Waterway Barrier Design for Protection of Native Aquatic Values

Report prepared by University of Canterbury

for Department of Conservation

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UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

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All photos provided by DOC, except where noted

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1 Introduction

New Zealand has around 51 species of native freshwater fish, with an additional 3 colonist species and 20 introduced species that are now considered naturalised in New Zealand waters (Allibone et al., 2010). Some of New Zealand's native fish are vulnerable to direct predation and/or competition by introduced, invasive species, as well as adverse changes to aquatic habitat caused by these introduced species (Rowe and Dean-Speirs, 2009).

Many species are diadromous, moving between freshwater and salt water during their life cycle, and the ability to migrate between streams, lakes and the sea is therefore vitally important to their population health (McDowall, 2000), while there are also a number of non-diadromous species that are specialised to specific habitats. It has long been recognised that dams prevent fish migration and consequently there has been much research conducted into overcoming these barriers to ensure fish passage. However, the vulnerability of New Zealand's native fish and other aquatic values, e.g. macrophytes, to invasive species suggests some barriers, whether natural or built, could be used to create protected habitats for some native species in key locations. Kates et al. (2012) noted that "rather than try to eliminate invasive species after introduction, preventing their spread is a more efficient strategy to mitigate impact." Waterway barriers in some locations provide a means of preventing spread of invasive fish species naturally, while in other locations natural barriers have been enhanced or barriers installed to facilitate the removal of invasive species from key native locations to create protected areas.

2 Scope of Review

This review collates international and New Zealand experience to date of built barriers and New Zealand natural barriers that protect native fish and other values by exclusion of invasive species, predominately trout. This review aims to summarise current knowledge of the following questions:

1. What types of barriers exist?
2. What is the known effectiveness of each of these types of barrier?
3. What design components are necessary to create an effective barrier to control movement of certain species upstream?
4. What does experience suggest would be most effective for protection of New Zealand's native fish species?

Most fish passage and barrier management publications in New Zealand have focused on how to reduce or remedy the impacts of barriers to fish migration (i.e. promote fish passage), whereas this review focuses on specific situations where barriers should be maintained or built to protect native values. The focus of this work is on small scale structures (<4 m in height). This review encompasses English-language peer-reviewed literature.

3 Waterway Barrier Design Files

3.1 Companion Files

This review document is a companion to the Waterway Barriers Database, EndNote Library, Photo and Drawings Library and Design Review Checklist (see Table 3-1). In particular, Sections 5 and 6 of this document present a descriptive review of natural and built barrier case studies that are included within the Database. The companion files have been developed as living documents, with the intention that users of the files add in details of existing barriers and new barriers as they become available. Screenshots of the various companion files are provided in Appendix A to help readers understand the scope and presentation of information within the files.

Table 3-1: Waterway Barrier Design Companion Files

File	Purpose
Database	Summarises known characteristics and design details of Otago natural barriers and a selection of built barrier case studies from New Zealand and overseas.
EndNote Library	This library (created in EndNote version X6) records relevant literature. The user can search within the library by keywords (refer to tab in Database titled 'EndNote Library Keywords').
Photo and Drawings Library	Photos of natural and built barriers are linked from the Waterway Barriers Database, where available.
Design Review Checklist	Includes a checklist to define the barrier objectives (as the basis of design) and a checklist of design factors that should be considered.

3.2 Using the Waterway Database Files

This review report and its companion files, particularly the Waterway Barriers Database and Design Considerations Checklist, are intended to provide guidance for design of future barriers by collating and analysing the information learnt from existing barriers. Figure 3-1**Error! Reference source not found.** is a flowchart of the suggested process and information inputs to be referred to when designing a new barrier.

