impacts of natural barriers on stream communities are generally of little ecological concern and should not be removed or changed. The exception is when natural barriers provide protection for critical habitats or native fish populations, and/or constrain the spread of undesirable or exotic species. In such cases it is critical that these benefits are taken in to consideration when developing a barrier management strategy (see Section 6 for further details).

In some cases, barriers are constructed intentionally to prevent fish accessing certain areas (Franklin et al. 2014, Charters 2013). These intentional barriers can be physical obstructions (e.g., perched culverts, overhangs, dams, screened water intakes), that are designed to exceed the exotic or all fishes' ability to negotiate the barrier, or non-physical (e.g., acoustic and air bubble barriers, electric fields and strobe lighting), which are intended to stimulate an avoidance response by exotic or all species (Charters 2013). Design considerations for these intentional built barriers are presented in Section 6.

Overall, there are a number of key structural features that can result in fish movements being impeded that may be present in natural and artificial, and in unintentional and intentional barriers. The following sections highlight some of these features and explain how they contribute to impeding fish movements.

Fall height

Any instream configuration, whether natural or artificial, can become an insurmountable obstacle for fish if it causes a sudden change in the water surface or bed level (Figure E-1). In the case of an artificial structure (e.g., culvert), this situation may occur at installation, or develop as a result of subsequent erosion. The vertical distance between the water level of the structure and the water level of the stream below is generally used to define the fall height of the structure.

Figure E-1: Example of a perched culvert illustrating fall height.

The energy requirements for fish negotiating barriers increase with fall height, and the ability of different fish species to surpass obstacles will depend upon their individual swimming, climbing or jumping abilities, as well as their life-stage. Baker (2003) examined the effect that the height of a weir may have upon two migrating native fishes (the common bully and inanga) that migrate by swimming. As fall height increased, the number of juvenile inanga passing the weir decreased significantly, with only around 30% of fish passing the weir at 50 mm and none passing the weir with a 100 mm fall height (Figure E-2). For adult inanga, the number of fish able to pass the weir as the fall height increased from 50 to 200 mm reduced rapidly from around 75% at 50 mm to no inanga able to pass at the maximum fall height of 200 mm (Figure E-3). For adult inanga, the size of the fish was significant in determining successful passage over the weir, with larger fish surmounting the weir with greater ease than smaller fish (Figure E-3). It is thought that the differences in fish passage ability between life-stages of inanga may be related to differences in muscle mass between juvenile fish (that had spent their lives in the sea and had relatively little muscle) and adults (who had been living in the river environment and had developed more musculature to cope with the flowing water they experience).

For common bullies, the number of bullies successfully passing the weir also decreased significantly as fall height increased. Again, fish size significantly influenced successful passage over the weirs with larger fish surmounting the weirs with greater ease than smaller fish (Figure E-4). No small common bullies passed the weir when the fall height was 100 mm or more and only 40% were able to pass at a fall height of 25 mm. Around 80% of large bullies could pass the 25 mm fall height, but this was reduced to 40% at 75 mm and zero at 125 mm (Figure E-4).

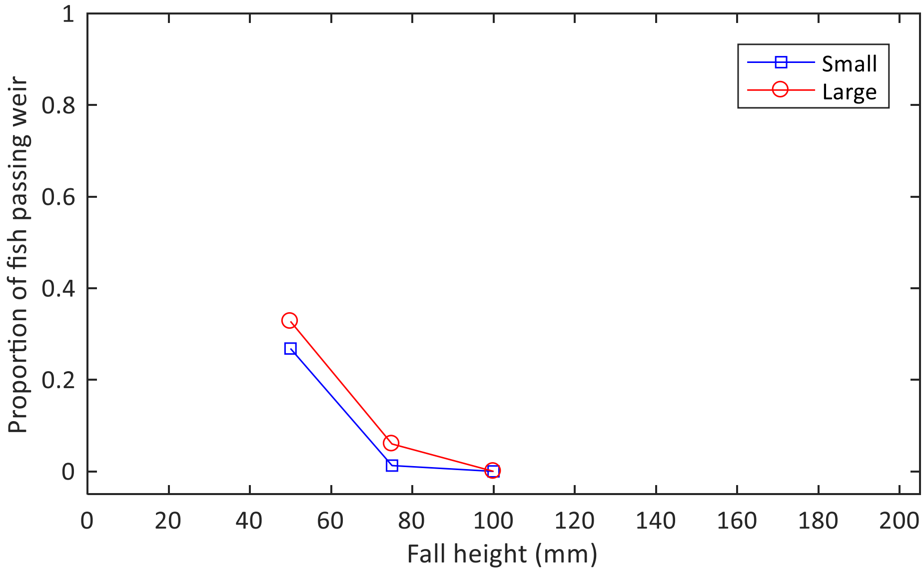


Figure E-2: Proportion of juvenile inanga that passed a V-notch weir at different fall heights. 'small' = average size of 47 mm; range 45-49 mm. 'large' = average size of 51 mm; range 50-59 mm. Reproduced from Baker (2003).

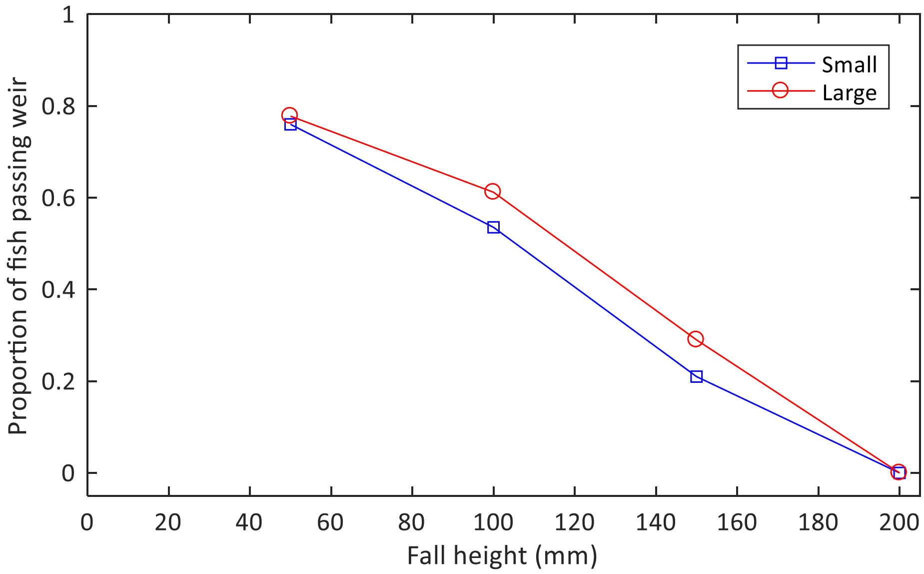


Figure E-3: Proportion of adult inanga that passed a V-notch weir at different fall heights. 'small' = average size of 55 mm; range 44-60 mm. 'large' = average size of 66 mm; range 61-110 mm. Reproduced from Baker (2003).

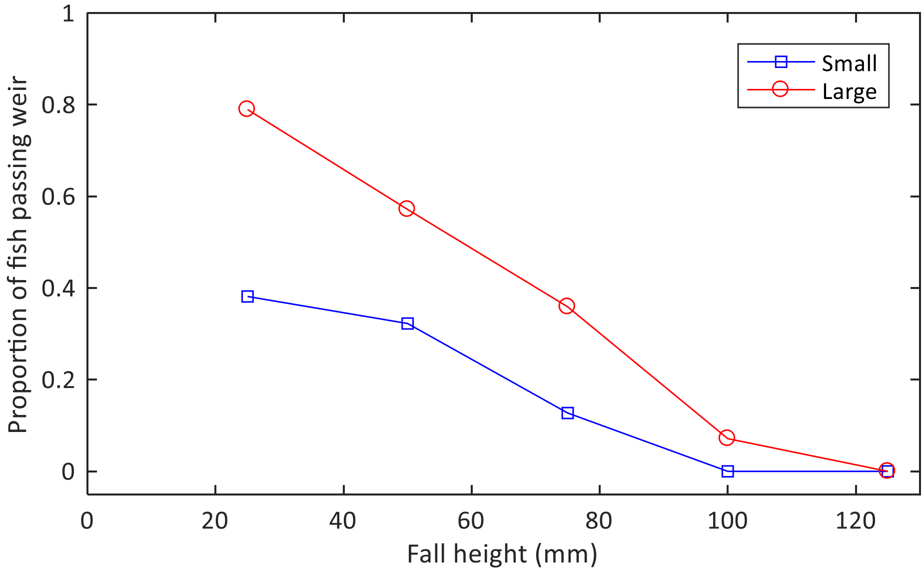


Figure E-4: Proportion of common bullies that passed a V-notch weir at different fall heights. 'small' = average size of 40 mm; range 28-50 mm. 'large' = average size of 57 mm; range 51-95 mm. Reproduced from Baker (2003).

Most climbing species are able to overcome significant fall heights, as long as there is a continuous wetted surface available for them to climb. However, where structures become undercut and an overhang develops, even climbers are unable to successfully pass. It is unclear what the potential energetic costs of climbing are when compared to swimming.

There is a lack of information about the jumping abilities of native species. However, the introduced brown trout (*Salmo trutta*) is known to traverse falls of at least 40 cm by jumping (Holthe et al. 2005) and brook trout (*Salvelinus fontinalis*) have been recorded jumping 74 cm (Kondratieff and Myrick 2006). The majority of research into fish jumping behaviours has been conducted on salmonids. Factors affecting the height of falls that can be jumped by salmonids include fish length and downstream pool depth (Brandt et al. 2005; Lauritzen et al. 2005; Kondratieff and Myrick 2006), water temperature (Holthe et al. 2005; Symons 1978) and upstream water velocity and turbulence (Stuart 1962 in Symons 1978). It is reasonable to assume that similar factors affect jump heights of other fishes. The ability to jump barriers means that small fall heights from culverts and weirs present less of an obstacle for upstream migration of brown trout and the other salmonids than to non-jumping species.

Water velocity

When water velocities exceed the swimming capability of fish, upstream migration will be prevented (Warren and Pardew 1998; Haro et al. 2004). This may occur around instream structures, naturally within the stream environment, or where channels have been modified (e.g., straightened or artificial channels). The ability of a fish to overcome high water velocities is a function of their swimming capabilities, the distance over which they have to travel, whether low velocity refuge areas where they can rest and recover after swimming to exhaustion are present, and environmental conditions (Peake et al. 1997; Castro-Santos 2004; Katopodis and Gervais 2012; Goerig et al. 2015). If water velocity restricts the distance a fish can travel at any one time to less than the full distance it needs to pass, low velocity refuge areas will be required to allow fish to recuperate after bursts of swimming. However, even if a fish can maintain a stationary position between periods of forward movement, the energetic requirements to achieve this may mean that they become exhausted before they reach the end of the channel (Brett 1964; Enders and Boisclair 2016). Furthermore, there may be a cumulative effect associated with the energy expended making multiple attempts to overcome a barrier, and/or in overcoming multiple barriers in sequence (Hinch and Rand 1998; Castro-Santos 2004).

To make upstream progress a fish must swim at a speed greater than the velocity of the water it is swimming in to (Peake et al. 1997; Laborde et al. 2016). However, the duration for which a fish can maintain a given speed reduces as its swimming speed increases. Consequently, there is a trade-off between water velocity, swimming speed and the distance that can be travelled, and this must be taken in to account when setting appropriate water velocity design criteria. However, it should be noted that this relationship will vary between individuals and species, with fish size, environmental conditions (e.g., water temperature) and the distance to be travelled. This variation is illustrated in the example in Figure E-5, which shows the range of passable water velocities for inanga of different sizes passing through culverts of different lengths.