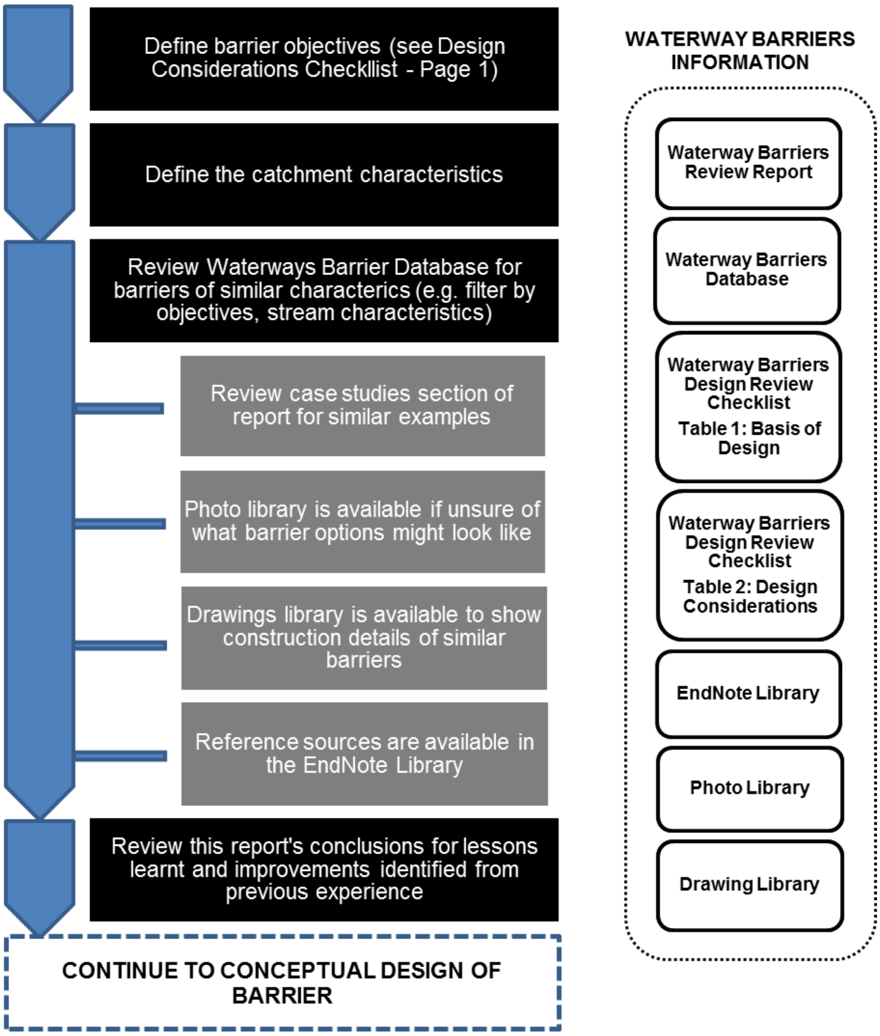

Figure 3-1: Suggested process of using Waterway Barrier Design files in development of a new barrier

4 Overview of Fish Species

4.1 Species to be Protected

New Zealand has around 51 species of native freshwater fish, with an additional 3 colonist species and 20 introduced species that are now considered naturalised in New Zealand waters (Allibone et al., 2010). Several species are diadromous, moving between freshwater and salt water during their life cycle, while other do not migrate, and a few diadromous fish species have been found to form landlocked populations if environments similar to the marine environment are available i.e. large lakes. Before European settlement, galaxias were the dominant group of native freshwater fish in New Zealand. Galaxias are a cool-water group, with many non-diadromous representatives specialising in high-altitude upland streams, rivers and lakes.

Table 4-1 summarises the native fish species that could benefit from the protection provided by a waterway barrier against invasive fish species. Threatened or sparse non-migratory galaxiid species with fragmented distributions would benefit from natural or built barrier protection and are the main focus of this review as some key non-migratory galaxiid locations will suffer extinction if barriers are not established to protect them. Most other species listed would not benefit from natural or built barriers, except where the barrier is only a partial barrier and provides access for some species over the barrier via climbing, while preventing non-climbing invasive species from moving upstream. It should be noted that water intakes (as screened barriers) are the exception and should generally exclude all species if possible, as otherwise these fish are lost to the fishery, especially diadromous species (see highest priority species Table 4-1).

Table 4-1 also summarises species characteristics, including climbing ability (which can vary with a species' lifestage, e.g. small elvers (juvenile eels) are strong climbers, while adult eels are less so), whether the species is diadromous or non-diadromous. These characteristics should be taken into consideration when determining the need for downstream barriers and in the design of any waterway barrier (see Section 4.3).

Note that the importance of having natural or built barriers to protect a species is also dependent on the prevailing environment that the species live in. Where an environment has been modified, the importance of barriers to provide protection increases, whereas the same species may not need the same support where it is able to exist in a less modified environment.

Table 4-1: New Zealand freshwater fish species that need to be considered in barrier establishment and/or protection (Adapted from Boubée et al. (2000); Charteris and Hamblett, 2006; DOC)

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Genera	Common Name	Scientific Name	Climber?	Diadromous (D), non-migratory (NM) or can form landlocked populations (LL)	Importance of built or natural barriers for protection (High, Med, Low)	Need to be excluded from screened barriers (water intakes) (H, M. L – priority to exclude in Canterbury (Charteris and Hamblett, 2006))
Aldrichetta	Yelloweye mullet	*A. fosteri*	Poor	NM	L	✓L
Anguilla	Shortfin eel	*A. australis*	Strong	D	L	✓L
	Longfin eel	*A. dieffenbachii*	Good	D	L	✓M
	Spotted eel	*A. reinhardtii*	--	D	L	✓
Cheimarrichthys	Torrent fish	*C. fosteri*	--	D	L	✓M
Galaxias	Central Otago roundhead galaxias	*G. anomalus*	--	NM	H	✓
	Giant kokopu	*G. argenteus*	Average-good	D, LL	L	✓H
	Köaro	*G. brevipinnis*	Average-good	D, LL	L	✓L
	Lowland longjaw galaxias	*G. cobitinis*	--	NM	H	✓H
	Taieri Flathead galaxias	*G. depressiceps*	--	NM	H	✓
	Dwarf galaxias	*G. divergens*	--	NM	H	✓H
	Eldon's galaxias	*G. eldoni*	--	NM	H	✓
	Banded kokopu	*G. fasciatus*	Average-good	D	L	✓M
	Gollum galaxias	*G. gollumoides*	--	NM	H	✓
	Dwarf inanga	*G. gracilis*	--	NM	M	✓
	Bignose galaxias	*G. macronasus*	--	NM	H	✓H
	Inanga	*G. maculatus*	Average	D, LL	L	✓L
	Alpine galaxias	*G. paucispondylus*	--	NM	H	✓M
	Shortjaw kokopu	*G. postvectis*	--	D	L	✓H
	Upland longjaw galaxias	*G. prognathus*	--	NM	H	✓H
	Dusky galaxias	*G. pullus*	--	NM	H	✓
	Clutha flathead galaxias	*G. 'species D'*	--	NM	H	✓
	Northern flathead galaxias	*G. 'species N'*	--	NM	H	✓M

Genera	Common Name	Scientific Name	Climber?	Diadromous (D), non-migratory (NM) or can form landlocked populations (LL)	Importance of built or natural barriers for protection (High, Med, Low)	Need to be excluded from screened barriers (water intakes) (H, M. L – priority to exclude in Canterbury (Charteris and Hamblett, 2006))
Galaxias cont'd.	Canterbury galaxias	*G. vulgaris*	--	NM	M	✓M
	Dune lake galaxias	*G. sp.*	--	NM	M	✓
	Southland flathead galaxias	*G. Southern sp.*	--	NM	H	✓
	Teviot flathead galaxias	*G. Teviot sp.*	--	NM	H	✓
	Nevis galaxias	*G.aff gollumoides Nevis sp.*	--	NM	H	✓
Geotria	Lamprey	*G. australis*	--	D	L	✓M
Gobiomorphus	Tarndale bully	*G. alpinus*	Average-good	NM	L	✓
	Cran's bully	*G. basalis*	Average-good	NM	L	✓
	Upland bully	*G. breviceps*	Average-good	NM	L	✓L
	Common bully	*G. cotidianus*	Average-good	D, LL	L	✓L
	Giant bully	*G. gobioides*	Poor (uncertain)	D	L	✓L
	Bluegill bully	*G. hubbsi*	Average-good	D	L	✓L
	Redfin bully	*G. huttoni*	Average-good	D	L	✓L
Neochanna	Brown mudfish	*N. apoda*	--	NM	L	
	Canterbury mudfish	*N. burrowsius*	--	NM	M	✓H
	Black mudfish	*N. diversus*	--	NM	L	
	Northland mudfish	*N. heleios*	--	NM	L	
	Chatham mudfish	*N. rekohua*	--	NM	L	
Retropinna	Common smelt	*R. retropinna*	Average	D, LL	L	✓L
Rhombosolea	Black flounder	*R. retiaria*	--	D	L	✓L
Stokellia	Stokell's smelt	*S.anisodon*	--	D	L	✓M

4.2 Species of Concern

At least 21 species of introduced freshwater fish have established self-sustaining populations in New Zealand waters (Dean, 2001) 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). Table 4-2 presents the introduced species of high risk in terms of establishment and adverse ecological impact. Perch are known to adversely affect native fish population such as galaxias (Ludgate and Closs, 2003, and Rowe and Smith, 2003, in Wilding and Rowe (2008)), as well as facilitating algal blooms in eutrophic lakes (Smith and Lester, 2007, in Wilding and Rowe (2008)). Salmon and trout species are implicated in the decline of native fish populations via competition and predation (Dean, 2001) and there is little habitat where galaxias species are free from predation from salmonids (McDowall, 2006). Trout predation has caused local extinctions and impacts on many of our threatened non-migratory galaxiids (Woodford and McIntosh (2013); McDowall (2006); McIntosh et al. (2010)). Other introduced species such as rudd, a herbivore, damage the aquatic habitat through overgrazing of aquatic plants, decreasing water transparency and subsequent eutrophication (Rowe, 2007) and therefore reduce the available habitat for native species.

Some native fish species (e.g. eels, köaro) have also been found to impact on other native fish populations. For example, köaro are known to compete with other galaxias species for habitat (Allibone, 2000) and therefore their exclusion may be desired where their presence is negatively impacting on another vulnerable native species.

Table 4-2: Primary Invasive Species of Concern in New Zealand by Risk of Establishment and Ecological Impacts (Source: Wilding and Rowe, 2008)

Species Name	Common Name	Fish Risk Assessment Model scores [1]			Comment on species groups
		Establishment Risk (max. 16)	Ecological impact risk (max. 61)	Overall ecological risk (max. 77)	
Perca fluviatilis	Perch	14	33	47	Species that have caused environmental impacts in NZ [2]
Cyprinis carpio	Koi carp	13	33	46	
Ameiurus nebulosus	Bullhead catfish	15	30	45	
Gambusia affinis	Gambusia	13	27	40	
Salmo trutta	Brown trout	13	26	39	
Leucisus idus [2]	Orfe	13	25	38	
Oncorhynchus mykiss	Rainbow trout	13	24	37	
Scardinius erythrophthalmus	Rudd	14	23	37	
Tinca tinca	Tench	13	19	32	No impacts reported, but wide

Species Name	Common Name	Fish Risk Assessment Model scores [1]			Comment on species groups
		Establishment Risk (max. 16)	Ecological impact risk (max. 61)	Overall ecological risk (max. 77)	
Carassius auratus	Goldfish	13	17	30	potential distribution
Oncorhynchus nerka	Sockeye salmon	11	19	30	
Salvelinus fontinalis	Brook char	13	16	29	
Oncorhynchus tshawytscha	Chinook salmon	9	20	29	No impacts known because distribution restricted
Ctenopharyngodon idella	Grass carp	3	25	28	
Salmo salar	Atlantic salmon	8	20	28	
Salvelinus namaycush	Mackinaw	6	20	26	
Phallocerus caudimaculatus	Caudo	6	16	22	No impacts known and very restricted distribution
Hypophthalmichthys molitrix	Silver carp	3	17	20	
Xiphophorus helleri	Swordtail	3	12	15	
Poecilia latipinna	Sailfin molly	3	12	15	
Poecilia reticulata	Guppy	3	11	14	

[1] See Appendix B for more details on the Fish Risk Assessment Model framework

[2] Orfe are not known to cause impacts in New Zealand but this is because they are recorded from only one location and this has not been subjected to any study

4.3 Fish Factors

Table 4-3 outlines the primary factors influencing a species' ability to successfully negotiate a barrier. Both hydrological and behavioural factors contribute to this.