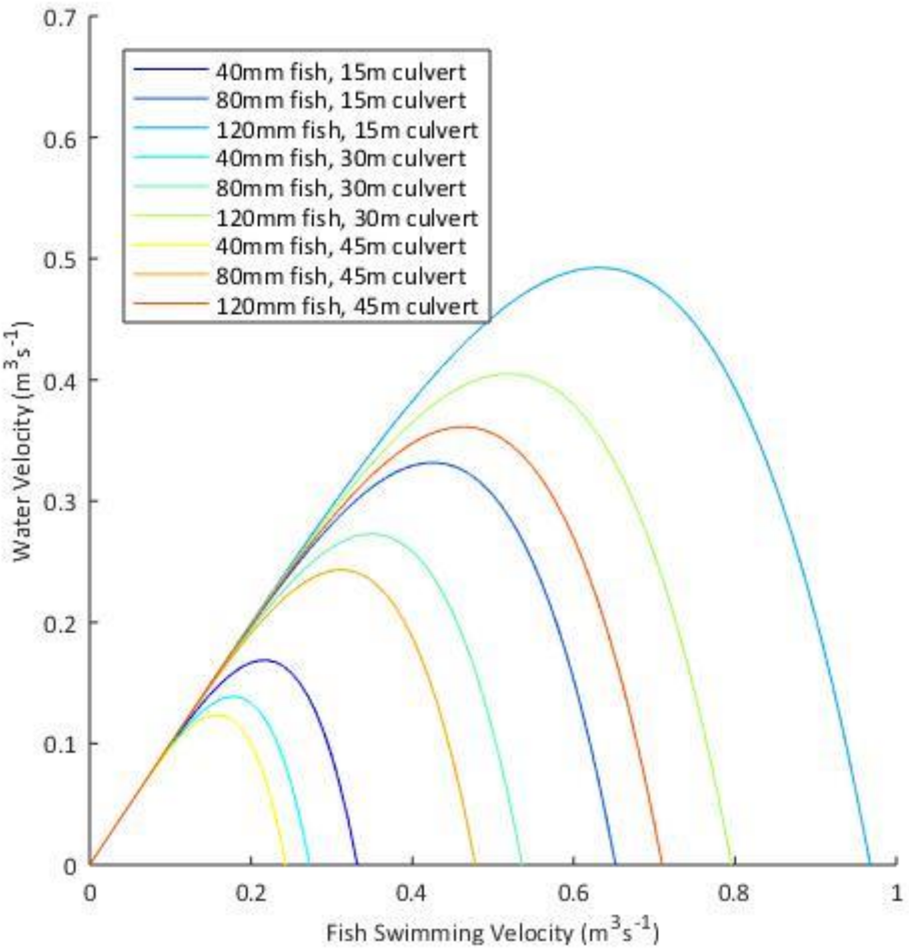


Figure E-5: Variation in passable water velocity for different sized inanga in different culvert lengths.

It is also appropriate to recognise that in any situation there is spatial variability in water velocity and that fish are well adapted to exploiting these variations. For example, water velocity is always lower close to the bed or edges when compared to mid-stream, due to the effects of friction. Fish (particularly benthic species such as bullies) will utilise these boundary layer conditions where water velocity is lower to facilitate their upstream movements. For example, this was suggested as a key driver for the greater passage success of salmonids through corrugated culverts as opposed to smooth culverts where the corrugations create a larger boundary layer with low velocity resting zones (Goerig et al. 2015).

Water depth

Insufficient water depth over or through structures can cause passage problems for fish. Shallow, flat aprons at the outlets of culverts or below weirs are an area where this commonly occurs (Figure E-6). Swimming ability is compromised for a partly submerged fish both due to impacts on the efficiency of swimming (e.g., reduced thrust) and, if the gills are not fully submerged, reduced oxygen availability impacting aerobic performance (Webb 1975; Webb et al. 1991). Water depth design criteria are, therefore, typically defined based on the water depth required to fully submerge the target fish species and will be greatest where passage provisions are required for deeper bodied fish, e.g., adult kōkopu or trout.

In New Zealand, many upstream migrating fish species are small, can spend short periods out of water and have good climbing ability (McDowall 2000). Consequently, shallow depth is not necessarily a problem for these fish and water depth could potentially be exploited as a means of limiting the movement of some of the larger exotic fish species present in New Zealand (see Section 6). However, in negotiating shallow water, fish are more susceptible to predation and the energetic implications of having to climb rather than swim are poorly understood (Kemp et al. 2009; McLaughlin et al. 2013).

Figure E-6: Example of shallow water that can act as a barrier to movement for fish. Credit: Eleanor Gee.

Turbulence

Most studies of fish swimming performance and locomotion have been carried out in a simplified hydrodynamic environment under uniform flow conditions (Liao 2007). However, such conditions are rare in nature and there is increasing evidence to show that fish swimming performance can be significantly altered in complex hydrodynamic environments (Enders et al. 2003; Liao et al. 2003a; Lupandin 2005; Silva et al. 2012).

When water flows over, through or around a structure, either natural (e.g., a rock) or artificial (e.g., a weir), velocity gradients are created which result in turbulent conditions of varying scales and intensities. Depending on the characteristics of turbulence in a given situation it can either attract or repel fish (Liao 2007). For example, there are numerous studies that document the increased energetic costs of swimming in turbulent flow (Hinch and Rand 1998; Enders et al. 2003; Tritico and Cotel 2010). However, turbulent flows that maintain an aspect of predictability can be exploited by fish to reduce the energetic costs of swimming (Liao et al. 2003a; Liao et al. 2003b). Other studies have demonstrated little difference in swimming performance between environments with uniform and turbulent flows, but acknowledge that this may be related to the scale of turbulent eddies relative to fish size (Nikora et al. 2003).

The differences in swimming performance between laboratory forced swimming experiments in controlled hydrodynamic conditions and volitional swimming behaviour in real-world situations are likely, in part, a consequence of fish exploiting natural hydrodynamic variability to facilitate upstream movements (Vowles et al. 2013). Large eddies (relative to body size) can provide low velocity resting areas, and the boundary layer close to the stream substrate also offers conditions that fish can exploit to save energy and improve passage rates. However, where structures create turbulence that elicits avoidance behaviour or that exceeds the swimming performance of fish, it can impede the passage of fish (Williams et al. 2012).

Physical blockage

Structures such as weirs, dams, tide gates and pumping stations can physically block the movement of fish, both upstream and downstream, by blocking streams and rivers. Jellyman and Harding (2012) showed that large dams alter freshwater fish communities in New Zealand as a consequence of blocking fish migrations, with sites above dams having lower species richness, a lower percentage of diadromous species, and a higher percentage of exotic fish species, when compared to below dams. Weirs also often act as a temporal barrier to fish migration, with passage dependent on flow conditions overcoming the blockage caused by the weir (Winter and Van Densen 2001; Keller et al. 2012) (Figure E-7).

Figure E-7: An intake weir that blocks fish migrations on the Te Arai River near Gisborne. Credit: Jamie Foxley.

Doehring et al. (2011a) found that tide gates act as a temporal barrier to upstream migration of inanga, with more than twice the number of fish passing an un-gated culvert than a culvert with a tide gate (e.g., Figure E-8). Delays in upstream migration were also observed at the gated site, with fish primarily moving upstream during high tide at the un-gated site, but having to wait until low tide when the gate was open at the gated site. Bocker (2015) also found a significant increase in the number of native fish (inanga and bullies) able to pass upstream through a tide gate when fitted with a fish friendly gate design. Bocker (2015) found that upstream migration of inanga primarily occurred on the incoming tide, which is also when tide gates are closed. The installation of fish friendly gate designs resulted in the gates remaining open for a longer period, including during the early phase of the flood tide. This allowed more fish to pass upstream with a twenty-fold increase in the number of whitebait captured upstream of the tide gate when the fish friendly gate was operating. Similar results have been observed in overseas studies, with Mouton et al. (2011) showing European glass eels blocked by a tidal barrier and Wright et al. (2016) reporting significant delays in upstream passage of adult brown trout at a tide gate.

Figure E-8: An example of a tide gate from the Waikato River catchment. Credit: Rimutere Wharakura.

Crest shape

The shape of a weir's crest has also been shown to impact on the ability of fish to pass. Baker (2003) investigated the effect of notch shape on fish passage over an experimental weir at varying fall heights (Figure E-9). It was shown that while notch shape had relatively little effect on the passage of inanga, it did have a significant effect on the passage of common bullies under the conditions tested. The optimal notch shape under the conditions tested by Baker (2003) was a v-notch design, with the least effective design being a wide rectangular notch. The differences in performance were attributed to the availability of low velocity margins on the edges of the channel that allowed fish to approach the weir before seeking out the high velocity flow at the base of the weir.

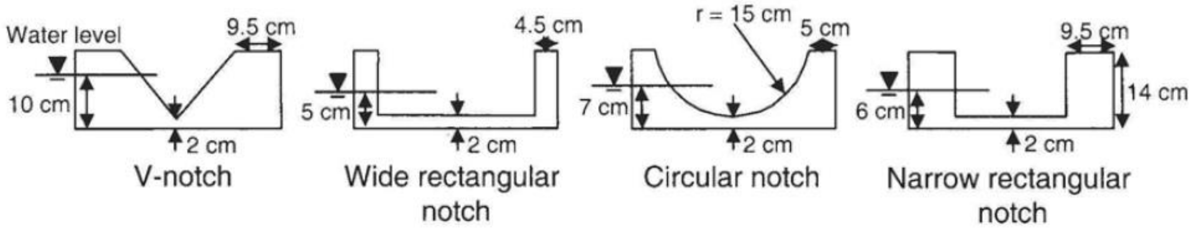


Figure E-9: Weir notch lateral cross-section shapes tested by Baker (2003).

A weir's longitudinal profile also impacts on the ability of climbing fish species to pass. Overhanging weir crests or weir crests with sharp (e.g., 90°) angles are more difficult for fish to pass than weir crests with a rounded profile (Figure E-10).

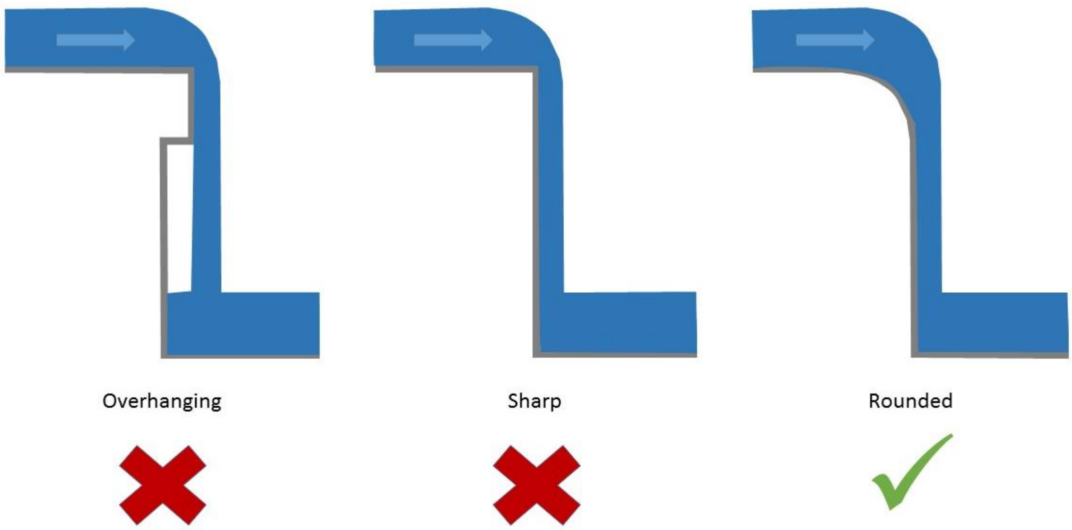


Figure E-10: Examples of different weir longitudinal cross-sectional profiles that influence fish passage success.

Silva et al. (2016) have also recently demonstrated that the inclination of the upstream face of a spillway or weir impacts on downstream passage success of fish. They evaluated downstream passage success of the European eel (*Anguilla anguilla*) and Iberian barbel (*Luciobarbus bocagei*), a cyprinid species, at weirs with 30°, 45° and 90° upstream inclinations (Figure E-11). It was observed that both species avoided the turbulent area immediately upstream of the 90° weir, resulting in lower passage success, particularly for eels. However, with the sloped weir faces, this turbulent area was eliminated resulting in enhanced passage.