Table 4-3: Factors influencing fish behaviour and likelihood of successfully negotiating barrier(s) (Adapted from Rowe and Dean-Speirs (2009); Noatch and Suski (2012))

Fish 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)
Upstream swimming	Fish species
	Size of fish (i.e. juvenile versus adult)
	Water velocity
	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

A key consideration in the design of any barrier is whether the objective is for a full exclusion barrier or a barrier that enables some fish passage. The diadromous nature of many of the native species indicates that they need to be able to negotiate the barrier to maintain their migratory lifecycle or ensure certain lifestages can still disperse or migrate. A very limited number of species (Table 4-1) have been found to form landlocked populations. For example, studies in the Tarawera River (Bleackley, 2008) identified a population of common bully that had abandoned its migratory phase, suggesting that a normally-diadromous population may successfully survive without migration if there is sufficient habitat to reproduce and sustain a healthy population (Fausch et al., 2009). However, the risk of localised extinction, whether the fish species can carry out its full lifecycle within the barrier area, and the chance of creating sink populations (i.e. populations that are unable to reproduce such that they can disperse and contribute numbers to other populations) must all be considered in the decision to adopt a full exclusion barrier.

Some highly threatened non-migratory galaxiid species only exist in fragmented head water locations so a full exclusion barrier is critical for their future survival. 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. Without a barrier against invasive species, extinction of the non-migratory galaxiid species is likely. 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).

5 Overview of Barriers

5.1 Natural Barrier Features

Due to different species' climbing and swimming abilities, some natural barriers prevent access for some species, while allowing access for others. As a result, some of New Zealand's waterways have natural barriers that 'unintentionally' exclude introduced species from the upstream reaches, many of which are identified through routine native fish surveys (Collis, 2008). These are typically physical barriers that are created by in-stream features that exceed the fishes' ability to negotiate it. However, some natural barriers are also created by environmental conditions that cause stress or intolerance in fish. For example, studies in the Manuherikia River (Leprieur et al., 2006) found trout were more susceptible than the native fish to stresses associated with low flows, and seem to be prevented from eliminating galaxiid populations from sites in low gradient streams where there is a high level of water abstraction as the trout cannot handle as low flow conditions as the native fish can. Table 5-1 summarises the range of natural barriers.

Table 5-1: Types of Natural Barriers

Type of Natural Barrier	Mechanism that Creates Barrier
1. Waterfall	Height of waterfall prevents jumping
2. Overhang	Can prevent climbing and/or jumping
3. Swamp	Vegetated channels with lack of surface flow prevent fish swimming upstream
4. Dry stream bed	Prevent swimming/access to habitat
5. Low water levels	Prevent swimming, also known to cause stress for fish.
6. Uninhabitable zone	Species-specific – what one species cannot tolerate, another may be perfectly healthy in.

5.2 Built Barrier Features

Built barriers are typically classified as either physical or non-physical barriers. Physical barriers create an environment that the fish are physically unable to negotiate, while non-physical barriers induce an ‘avoidance response’ in fish by creating a zone where the fish experience discomfort and/or disorientation.

Historically, many physical structures have been placed in streams for multiple reasons, e.g. road crossings, flood control or drainage, and some of these have created fish passage barriers. The need to remove or maintain such barriers is dependent on what species are currently found in these locations and what species should naturally be present. If the barrier is found to be protecting a key native value, then there is merit in retaining and protecting the existing barrier. However, this is considered to likely be in the minority of situations. When complete barriers are found that are preventing access to key migratory habitat upstream, many barriers have been retrofitted to provide passage as keeping it as a barrier does not provide any advantage for aquatic values. Non-physical barriers have historically been developed in the context of fish control systems for aquaculture (i.e. fish exclusion and containment systems). However, the installation of built barriers is becoming increasingly common for species conservation (Baxter et al, 2003).

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Table 5-2 and Table 5-3 summarise different types of non-physical and physical barriers respectively (excluding those already covered in natural barriers in Section 5.1, e.g. high velocity zones, habitat barriers such as swamps and dry stream beds)). The tables also outline the underlying mechanisms for how each barrier type works. The majority of these barriers work by controlling upstream movement of fish, but some barriers are effective at controlling downstream movement. For example, where an invasive fish species may have been introduced into a lake environment, a barrier could be installed to prevent spread and migration into downstream waterways.

The tables also present the factors that influence the effectiveness of different physical barrier types, and outline their key advantages and limitations.