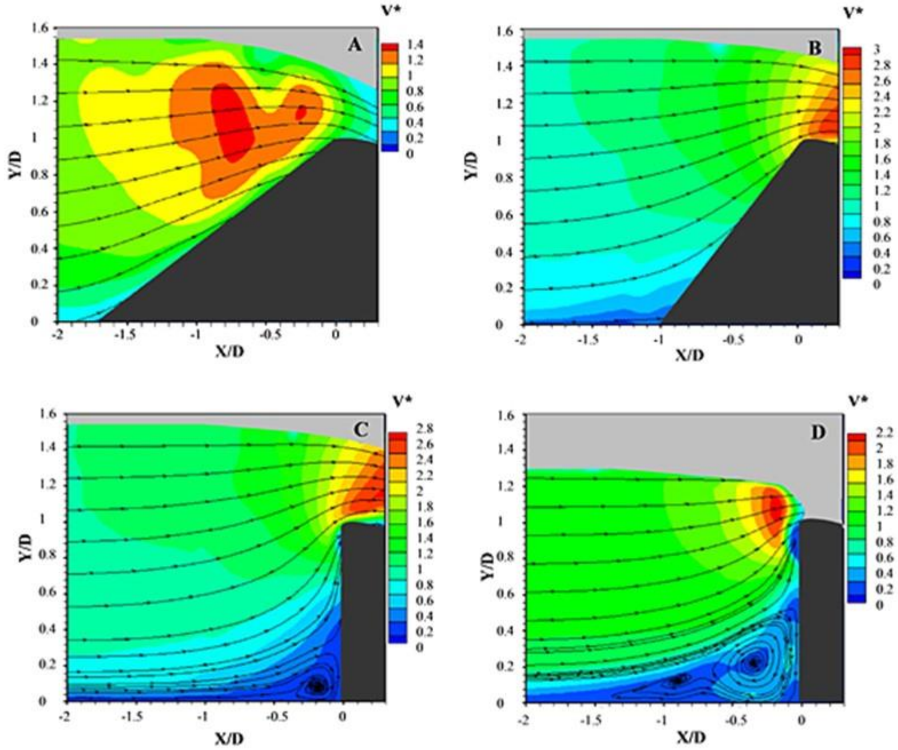


Figure E-11: Dimensionless water velocity (V*) and streamlines for the four experimental weir designs tested by Silva et al. (2016). Experiments conducted with depth of the approach flow H = 0.42 m and upstream face inclination of 30° (A), 45° (B) and 90° (C); and H = 0.32 m with upstream face inclination of 90° (D). Structures and areas outside the measured flow region are in dark and light grey, respectively. Dimensionless velocity V* values correspond to colours. Flow enters from the left. Source: River Research and Applications, Volume 32, Issue 5, pages 935-945 (http://onlinelibrary.wiley.com/doi/10.1002/rra.2904/full).

Attraction flows

Fish have an innate behaviour that leads them to orientate themselves into the flow (rheotaxis) (Arnold 1974). Rheotaxis is a multisensory behaviour in which the relative role of the different sensory cues is thought to vary with factors such as reference frame and proximity of objects (Baker and Montgomery 1999; Bak-Coleman et al. 2013; Elder and Coombs 2015). Rheotaxis behaviour is influenced by flow turbulence, and the presence of olfactory cues, and is a key behaviour driving migration.

During their upstream migration, fish are naturally drawn to conditions that indicate their migratory pathway will keep them within the main flow of a river (Williams et al. 2012). Instream structures typically alter flow pathways and hydraulic conditions, thus altering the cues for rheotaxis. Consequently, the flow conditions that a fish experiences at an instream structure are fundamental to achieving successful passage (Bunt et al. 2012). If appropriate flow conditions do not exist, fish will avoid, or fail to locate, the correct pathway upstream. This is a particular problem where only a small proportion of the flow is made available at a fish bypass, while the majority of flow passes over or through a structure, e.g., at dams and weirs. In this situation, sufficient attraction flow must be made available in the right configuration relative to the main flow to allow fish to locate the bypass and enter it without delay. Little work has been done with respect to attraction flow configuration for native species in New Zealand. O'Connor et al. (2015) provides some guidance on general principles of good attraction flow configuration.

During their downstream migration, eels effectively use a 'reverse rheotaxis' and actively seek out the dominant downstream flow pathways (Jellyman and Unwin 2017). Consequently, there is a challenge in ensuring adequate flow is provided to guide eels past instream structures. In contrast, the downstream dispersal of many of our other freshwater species during the larval life stage, e.g., galaxiids and bullies, is likely to be largely passive (e.g., Jarvis and Closs 2015).

Other factors

A range of other factors have also been identified that may have an impact on passage success at an instream structure. Slope has been shown to influence passage success over ramps (Doehring et al. 2011b; Baker 2014). At a slope of 15°, both inanga and common bullies could pass ramps from 3 to 6 m in length, although passage success decreased with increasing ramp length. However, at 30° inanga could only pass a 3 m ramp, and common bullies were incapable of passing any ramp length tested (Baker 2014). Passage success of redfin bullies was also reduced as ramp slope increased, but there was no significant effect of ramp length (Baker 2014). Doehring et al. (2011b) also found that as ramp angle increased from 5° to 20°, there was a significant reduction in the passage success of inanga over a 3 m ramp with an artificial grass substrate. However, ramp slope has a significant effect on water velocity, with higher water velocities at higher slopes. It is, therefore, not clear to what extent the observed effect is a direct consequence of slope as opposed to greater water velocity or other hydrodynamic factors.

Light has also been proposed as having an effect on passage success, but there is limited evidence available to directly support this. Vowles and Kemp (2012) found that downstream migrating trout, which typically avoid sudden increases in water velocity, were extra-avoidant when light was present than when it was absent. Kemp et al. (2006) investigated the effects of light and dark conditions on downstream migrating salmon smolts passing a weir and found that different species and different sized conspecifics reacted differently in the presence or absence of light. The implications of these findings for upstream passage of juvenile fish in New Zealand are ambiguous, especially given the differences between species found by Kemp et al. A mark-recapture test of passage success of young-of-the-year *Galaxias spp.* in southern Australia through a 70 m long culvert found that passage success was unaffected by light conditions (Amtstaetter et al. 2017). However, in another Australian study, low light was shown to inhibit native fish movements through a vertical slot fishway suggesting that instream structures that alter light intensity may act as behavioural barriers to fish movement (Jones et al. 2017). In the same study, provision of artificial light of a similar intensity to daylight mitigated for the impact of reduced light.

Barotrauma, physical injuries caused by changes in water pressure, has been demonstrated as a cause of mortality in larval herring (Hoss and Blaxter 1979), and suggested as an explanation for higher mortality associated with fish passing undershot weirs than overshot weirs (Baumgartner et al. 2006). The construction or modification of structures should therefore avoid instigating conditions which lead to sharp changes in hydraulic head or water depth to minimise the risk of barotrauma to fish passing the structures.

Injury due to entrainment in flood control or irrigation pumps is a risk to migrating fish; in New Zealand this is especially relevant to eels. Pump rotational speed appears to be a critical factor in rates of mortality, and grills over pump intakes during non-operational times may help prevent mortalities by excluding eels from sheltering in these spaces (Bloxham, Burnett and Olliver 2017). Large eels (> c. 600 mm) may suffer much higher mortality than smaller eels (Vaipuhi Consulting 2017). The type of pump impeller may also affect mortality. Downstream migrating European silver eels (*Anguilla L.*) suffered mortalities around 97% upon passage through a propeller pump, and around 17 – 19% when passing through an Archimedes screw pump (Buysse et al. 2014).

Bannon and Ling (2003) also demonstrated the potential consequences of degraded water quality on fish migrations through effects on fish swimming abilities. The sustained swimming abilities of juvenile rainbow trout, and larval and post-larval inanga were shown to be compromised under elevated water temperatures and under mild hypoxia (75% dissolved oxygen saturation). This suggests that movement of migratory fishes through lowland rivers with degraded water quality could be significantly limited. In addition, point source discharges of pollutants can also alter migration patterns and heavy metals can render migratory fish unable to perceive odour and modify migration cues.

Examples of barriers

In practice, instream structures that are barriers to fish movements often combine several of the different features outlined above. The following pages contain examples of a range of obstructions to fish passage, with brief descriptions of why each constitutes a barrier. It is hoped that they will be instructive to those who are new to the topic of fish passage.

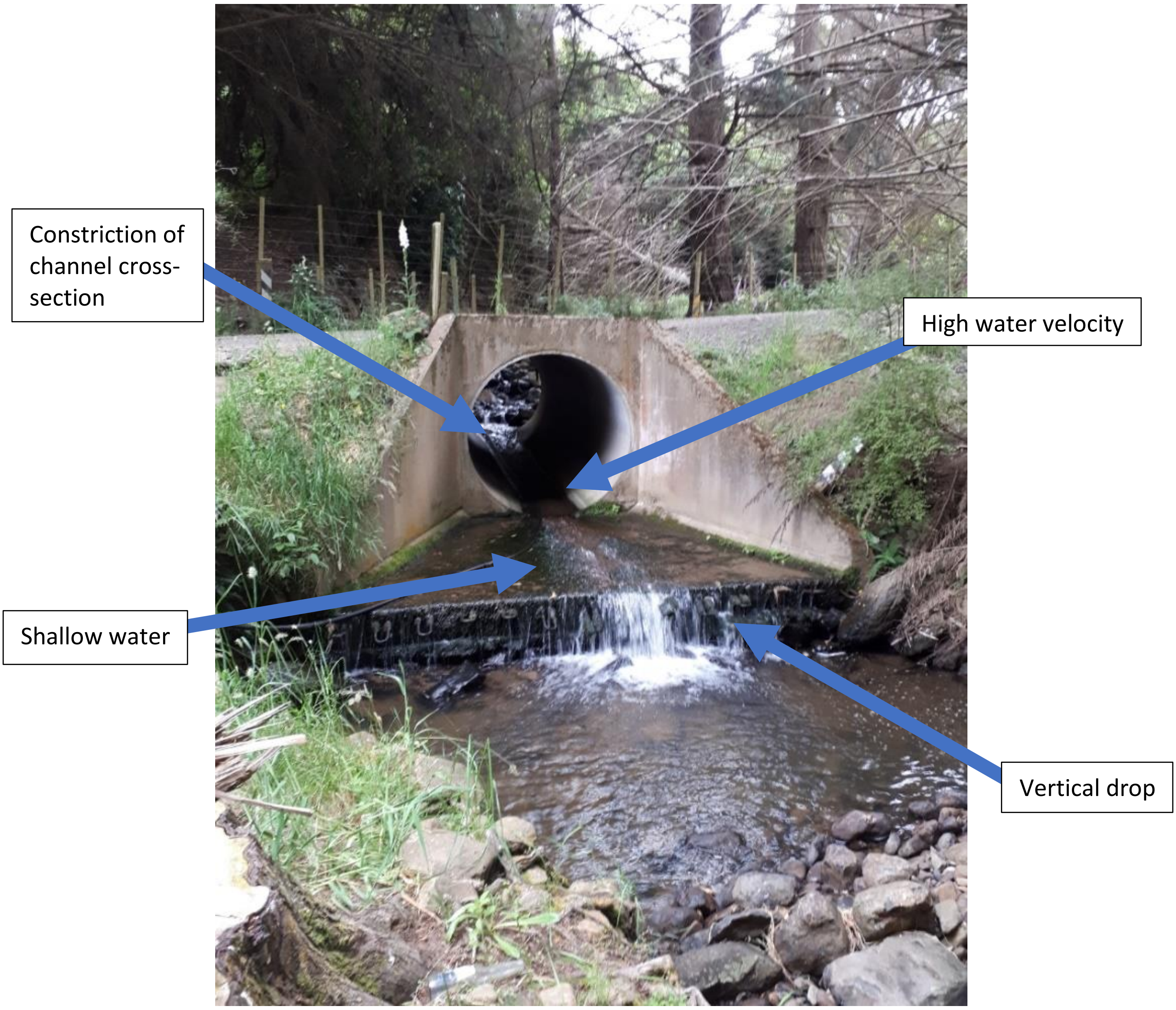


Figure E-12: Fish passage at this culvert will be impeded by the drop at the downstream end of the apron and the shallow water on the apron. Credit: Sam Ammon.

Figure E-13: Example of a weir in central Christchurch. Fish passage will be impeded by the fall height of the steps in the weir and the salmonid fish passes. Credit: Megan Brown.

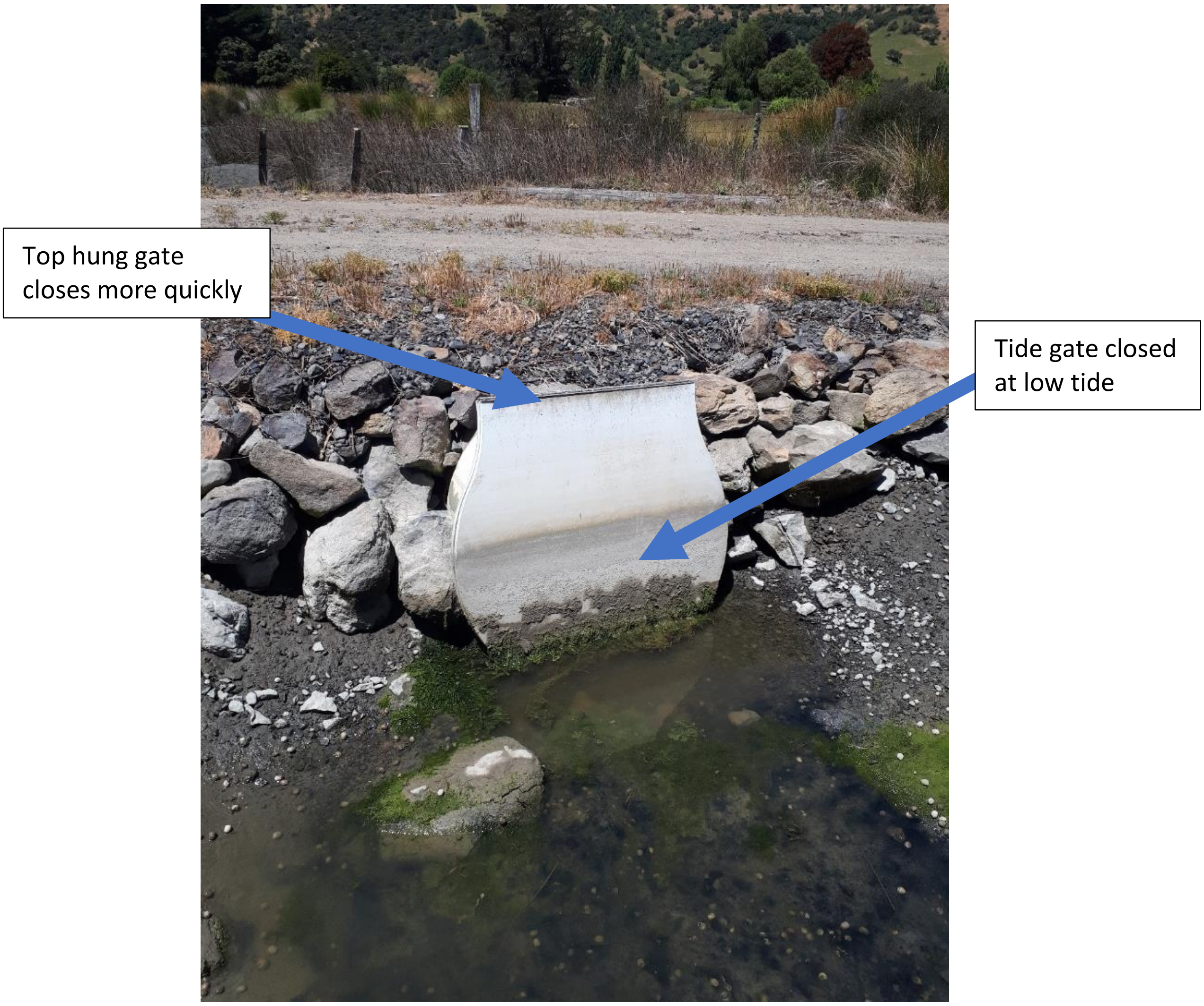


Figure E-14: Example of a culvert with a flap gate. Fish passage will be impeded by the flap gate being closed, even at low tide. Credit: Sam Ammon.

Figure E-15: Fish passage will be impeded by the fall height and undercut at the culvert outlet. The smooth culvert barrel will also lead to higher water velocities and limit fish movements under higher flows. Credit: Megan Brown.

Figure E-16: A double barrel culvert where passage will be impeded by the fall height at the culvert outlet. Passage for climbing fish species may be possible over the rocks below the culvert in the right of the picture. Credit: Sam Ammon.

Figure E-17: Fish movements will be impeded by the fall at the downstream end of the apron and shallow water on the apron. Credit: Sam Ammon.

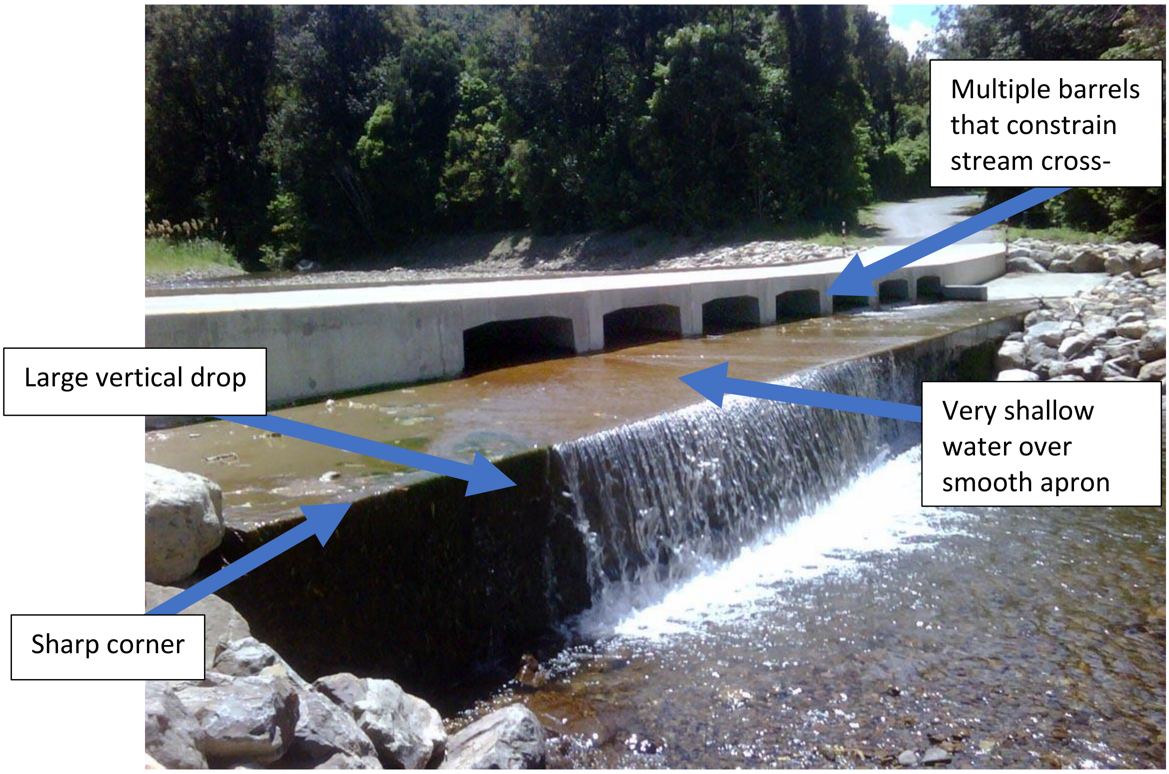


Figure E-18: An example of a drift-deck ford. This is a significant barrier to fish due to the large fall height on the downstream side of the structure. Passage may also be impeded by the sharp corner on the edge of the apron, shallow water, and high water velocities during high flow.

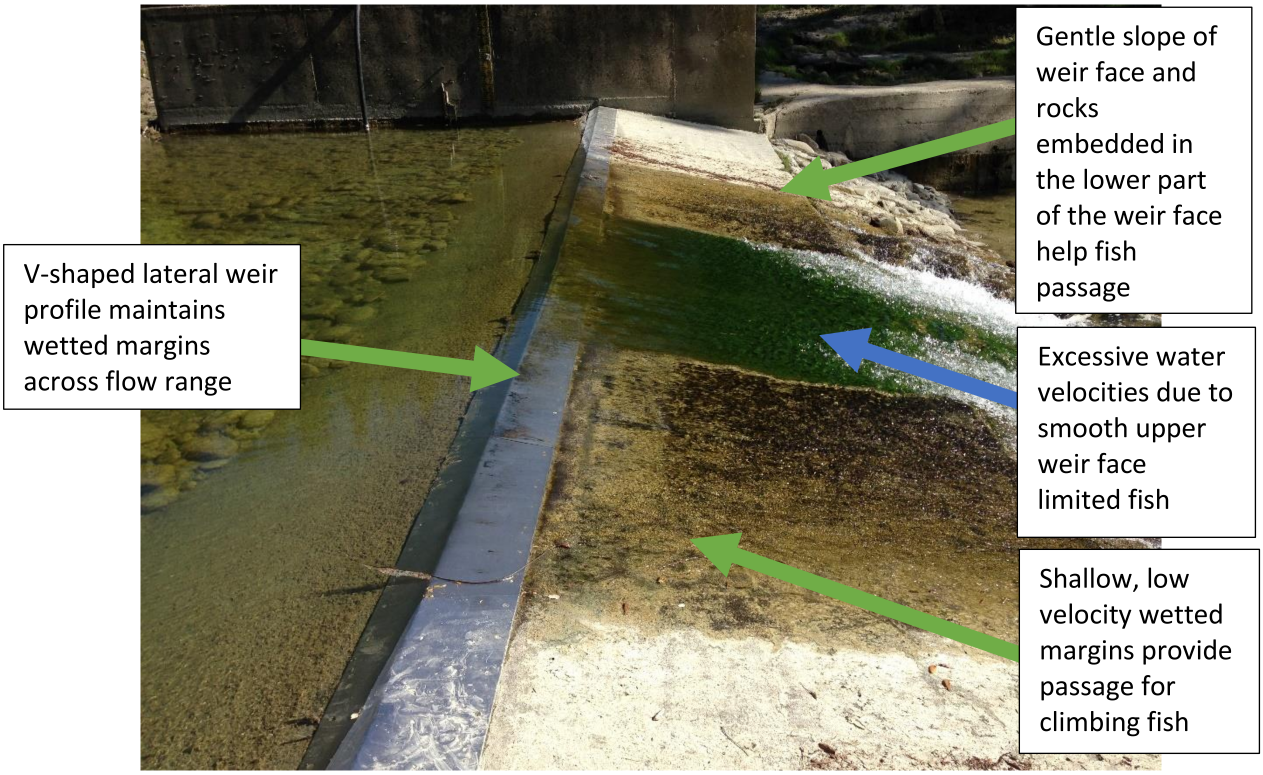


Figure E-19: An example of a crump weir used for hydrological gauging. Fish passage was impeded for swimming fish at this weir by the high water velocities. Climbing fish were able to use the wetted margins on each side of the weir to pass. Credit: Paul Franklin.

Figure E-20: Example of a ford from the Te Arai River. The fall height at the two steps on the downstream side of the ford makes a complete barrier to swimming fish species. Passage for climbing fish will be impeded by the sharp corners on the steps and shallow water across the ford, but some may access upstream habitats by taking advantage of the wetted margins to climb. Credit: Paul Franklin.

Figure E-21: The fall height on this ford on the Te Arai River is a significant impediment to the upstream passage of fish. Credit: Paul Franklin.