Table 5-2: Non-Physical Barrier Types

Type of Built Barrier	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Electrical or electromagnetic	An electric field is created by placing two electrodes in the water and applying a voltage between them. Current is then conducted in the water between the two electrodes. Fish senses discomfort when it passes into the field, as current passes through fish (Bullen and Carlson, 2003). The electric current can cause taxis (forced swimming) or immobilisation in fish (Noatch and Suski, 2012).	• Conductivity of the water • Attenuation of the electric field (i.e. the electric field dissipates at increasing distance from the field source) • Maintenance of adequate power source • Species' response to electric field	• Proven effective at excluding fish, particularly in constricted waterways (Noatch and Suski. 2012) (Bullen and Carlson, 2003)	• Fish are unable to detect the direction of an electric field source. Bullen and Carlson (2003) report observations of fish, having found themselves subjected to an electric field, swimming into a region of stronger field to their eventual death. • The electric field may pose a danger to other species. • The barrier is deactivated during a power outage. • Small fish may be unaffected by electric fields (Reynolds, 1996 in Noatch and Suski, 2012)
Acoustic (high and low frequency sound, sonar)	An acoustic field is created by pressure waves. Fish use sound to assess and sense their surrounding environment, and therefore sound can act as a deterrent or guidance stimulus.	• Bottom morphology • Waterway hydrology • Angle and intensity of sound waves (Katopodis et al, 1994 in Noatch and Suski, 2012) • Frequency of sound influences wave propagation – from example, low frequency sounds propagate poorly in shallow water and across hard substrates (Popper and Carlson, 1998)	• Sound is directional, rapidly transmitted over long distances through water, not affected by turbidity and unaffected by light changes (Bullen and Carlson, 2003). • Effective on young fish (whereas, for example, electrical barriers may not be)	• Trials have shown fish may acclimatise to the acoustic barrier and the discomfort is insufficient to dissuade the fish from crossing the barrier when another positive stimulus, such as food, is present on the other side of the barrier. • Field tests have returned highly variable results
Air bubble curtains	Air bubbles are released from perforated pipes at a controlled rate, which: a) Creates an acoustic field through pressure wave fluctuations b) Creates a hydrodynamic field through velocity fluctuations and turbulence These fields are detected by the fish's sensory system (Zielinski, 2011). The bubble barrier also creates an unusual visual cue for the fish.	• Frequency of the acoustic field as this dictates the attenuation rate of the field • Sensitivity range of the fish species that the barrier is required for	• Effective where water clarity precludes the use of light barriers (Noatch and Suski, 2012) • Because bubble barriers adapt instantaneously to changes in water depth and also experience minimal decrease in field strength due to depth, Zielinski (2011) considered bubble barriers ideal for flashy streams.	• Noatch and Suski (2012) consider bubble barriers to have limited effectiveness as a sole barrier, and because they are unable to maintain equal air pressure across differing depths, design would be complex for a waterway with a rugged cross-section. • The acoustic field frequency needs to match the sensitivity range of the species of concern. However, carp have a target sensitivity range of 100-150 Hz, and acoustic fields at this frequency rapidly attenuate. Therefore, the barrier would need to be installed in shallow water only to ensure the field strength is reasonable for the full water depth (Zielinski, 2011).
Light (presence/ absence, strobes)	Strobe (or other) lights are set in the water and programmed to flash etc. Many fish are highly responsive to visual signals (Bullen and Carlson, 2003) and light levels influence fish behaviour such as orientation (Noatch and Suski, 2012).	• Fish species and their response to light (can vary from obvious avoidance to attraction to light) • Strength of lights • Turbidity • Ambient light levels (i.e. this controls the contrast between the ambient and applied light) (Noatch and Suski, 2012)	• Light has high transmission rate in water (Bullen and Carlson, 2003) • Less infrastructure, potentially lower costs compared to other non-physical barrier systems	• Reported effectiveness varies – Noatch and Suski (2012) indicate strobe barriers do not provide full exclusion when used as the sole means of barrier. • Affected by water clarity and contrast between artificial and natural light. • Monitoring of salmon and rainbow trout responses to a strobe barrier identified possibility of prey species being attracted to the light, creating a foraging opportunity for the predator species (Johnson et al, 2013)
Hypoxia or hypercapnia (high CO_2)	Carbon dioxide gas is bubbled into the water (typically via perforated pipes at a controlled rate). This creates an uninhabitable zone of water that fish cannot pass through (e.g. hypoxic or hypercapnic zone).	• Fish species' response to individual water quality parameters	• Potential to be effective against a wide range of fish species	• Lack of experience in such types of barriers to control fish passage - need to consider safe storage space and handling requirements of gas • Likely to have significant adverse effects on general aquatic ecosystem health • Kates et al. (2012) concluded that a zone of CO_2 would not be 100% effective at preventing the movement of all fishes
Pheromones	Alarm pheromones are known to trigger avoidance responses in fishes, and so can be dosed into water to create a chemical barrier.	• Fish species' response to pheromones	• Potential to selectively exclude particular fish species	• Lack of experience in such types of barriers to control fish passage • Likely difficulty sourcing adequate quantity of pheromones
Chlorine	Chlorine gas is bubbled into the water (typically via perforated pipes at a controlled rate). This creates an uninhabitable zone of water that fish cannot pass through.	• Concentration of chlorine • Hydraulic mixing • Species' response to chlorine	• Potential to exclude virtually all fish	• Likely to have significant adverse effects on general aquatic ecosystem health

Table 5-3: Physical Barrier Types

Type of Built Barrier	Barrier Mechanism	Factors Controlling Effectiveness	Advantages	Limitations
Dams	The dam creates a full exclusion barrier in the waterway (preventing swimming, jumping or climbing)	• Height of dam • Presence of spillway (weir) • Presence of built fish passage	• Full exclusion barrier • May have been installed for another purpose but exclusion of downstream species results	• Significant alteration of stream hydrology, sediment transportation and consequently, in-stream habitats • Large amount of infrastructure, high cost • Negative publicity
Chutes (Velocity)	High water velocity fatigues fish before they can fully negotiate a barrier (i.e. it exceeds their maximum swimming speed and/or the swim distance they can achieve at their maximum (anaerobic) swimming speed). Increased velocities can be achieved through placement of a culvert, chute or flume that constricts the water flow. Shallow water depths in these constrictions also prevent larger fish from swimming as well as inhibiting their ability to jump, also contributing to the effectiveness of the barrier.	• Velocity of water in chute • Depth of water in chute • Hydraulics during high flow conditions • Fishes' maximum speed and fatigue time relative to the barrier hydraulics (Castro-Santos, 2006)	• Less hydrological effect than weirs or dams • Can function as partial 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.
Falls/weirs	A weir can be used to create a full exclusion barrier by various mechanisms, including a vertical barrier exceeding fish jumping height, or creating a concentrated zone of fast flow over its crest	• Height of crest • Presence of a downstream pool • Presence of an upstream pool • 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))
Screens	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 fish need to be prevented from being entrained or impinged on screens otherwise they are lost to the fishery.	• Dimensions of gaps in screen • Hydraulics during high flows (e.g. can overtopping occur?) • Screen material • Intake set up • Approach and sweep velocity.	• Screens allow stream flow to continue through barrier, with minimal impact on hydraulics • Can be used as partial barrier to selectively allow smaller and/or juvenile fish to pass while excluding larger adult fish • Barrier to prevent downstream movement	• Screen material, such as gabions, have been known to degrade and deform over time, adversely affecting their performance as a barrier • High velocities at screen interfaces may trap or harm fish
Overhanging lips	Overhangs can be created by solid or grated lips hanging out from the downstream face of a barrier. The overhang can prevent climbing and jumping.	• Length overhang protrudes from downstream face • Angle of overhang • Grate spacing, if not solid overhang	• Provides additional barrier against jumping • Exclusion barrier for climbing species	• Can block native climbing species