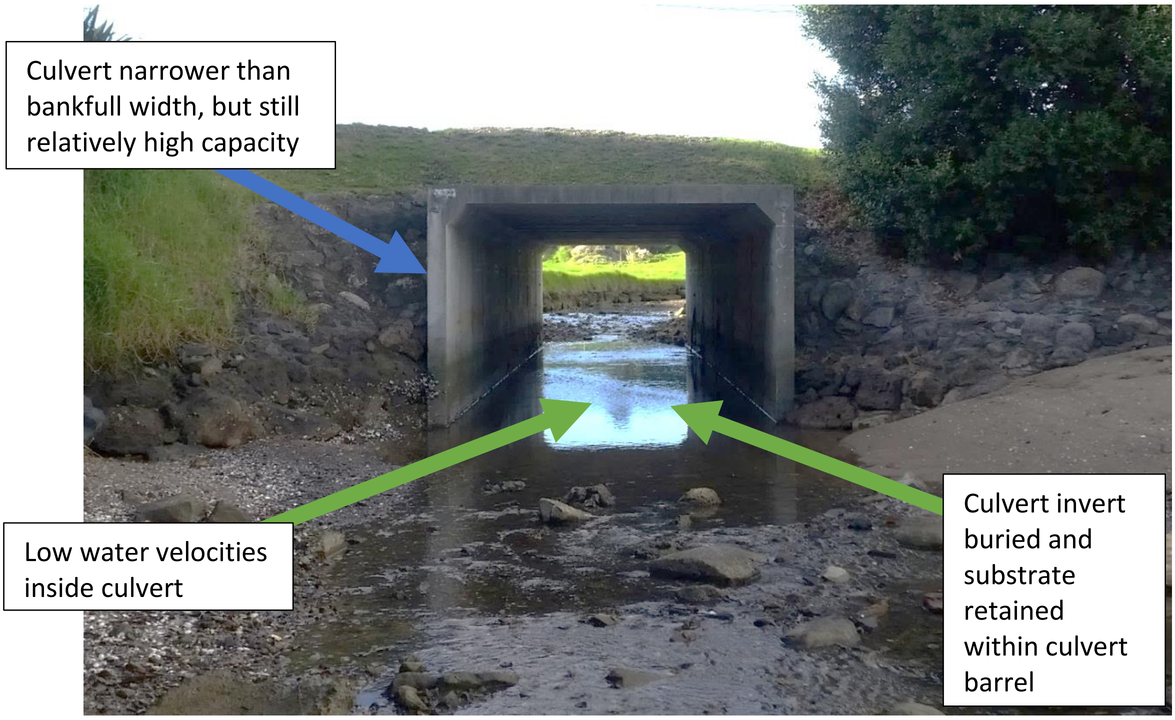


Figure E-22: Example of a culvert in a tidally influenced area. The culvert invert is embedded meaning that natural substrate is retained through the culvert. Culvert width relative to the stream bankfull width is lower than recommended, but because the culvert is in a tidal area, low water velocities will exist through the culvert during slack tide conditions. Credit: Bryn Quilter.

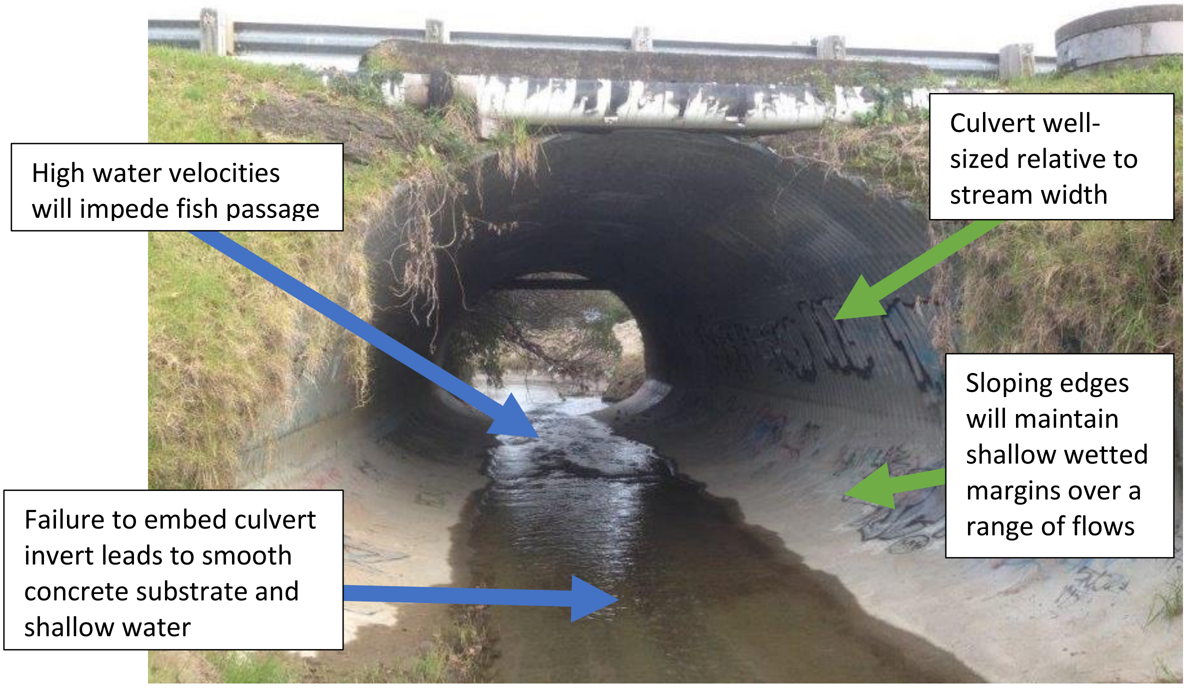


Figure E-23: Culvert well sized relative to stream width, but failure to embed the culvert invert leads to shallow water depths and high water velocity. If this culvert had been embedded so that substrate was retained through the culvert it would have been a good example of how culverts can provide fish passage. Credit: Mark Pennington.

Appendix F Fish swimming speed look-up tables

Table F-1: Maximum allowable water velocity (U_w; m s^{-1}) for a range of fish (L_f) and culvert sizes (L) for inanga. These values are derived using the method described in Section 4.2.2 and are based on the relationship provided by Nikora et al. (2003). Grey areas are outside the range of the published relationship (t>400 s and 4< U_f/L_f <18). Maximum allowable water velocity should be calculated as the mean cross-sectional water velocity in the culvert.

		Fish length (mm)								
		40	50	60	70	80	90	100	110	120
Culvert length (m)	5	0.16	0.20	0.24	0.28	0.32	0.36	0.39	0.43	0.47
	10	0.13	0.16	0.20	0.23	0.26	0.29	0.32	0.36	0.39
	15	0.12	0.15	0.18	0.20	0.23	0.26	0.29	0.32	0.34
	20	0.11	0.14	0.16	0.19	0.21	0.24	0.27	0.29	0.32
	50	0.08	0.10	0.12	0.15	0.17	0.19	0.21	0.23	0.25
	75		0.09	0.11	0.13	0.15	0.17	0.18	0.20	0.22
	100			0.10	0.12	0.14	0.15	0.17	0.19	0.20
	150							0.15	0.17	0.18
	200									

Appendix G Minimum design standards for fish passage at instream structures

1. Minimum design standards for fish passage will achieve:
    a. Efficient and safe passage of all aquatic organisms and life stages with minimal delay, except where specific provisions are required to limit the movement of undesirable exotic species.
    b. A diversity of physical and hydraulic conditions leading to a high diversity of passage opportunities for aquatic organisms.
    c. A structure that will provide no greater impediment to fish movements than adjacent stream reaches.
    d. Structures that have minimal maintenance requirements and are durable.

2. Culverts installed in freshwater bodies will meet the following minimum design standards for fish passage[11]:
    a. Alteration of natural stream channel alignment will be avoided or minimized.
    b. Alteration of natural stream gradient will be avoided or minimized.
    c. Culvert span[12] will be:
        i. Equal to or greater than 1.3 x stream bankfull width[13] for streams with a bankfull width ≤3 m.
        ii. Equal to or greater than 1.2 x stream bankfull width + 0.6 m for streams with a bankfull width >3 m.
    d. Open bottom culverts will be used or the culvert invert will be embedded by 25-50% of culvert height.
    e. Well graded substrate will be present throughout the full length of the culvert bed.
    f. Substrate within the culvert will be stable at the high fish passage design flow[14].
    g. Mean cross-sectional water velocity in the culvert over the fish passage design flow range will be equal to or less than the greater of:
        i. mean cross-sectional water velocity in adjacent stream reaches, or
        ii. the maximum allowable water velocity calculated from fish swimming speeds of agreed target fish species and/or life stages[15].
    h. Minimum water depth in the culvert at the low fish passage design flow will be the lesser of:
        i. 150 mm for native fish passage, or 250 mm where adult salmonid passage is also required, or
        ii. mean cross-sectional depth in adjacent stream reaches.
    i. Ancillary structures must not create an impediment to fish passage.
    j. Vertical drops will be avoided throughout the structure.
3. Weirs installed in freshwater bodies will meet the following minimum design standards for fish passage:

[11] Culverts must also meet relevant hydraulic conveyance and technical design standards
[12] Culvert span is defined as the width of the culvert at the point it intersects with the stream bed
[13] Bankfull width is defined as the width of the river channel at the bankfull discharge. The bankfull discharge is the discharge that fills a stable channel to the elevation of the active floodplain.
[14] Low (Q_L) and high (Q_H) fish passage design flows represent the range of flows at which fish passage is required. As a rule of thumb $Q_L \leq$ 95% exceedance flow and $Q_H \geq$ 20% exceedance flow.
[15] See Section 4.2.2.3 for methodology and 0 for look-up tables of maximum allowable water velocity.

a. Where practicable use a full width rock-ramp fishway as an alternative to a conventional weir for raising headwater levels in a river.
b. The slope of the weir should be:
    i. 1:30 for a rock-ramp weir where weakly swimming species such as inanga and smelt require passage.
    ii. Equal to or less than 1:10 for a conventional weir design where fall height is ≤1 m.
    iii. Equal to or less than 1:15 for a conventional weir design where fall height is 1-4 m.
c. The use of smooth concrete for the downstream weir face should be avoided.
d. Roughness elements should be added to the weir face. A suitable solution would be to cover the weir face with embedded mixed grade rocks 150-200 mm. Rocks should be closely (70-90 mm) and irregularly spaced to create a hydraulically diverse flow structure across the weir.
e. All weirs should have a V-shaped lateral profile, sloping up at the banks and providing a low-flow channel in the centre. 5-10° is a suitable slope for the lateral cross-section.
f. A continuous low velocity wetted margin should be provided up the weir throughout the fish passage design flow range.
g. Broad-crested weirs are recommended and the downstream edge of the crest must be rounded.
h. Backwatering of upstream habitats because of the weir should be minimized.

4. The use of fords in freshwater bodies will be avoided or minimized. Where fords are installed they will meet the following minimum design standards:
    a. Reduction in the channel cross-sectional area at the ford should be avoided or minimized over the fish passage design flow range.
    b. Fords must incorporate culverts and meet the minimum design standards for culverts.
    c. Where multiple culvert barrels are required circular culverts must be avoided and box culverts used.
    d. Substrate must be maintained through the full length of the culverts and remain stable across the fish passage design flow range.
    e. Alteration of natural stream channel alignment should be avoided or minimized.
    f. Alteration of natural stream channel gradient should be avoided or minimized.
    g. Ensure that the surface of the ford is roughened (e.g., through embedding rocks) to facilitate passage of fish over the ford when flows overtop the structure.
    h. The lateral profile of the ford should be V-shaped to ensure that wetted margins are maintained across the ford when it is overtopped during elevated flows.

Appendix H Remediation case studies

An archive of remediation case studies is being collated by the New Zealand Fish Passage Advisory Group. They provide key information and guidance about attempts to improve a variety of different types of fish passage barriers in New Zealand waterways.

The case studies can be accessed at www.doc.govt.nz/fishpassage.

Appendix I Monitoring case studies

Kara Stream, Manawatu

This case study describes the results of mark-recapture trials undertaken at a culvert on Kara Stream, Manawatu, which has been retrofitted with a rock-ramp and culvert baffles. This case study helps to illustrate the practical limitations of applying the mark and recapture methodology, but also how monitoring can inform design improvements to increase the efficacy of a structure.

Study design

During the remediation works, it was deemed unfeasible to build the rock-ramp on top of the existing culvert apron (Figure I-1). As such, one aim during the trials was to determine if the apron presented a bottleneck for fish passage and, therefore, also required retrofitting (Figure I-3). In addition, there was no documented field tests of the plastic baffles (0.18 m in height) installed at 1.24 m intervals along the length of the culvert barrel (Figure I-2). Consequently, to ensure each component of the instream structure was effective at promoting inanga passage, the culvert was assessed independently from the rock-ramp. To achieve these aims, three mark and recapture trials with juvenile inanga were carried out between 15 and 19 September 2014:

Trial 1 - Rock-ramp + culvert: Examining fish passage over the rock-ramp, unmodified apron and through the culvert.

Figure I-1: Remediated culvert on Kara Stream, Upper Kingston Road. Inset shows the unmodified culvert apron.

Trial 2 - Culvert: Examining fish passage through the culvert only.

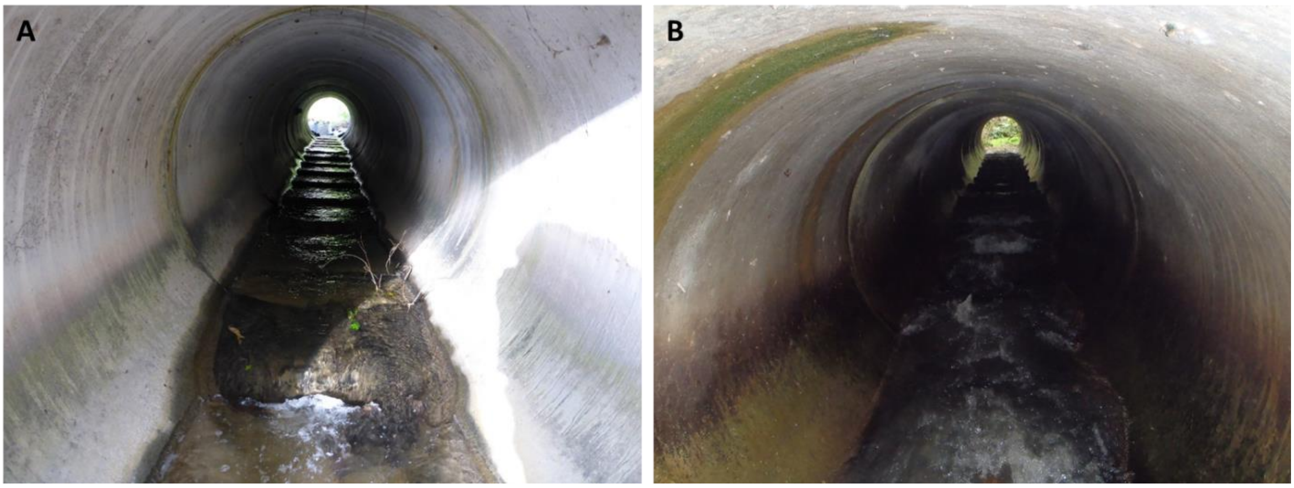


Figure I-2: Culvert under Upper Kingston Road. A, at low flow. B, at high flow.

Trial 3 - Rock-ramp + mod apron + culvert: Examining fish passage over the rock-ramp, modified apron and culvert.

Figure I-3: Culvert apron at Upper Kingston Road. A, unmodified. B, modified using boulders as baffling elements.

Because of logistics in co-ordinating NIWA and Horizons staff for testing the effectiveness of the fish pass at Upper Kingston Road, these trials were carried out under sub-optimal flow conditions. This unfortunately led to the final trial of the entire structure with the modified apron being washed out in rising flood water, but it does provide a good example of issues that can occur when undertaking mark and recapture experiments.

Control fish

For each of the three trials, inanga were marked in Rhodamine B and Bismarck Brown the day prior to release. After marking, between 30 and 50 fish of each colour were held as control fish. For all three sets of control fish, no mortality was observed after 48 hours. Inanga marked on the 15th September for the first trial, were held till the 19th September with no mortality recorded. This shows the marking procedure was not causing mortality in experimental fish.

Trial 1: Rock-ramp + culvert (24 h)

Three replicates containing 200 inanga (pink, orange and uncoloured (clear)) were released in the pool below the rock-ramp (see Figure 7-5). Each replicate was sequentially released at 30 minute intervals from 8:20am on 16th September 2014, and given 24 hours to pass the rock-ramp and culvert. For all three replicates, fish size ranged between 45 and 59 mm.

At the conclusion of the trial the proportion of fish that were recaptured in each section of the in-stream structure, missing and dead fish were relatively similar between marked (pink and orange) and uncoloured replicates (Figure I-4). This indicates that the marking procedure did not unduly influence behaviour or passage ability compared to inanga that were not subjected to the marking procedure.

After 24 hours, no inanga had successfully passed the instream structure, and no inanga were found inside the culvert itself (Figure I-4). Close to half of the inanga released were recaptured on the rock-ramp, in the pool below the rock-ramp, or below the first barrier net in the pools created by the rock weirs before the secondary stop net (Figure I-4; see Figure 7-3B & C for stop net positioning).

However, around half of the test fish were missing with a small proportion found dead in the barrier net (Figure I-4). As the trials were carried out at higher than base-flow conditions, it is likely that inanga were attempting to move downstream into quieter waters and were successful at passing the barrier nets. The small proportion of dead fish are most likely fish that succumbed to the cumulative stressors of capture, handling, and release into an area where they were vulnerable to damage or getting trapped by the barrier net when trying to move downstream.

The high proportion of fish moving downstream during the trial could also have been influenced by the fact that they were unable to move upstream and pass the structure. No inanga passed the culvert apron, even though inanga were observed reaching the apron and resting on the apron margins (Figure I-5). The average water velocity over the apron was considerably higher than that inside the culvert or over the rock-ramp (Table I-1). On average, 50-70 mm inanga can burst swim at 1.5 m s^{-1} for 4 sec, and 2 m s^{-1} for 2 sec (Stevenson and Baker 2009). Therefore, at the trial flows, water velocity over the apron (>1.5 m s^{-1}; Table I-1) would have been a limiting factor for juvenile inanga passage.

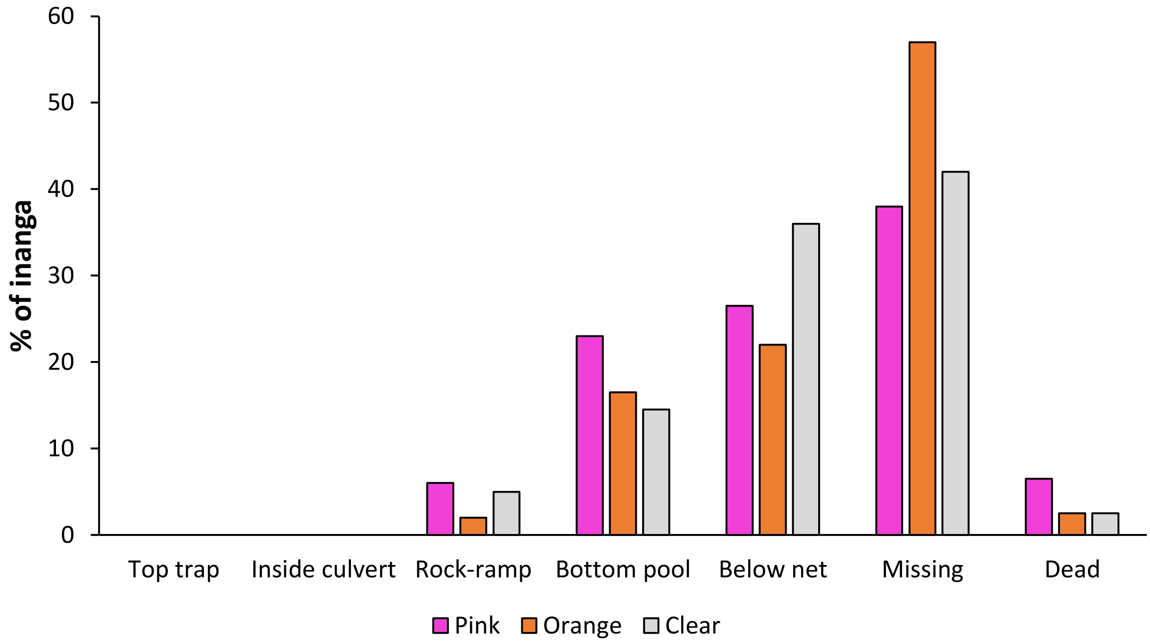


Figure I-4: Percentage of inanga successfully passing the rock-ramp and culvert, recaptured in different sections of the structure, dead or unaccounted for. 'Bottom pool' represents inanga in the pool at the base of the rock-ramp. 'Below net' represents inanga captured in the pools above the second barrier net. Results after 24 hours.

A further impediment for inanga is likely caused by the transition between the culvert apron and the baffling inside the culvert barrel, where a weir is formed immediately at the culvert outlet (Figure I-6). Should inanga successfully burst swim over the apron, there is no low velocity water or rest area prior to the requirement to burst swim over the weir. Consequently, the cumulative effect of water velocity over the apron and the weir at the culvert outlet are likely to be the key factors presently preventing inanga passage past the culvert. It should be noted, however, that species capable of climbing, such as banded and shortjaw kōkopu, (that are also found in Kara Stream) will not be prevented from passing over the apron and into the culvert as the wetted margin is sufficient for allowing passage of these species.

Figure I-5: Pink inanga resting on the culvert apron (red circle).

Table I-1: The flow ($m^3 s^{-1}$) of Kara Stream and mean water velocity ($m s^{-1}$) through the culvert, and over the apron and rock-ramp during each day of the trials. The float used for calculating the average velocity (mandarin or stick) is also provided. For each day, the velocity given is the average of six replicates. - indicates measurements were not recorded that day. † The float over the rock-ramp needed to be changed from the mandarin because of issues with the mandarin getting stuck in the small pools on the ramp.

			Mean water velocity ($m s^{-1}$)			
Date	Trial start	Flow ($m^3 s^{-1}$)	Rock-ramp	Unmodified apron	Culvert	Modified apron
			Stick†	Mandarin	Mandarin	Mandarin
15 Sept		0.017	0.50	1.53	0.36	-
16 Sept	Rock-ramp + culvert	0.025	0.45	1.52	0.34	-
17 Sept	Culvert	0.019	-	-	0.43	-
18 Sept	Rock-ramp + mod apron + culvert	0.015	-	-	-	0.25
19 Sept		0.180	-	-	-	-

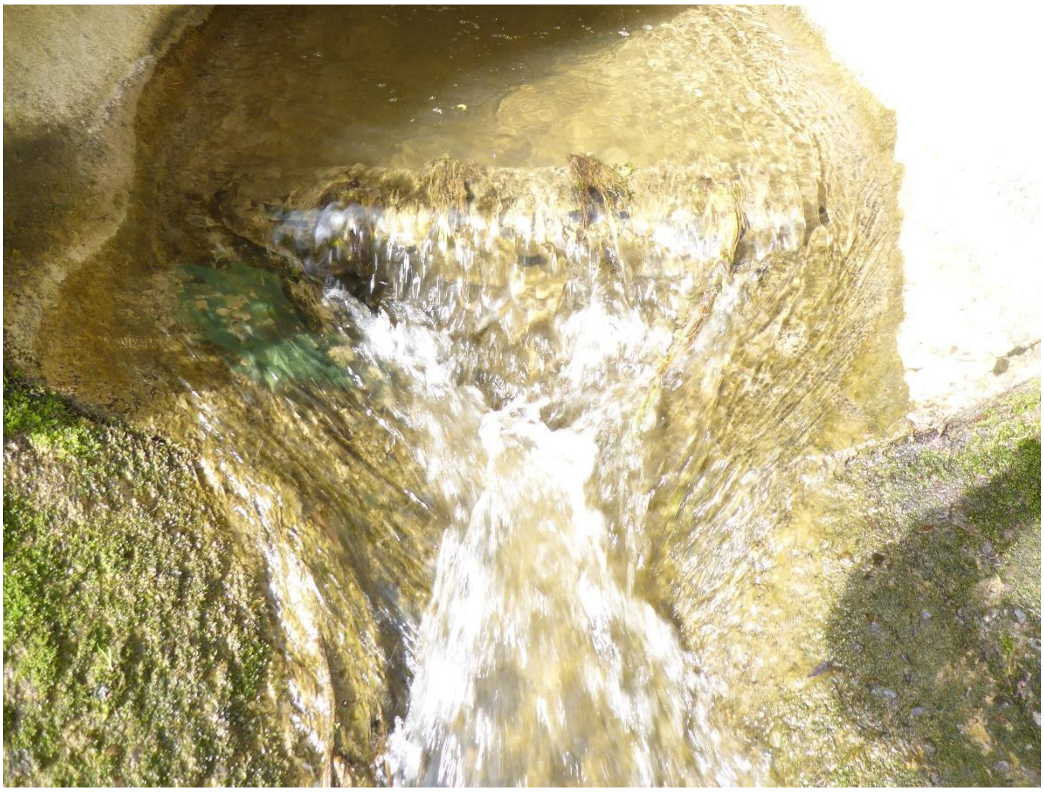


Figure I-6: Weir created by the baffle at the transition point between the culvert outlet and apron.