A consistent finding from barrier research is that the barrier types need to be used in combination to improve their effectiveness. For example, Rowe and Dean-Speirs (2009) report that the use of a shallow apron (chute) is often used in the US to enable effective low-head barriers to be installed so desirable fish can pass. For non-physical barriers, strobe lighting and an air bubble curtain have been more successful together than when tested individually (Noatch and Suski, 2012)). This could be expected because the failure modes (i.e. how the barriers may be compromised) are different between the barrier types, and so the barrier types are complementary in their effects. The combined barriers collectively act upon several fish factors (see Section 3.3) to create an effective overall barrier.

Overall, experience with non-physical barriers suggests they should not be relied upon where full exclusion is required (see Table B of the Waterway Barriers Database). However, in situations where partial exclusion is acceptable, non-physical barriers can offer advantages such as not changing the hydraulics of the waterway and not being permanent (e.g. can be turned on and off as needed).

6 Natural Barrier Case Studies

6.1 New Zealand Case Studies

6.1.1 Database of Otago Region Barrier Assessments

A database has been developed of known fish barriers within the Otago Region, of which 69 have been field inspected and evaluated by Department of Conservation staff. The majority of these are natural barriers, and Figure 6-1 indicates the geographical spread of the recorded barriers. There are notable clusters in the Waipori River and its tributaries and the upper reaches of Deep Stream. Both these catchments are themselves tributaries of the Taieri River.

This intensive barrier inventory has been undertaken in the Otago Region because Otago is a ‘hot spot’ for threatened non-migratory galaxiids that are impacted by invasive fish. These non-migratory galaxiids have a very fragmented distribution due to impacts of trout and the presence of barriers. Barrier type and location is therefore critical to the protection and management of these key species habitats and populations. Other barrier assessments have likely been undertaken within NZ and overseas, however due to limited time and with ready access to the Otago inventory, this particular dataset was seen as a priority case study to include in this review.

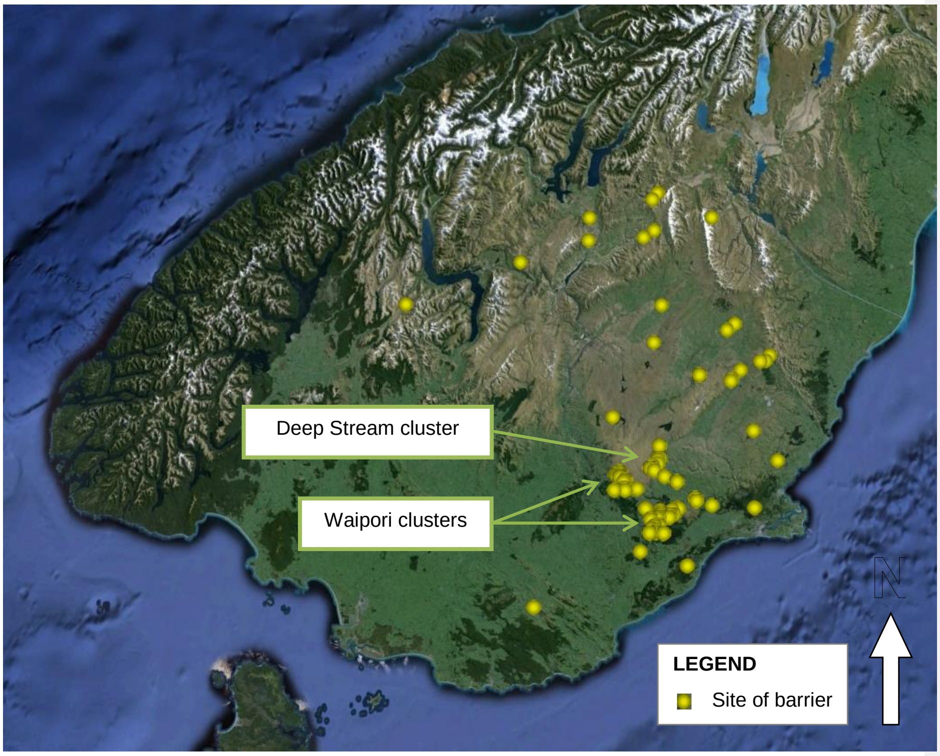


Figure 6-1: Map of Known Natural Barriers in DOC Otago Area

Each barrier evaluation assigned risk rankings for various factors that indicate the overall risk to vulnerable species at that site (see Appendix C for the evaluation matrix used to assign rankings), with a high ranking number indicating high risk.

Figure 6-2 shows the spread of rankings for each factor as assessed across all 69 barrier sites. For example, nearly 95% of the sites were assigned an invasive species downstream risk factor of 5, the highest possible risk value for that factor. The factors assigned the highest risk rankings were the presence of invasive species downstream, the upstream presence of a species classified as 'threatened' under the New Zealand Threat Classification System, limited coexistence observed in downstream areas (i.e. the upstream species was not often found in high numbers downstream of the barrier) and long distances between barriers. This provides evidence of the priority factors that need to be the focus of management for these barriers, to ensure protection of non-migratory galaxiid locations.

Figure 6-3 shows the range of species observed below and above each barrier. This clearly shows that when predatory species such as trout are not found in the upstream environment, the likelihood of observing non-migratory galaxiid species is significantly higher.

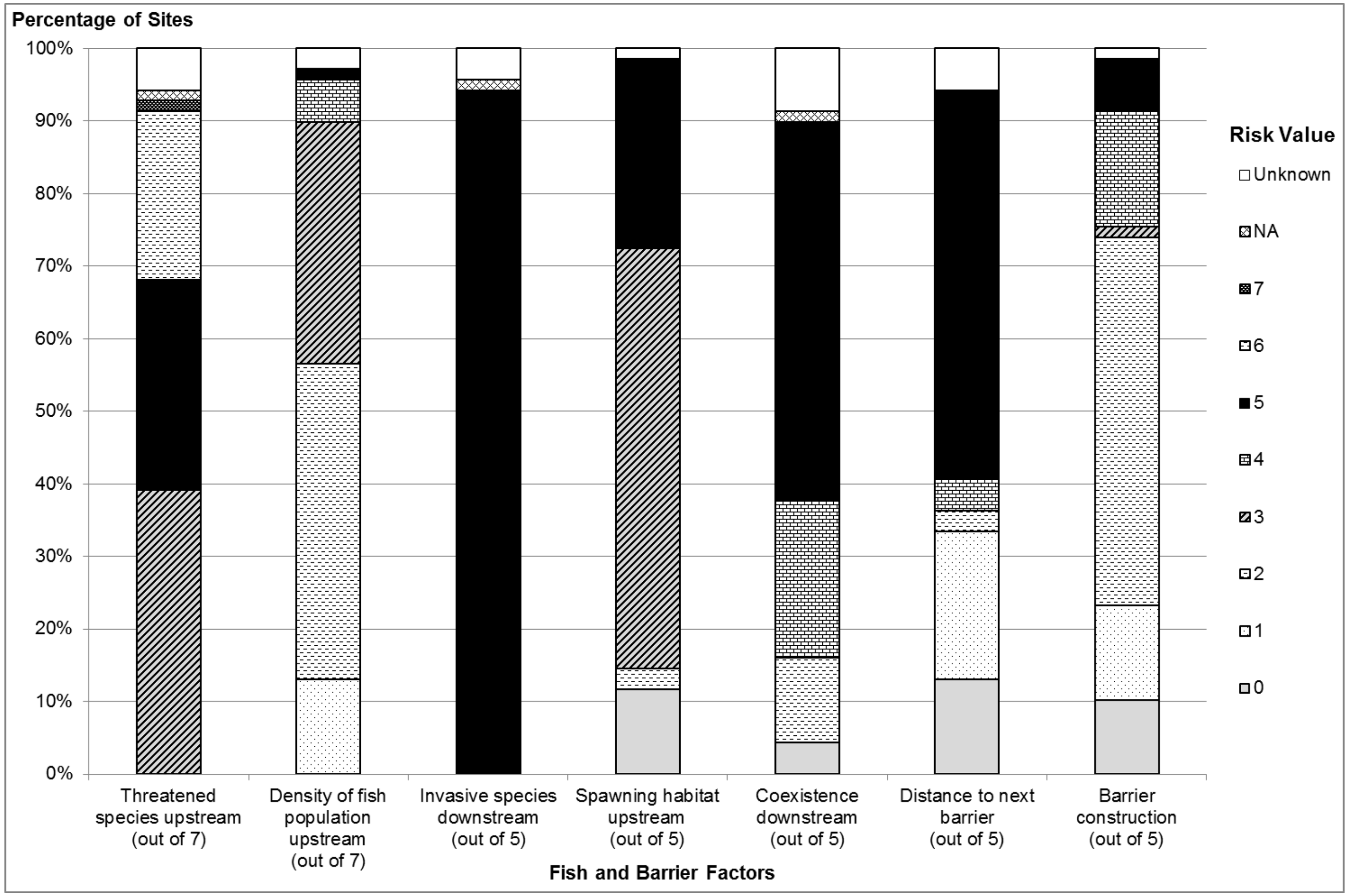


Figure 6-2: Risk Values for each Fish and Barrier Factors assigned to 69 Otago Barrier Sites

(Data extracted from Department of Conservation Barrier Assessments)