Trial 2: Culvert only (20.5 h)

Three replicates of fish (198 pink inanga, 200 orange inanga and 179 uncoloured (clear) inanga) were released at 12:30 pm on 17th September 2014, and given 20.5 hours to pass the culvert. All fish were released into the pool formed between the first and second baffles inside the culvert barrel. For all three replicates, fish size ranged between 45 and 75 mm. These juvenile and post-juvenile inanga were captured further inland than those used in Trial 1 and are more representative of the size of inanga that would be reaching the culvert at Upper Kingston Road.

In line with Trial 1, at the conclusion of the trial the proportion of fish that had passed the culvert or were still migrating within the culvert, and those unsuccessful, missing or dead fish were relatively similar between marked (pink and orange) and uncoloured replicates (Figure I-7). These data again support the notion that the marking procedure did not unduly influence behaviour or passage ability compared to inanga that were not subjected to the marking procedure.

On average, 31% of inanga successfully passed the culvert after 20.5 hours, with 10% of fish still migrating upstream within the culvert barrel (Figure I-7). In comparison, the trap was inspected after 5 hours and only a handful of inanga were visible. This suggests that passage through the culvert was slow and, therefore, inanga may need to be left for longer than 24 hours to accurately assess passage over the rock-ramp and culvert.

In contrast to Trial 1, the majority of inanga from each replicate were recaptured (Figure I-7). Here, the barrier nets were more effective due to the smaller wetted width of the stream and the more uniform shape of the culvert and apron. However, around half of the fish released were found dead against the barrier net (Figure I-7). The high death rate is most likely a result of carrying out the trials under higher, sub-optimal flows. Although the baffling inside the culvert creates a pool between the weirs, the pool is shallow (c. 18 cm), and under the trial flows, the pool was turbulent with areas of fast water velocities. It is likely that many of the smaller, weaker fish encountered, and were unable to swim against, the fast water velocities and ended up getting swept into the barrier net. Once pinned against the mesh, the fast water velocities would make it difficult if not impossible for small fish to free themselves (Figure I-8).

An examination of fish size successfully passing the culvert compared to those dead in the barrier net supports this notion (Figure I-9). For the orange and clear inanga, those successfully passing the culvert were significantly larger than those found dead in the barrier net ($P<0.05$; Figure I-9). Collectively, the pink inanga were significantly smaller than those in the clear and orange replicates ($P<0.019$), and although the larger of the pink fish were more successful at passing the culvert, the smaller variation in fish size within the cohort meant the difference was not significant (Figure I-9).

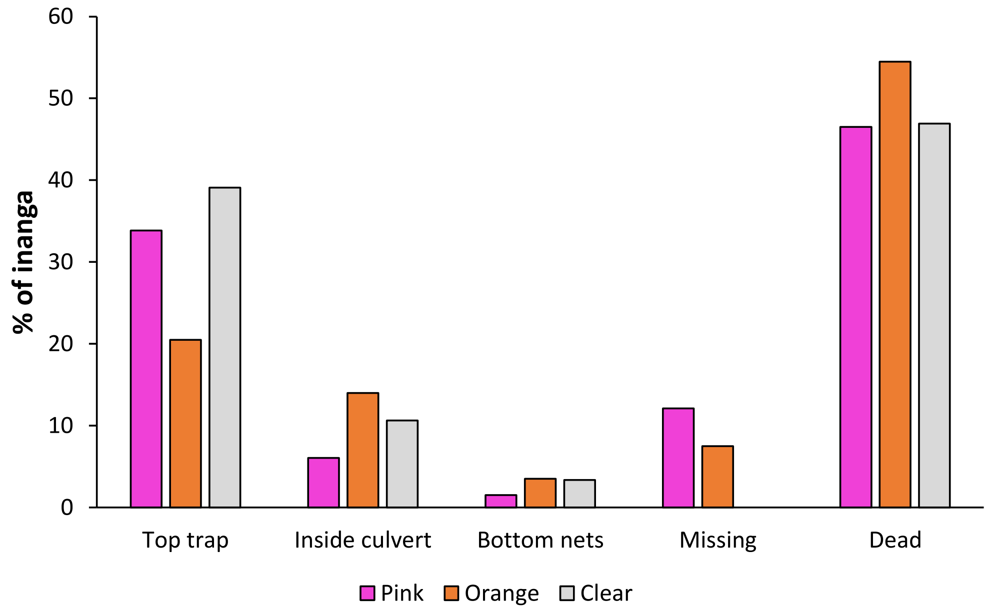


Figure I-7: Percentage of inanga in each state at the completion of the trial. Top trap = percentage of inanga successfully passing the culvert, Inside culvert = still migrating upstream inside the culvert, Bottom nets = caught in the bottom barrier nets, and fish either unaccounted for (missing) or found dead after 20.5 hours.

The effect of fish size on passage success suggests the culvert baffles may be less effective for small inanga. However, the size effect may have been partially biased from carrying out the trial under higher flows. This is because smaller fish encountering the faster water velocities in the pool were more likely to be swept into the barrier net as opposed to an area of low velocity refuge. As such, these fish were less likely to be able to undertake repeated attempts at passage over the weir before incurring damage or death. At lower flows, it would be anticipated that the more of the inanga would have successfully passed the culvert as opposed to expiring against the barrier net.

Figure I-8: Barrier net set upstream of the baffle at the culvert outlet.

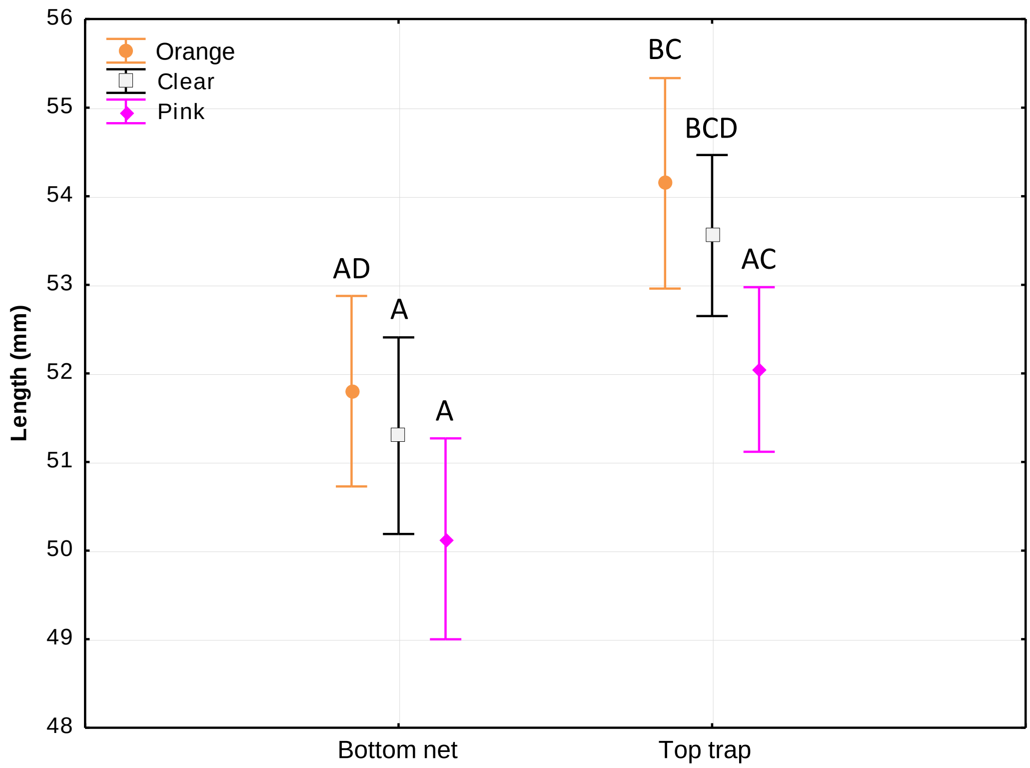


Figure I-9: Mean length (mm) of inanga successfully and unsuccessfully passing the culvert in 20.5 hours. 'Bottom net' represents expired fish collected in the first barrier net at the culvert outlet. Error bars denote ±95% confidence intervals. Different letters signify significant differences between means (Factorial ANOVA & Tukey HSD test, $P<0.05$).

Trial 3: Rock-ramp + mod apron + culvert (12 h)

Three replicates of fish (199 pink inanga, 199 orange inanga and 143 uncoloured (clear) inanga) were released at 10:30 am on 18th September 2014. Fish sizes were similar to Trial 2, ranging from 45 to 75 mm. However, 20 large adult inanga (85 - 120 mm) that were captured with the juvenile inanga were also released for comparative purposes. Of these, 15 were uncoloured and 5 were coloured in Bismarck Brown.

Because of high rainfall and concerns over the integrity of the trap and barricades in rising flows, the top trap was checked after 12 hours to determine if the modified apron had promoted inanga passage. In total, 24 inanga had successfully passed the rock-ramp and culvert with the modified apron. Of these, 12 were from the smaller juvenile and post-juvenile fish (45 – 75 mm), and consisted of 6 pink fish (51 – 53 mm), 4 orange fish (51 – 74 mm) and 2 uncoloured fish (50 & 51 mm). Of the 20 large adult inanga released, 10 uncoloured inanga (85 – 110 mm) and 2 orange inanga (105 & 117 mm) successfully passed the structure in the 12 hour window.

Based on the slower movement of juvenile inanga in Trial 2, it was anticipated that fish may require 36 hours to pass the rock-ramp and the culvert in Trial 3. However, nature intervened and the flow of Kara Stream rose around tenfold overnight (Table I-1). By 24 hours, the trap and barrier nets had been washed out and the trial had to be abandoned (Figure I-10 to Figure I-12). It should be noted that the trial results suggest passage of adult inanga is considerably quicker than for smaller fish, as over 50% of the adult fish released had successfully passed the rock-ramp and culvert within 12 hours.

Although the flood waters prevented an accurate assessment of inanga passage past the rock-ramp and culvert with the baffled apron, the successful passage of both small (50 mm) and large (>85 mm) inanga recorded after 12 hours confirmed that the culvert apron is the key factor limiting swimming fish passage. Consequently, retrofitting baffles to the apron was recommended to enhance fish passage past the culvert.

Figure I-10: Top trap during increasing flood waters at the conclusion of Trial 3.

Figure I-11: Flow through the culvert and over the rock-ramp at the conclusion of Trial 3.

Figure I-12: Bottom barricades at the conclusion of Trial 3.

Based on best practice guidance, the culvert apron was subsequently baffled by anchoring wooden spoiler baffles (0.25 m length, 0.12 m width and 0.12 m height) in staggered rows (Figure I-13). This has created resting areas for fish behind the baffles as well as producing low velocity margins (Figure I-13).

Figure I-13: Rectangular spoiler baffles anchored to the Upper Kingston Road culvert apron.

Although the Upper Kingston culvert has been used as a case-study for examining the effectiveness of rock-ramp retrofits in promoting passage of inanga, it provides an opportunity to fully document the success of the fish passage solution. The combined approach of BACI surveys and mark and recapture trials would provide the most comprehensive assessment of fish passage success. As the spoiler baffles have only recently been retrofitted, further mark and recapture trial can now be carried out to assess the effectiveness of the final solution. As electric-fishing surveys were carried out below and above the culvert prior to remediation, completion of the BACI surveys can then be undertaken to document changes to the fish community upstream of the remediated structure and, therefore, assess the effectiveness of the solution across a range of fish species. Ideally, electric-fishing surveys above and below the culvert should be carried out annually in January until changes to the upstream fish community are clear.

Bankwood Stream, Hamilton

This case study, which expands on the results of Franklin and Bartels (2012), highlights the combined approach of BACI surveys and mark and recapture trials for assessing the effectiveness of retrofitting a perched culvert on Bankwood Stream, Hamilton. The results also illustrate the importance of trial length, timing and the fish marking procedure in carrying out mark and recapture trials.

Remediation

Several indigenous fish species were excluded from Bankwood Stream by a perched concrete culvert (1.5 m diameter; 73.8 m length; gradient 0.3-2.55°) at the confluence with the Waikato River. To overcome the barrier posed by the perched culvert, in April 2007 a fish ramp and receiving pool were installed at the culvert outlet (Figure I-14). The 16 m long concrete ramp (0.9 m wide with a slope of 5.7°) was embedded with cobbles and angled laterally (5°) (Figure I-14). A receiving pool (1.7 m wide and 2.0 m long with a minimum depth of 0.2 m) was installed at the top of the ramp. However, the fish ramp alone was ineffective at providing passage for non-climbing fish species into the upstream habitats and baffling of the culvert barrel was subsequently undertaken to lower water velocities within the culvert (Figure I-15). Consequently, in January 2009, 36 UV stabilized polyethylene spoiler baffle sheets (2 x 0.9m) with baffles (0.25 x 0.10 x 0.12 m) spaced 0.10 m apart laterally and 0.25 m longitudinally were secured to the culvert base. Based on best practice guidance, the baffles were configured in alternating offset rows of 3-4 baffles (Figure I-15).

Figure I-14: The receiving pool and fish ramp operating under summer low flow conditions.

Figure I-15: The culvert barrel following installation of the spoiler baffle sheets.

BACI Monitoring

The BACI monitoring carried out since 2006 has effectively documented the fish community response to the remediation of the perched culvert. The monitoring has utilised two reaches, one located immediately upstream of the culvert entrance, and the other approximately 80 m upstream of the culvert. To enable population estimates to be calculated, multiple pass electric fishing was carried until there was a 50% reduction in the abundance of the most common fish species.

Prior to the retrofit, three species of indigenous fish were recorded upstream of the culvert in Bankwood Stream; longfin and shortfin eels, and giant kōkopu (Figure I-16). In the November 2007 and January 2009 surveys, following construction of the fish ramp at the culvert outlet, two additional indigenous fish species, common bully and torrentfish, were recorded in the stream above the culvert in low abundance (Figure I-16), but neither of the target fish species, smelt or inanga, were captured.

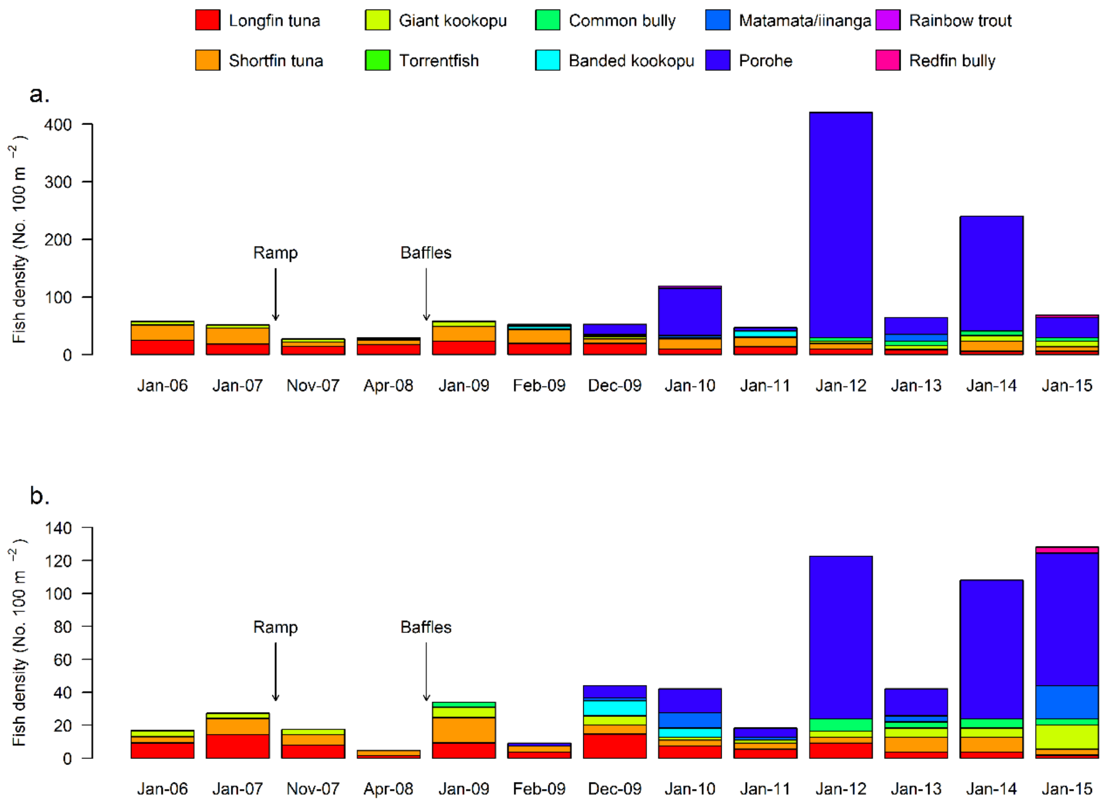


Figure I-16: Results of fish community monitoring upstream of the culvert. a. Reach 1 – immediately upstream of the culvert; and b. Reach 2 – downstream limit c. 60 m upstream of the culvert.

Surveys immediately following the installation of the spoiler baffles (February 2009 and April 2009 for Reaches 1 and 2 respectively) indicated that both smelt and inanga had gained access to the stream above the culvert (Figure I-16), the first record of these species since monitoring began in 2006. Follow-up surveys since January 2010 have shown that both smelt and inanga have continued to be present in the survey reaches. Species such as juvenile rainbow trout, torrentfish and common bullies have not been consistently captured within the stream. A further species that appears to have become established in the reach upstream of the culvert since it was retrofitted is banded kōkopu, which has been present in at least one of the survey reaches in every survey since the installation of the spoiler baffles (Figure I-16).

Mark and recapture studies

The BACI monitoring has required several years to confirm the remediation has been effective for enhancing upstream fish communities. In contrast, mark and recapture surveys can provide immediate results on the effectiveness of the retrofit and also examine passage of the target species over each component of the structure independently. To obtain more detail on the efficacy of the culvert retrofits for enhancing fish passage into Bankwood Stream, mark and recapture trials on both the ramp and baffled culvert were carried out using migratory inanga in 2009, with passage through the culvert retested in 2015.

To ensure the inanga tested were the same life stage reaching Bankwood Stream, in 2009 fish were caught using whitebait traps in the Waikato River at Huntly and in 2015, inanga were captured using gee minnow traps in Hamilton tributaries of the Waikato River. General procedures followed those outlined in Section 7.2, except for the marking method and trial length. In 2009, inanga were elastomer tagged (Northwest Marine Technology). In 2015, fish were batch marked using Rhodamine B, with unmarked inanga tested as a second replicate and control for the stained fish. Marking procedures followed those outlined in Section 7.2.3. After both marking procedures, fish were left to recover in live bins within Bankwood Stream for 24 hours prior to testing.

Rock-ramp

Inanga first reached the pool between 60 and 90 minutes after release (mean = 5.6% of marked fish; s.e. = 1.5%) (Table I-2). After nine hours a mean of 27.1% (s.e. = 4.5%) of marked inanga had passed the full length of the fish ramp. There was no statistically significant difference in the length of fish reaching the top of the ramp relative to those released (P = 0.115).

Table I-2: Summary of inanga (elastomer tagged) passage over the rock ramp. Reproduced from Franklin and Bartels (2012).

Trial date	Marked fish released (n)	Average length (±se) at release (mm)	Total trial time (hours)	Time inanga first recorded at top of ramp (hours)	Proportion of fish past ramp after 9 hours	Average length (±se) of fish that passed ramp (mm)
17-Dec-09	59	60.5 (± 0.15)	9.0	1.5	18.6	57.6 (± 0.46)
17-Dec-09	59	61.2 (± 0.15)	9.0	1.5	28.8	61.1 (± 0.48)
17-Dec-09	59	60.1 (± 0.14)	9.0	1.5	33.9	57.8 (± 0.31)

Culvert

In the 2009 trials examining elastomer tagged inanga passage through the culvert, it took between five and six hours for the first inanga to surpass the culvert (Table I-3). After twelve hours, a mean of only 6.2% (s.e. = 1.4%) of fish had reached the top of the culvert (Table I-3). At this stage, it was decided to leave the trial running overnight to check whether mean passage time was greater than the initial 12 h trial period. Following 24 h, the mean number of fish to have reached the top of the culvert had only increased to 7.9% (s.e. = 1.5%). There was again no statistically significant difference in the length of fish reaching the top of the culvert relative to those released (P = 0.307).

Table I-3: Summary of inanga passage through the culvert. Modified from Franklin and Bartels (2012).

Trial date	Marked fish released (n)	Marking method	Total trial time (hours)	Flow ($m^3 s^{-1}$)	Average length (±se) at release (mm)	% of fish passing the culvert	Average length (±se) of fish that passed culvert (mm)
16-Dec-09	59	Elastomer tag	12	0.034	56.5 (± 0.08)	8.5	59.4 (± 0.87)
16-Dec-09	59	Elastomer tag	12	0.034	59.1 (± 0.12)	3.4	60.5 (± 3.18)
16-Dec-09	59	Elastomer tag	12	0.034	58.5 (± 0.12)	6.8	60.3 (± 1.05)
31-Mar-15	200	Rhodamine B	24	0.026	65.2 (± 0.91)	28	65.1 (± 0.93)
31-Mar-15	200	Unmarked	24	0.026	64.1 (± 0.83)	27	64.5 (± 0.95)

In 2015, trial length was increased to 24 hours and after this time, 28% of pink and 27% of unmarked inanga had successfully passed the culvert (Table I-3). To determine if 24 h was an adequate trial length for passage through the 73.8 m culvert, the trial was extended to 48 h. Between 24 and 48 h a further 5.5% of pink and 6.5% of unmarked inanga had successfully passed the culvert, giving at total of 33.5% passage for both replicates. For both replicates, there was no statistically significant difference in the size of inanga passing the culvert relative to those released and there was no statistically significant difference between the size or number of pink and unmarked fish successfully passing the culvert ($P = 0.501$). This supports the findings from Kara Stream in that the marking procedure did not unduly influence the behaviour or passage ability of inanga compared to fish that were not subjected to the marking procedure.

Close to a five-fold difference in the passage success of inanga through the culvert was observed between the 2009 and 2015 trials. The main factors likely to be influencing inanga passage success between trial years are the size of inanga utilised, the stream discharge and the fish marking method. In both years, pigmented feeding inanga were tested as this is the life stage reaching Hamilton after whitebait recruit into the Waikato River. However, in 2015, trials were undertaken at the end of summer when the mean size of inanga was larger and this will have increased their ability to pass the culvert. For example, Baker (2014) found that the passage success of inanga over a 3 m baffled ramp nearly doubled between small (<60 mm) and large (>60 mm) fish. The lower flow present during the 2015 trials may also have increased the passage efficacy of inanga, although both sets of trials were carried out at close to base flow conditions. It is likely that the marking procedure will also have influenced the passage success of inanga. The elastomer tagging procedure subjects fish to increased handling and stress through anaesthetising and injecting the paint subcutaneously in all individuals, which is not required when batch marking fish in a solution of Rhodamine B or Bismarck Brown. Given the passage results with coloured fish at Kara Stream and Bankwood Stream produced results comparable to unmarked inanga, we recommend staining fish with Rhodamine B and Bismarck Brown when carrying out mark and recapture studies as opposed to elastomer tagging where trial duration is short (e.g., <4-5 days).