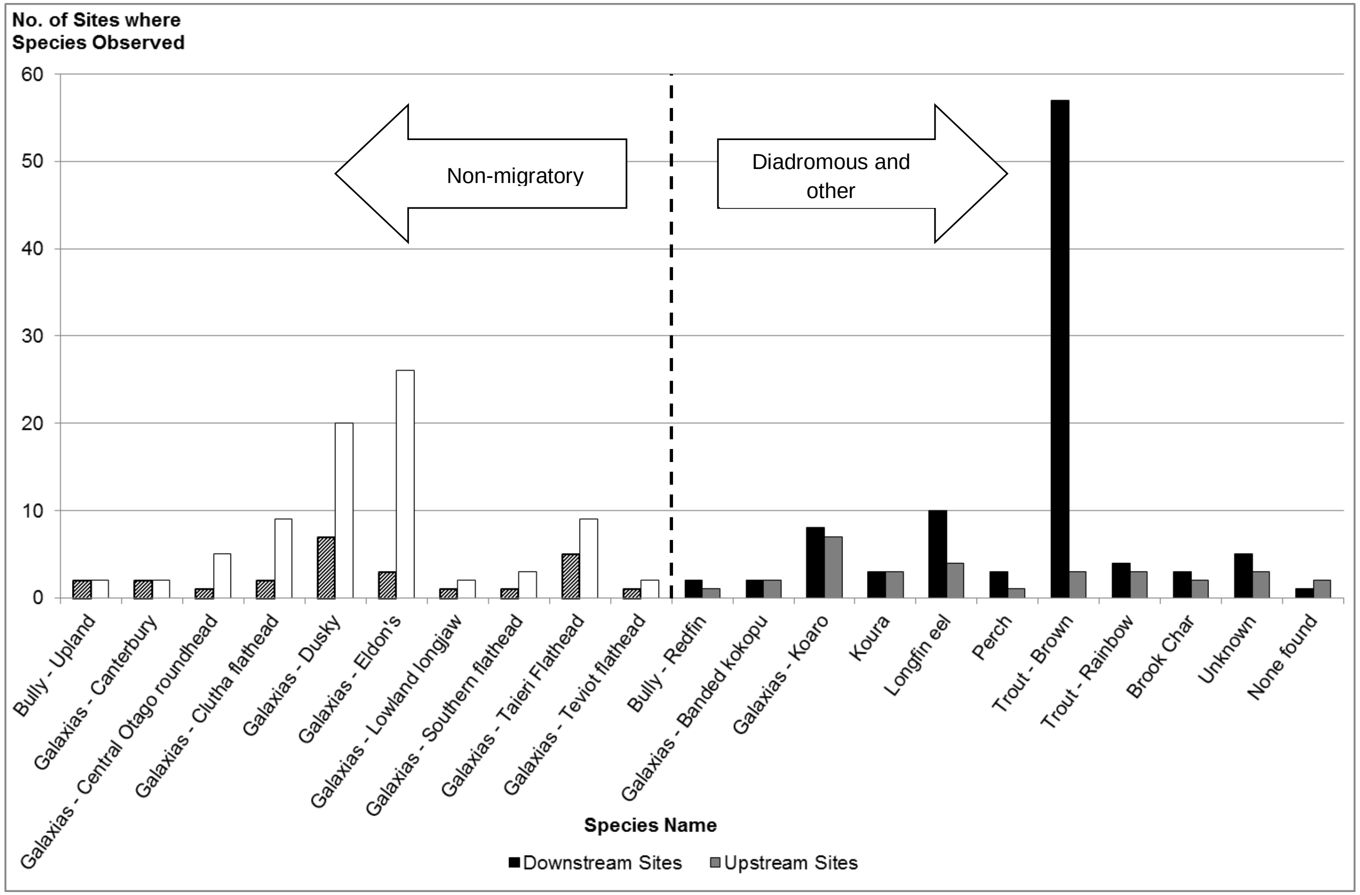


Figure 6-3: Observed Fish Species Presence Above and Below Barriers

(Data extracted from Department of Conservation Barrier Assessments)

Analysis of the database revealed the following statistics (see also Table 6-1):

- 54 of the barriers (i.e. 78%) were waterfalls, 6 were culverts (9%), 4 were weirs (6%), 3 were swamp (4%) and 2 were dry stream beds (3%)
- Of the barriers found not to be effective:
  - Non-effective waterfall barriers were all 1.5 m or less height
  - Non-effective culverts had invert levels 1 m or less above downstream pool
  - Six barriers (four waterfalls and two weirs) were found to ineffective at excluding köaro. Of these:
    - Three waterfalls (each ≥6 m high) were effective at excluding trout but not köaro, while one waterfall (1.5 m high) allowed both species passage upstream.
    - One weir was found to be ineffective at excluding köaro from the upstream area as there was no overhang at the weir crest. Another weir had been successfully modified with a larger solid steel overhanging plate as the previous short overhang piece had been ineffective at excluding köaro (Pete Ravenscroft, pers. comm.). Both weirs (0.8 and 1.5 m high) had downstream concrete aprons and were effective at excluding trout.
- Of the confirmed effective barriers:
  - Waterfall barriers started at 1.5 m, but the effective waterfalls of low height were typically coupled with a section of high velocity water (e.g. slot canyon, constriction in stream bed)
  - Trout were found downstream right up to the barrier, while galaxias were found directly upstream of the barrier. This suggests that while the trout could have incentive to negotiate the barrier they had not been able to.

Table 6-1: Summary of Barrier Type and Observed Effectiveness

Effectiveness of Barrier	Barrier Type					Total
	Waterfall	Culvert	Weir	Swamp	Dry Stream Bed	
Barrier effective	29	1	3	1	0	**34**
Not effective	5	3	1	0	0	**9**
Unspecified or unconfirmed	20	2	0	2	2	**26**

Of the 26 barriers that did not have confirmation of their effectiveness recorded in the barrier evaluation, no trout species were observed upstream of the barrier at the time of evaluation. More monitoring data is needed to confirm the barrier effectiveness, but the initial indications from the barrier evaluations suggest these barriers are likely effective at excluding trout, bringing the percentage of likely effective barriers to 87% (60 of 69).

It is important to note that some natural barriers change over time and therefore regular monitoring is critical to ensure the barrier has not been compromised. For example, DOC Otago have recently discovered that trout have managed to get upstream of natural waterfall in Akatore Creek that had previously excluded them from the upstream habitat (Department of Conservation, 2012) (see also Section 6.1.3). A weir has since been established on top of the natural waterfall and trout removed from upstream (Department of Conservation, 2012) (see also Section 7.1.10).

The following sections provide a further overview of natural barrier case studies where information has been available from journal papers and internal DOC reports.

6.1.2 Taieri River Barriers, Otago

A study by Townsend and Crowl (1991, in Townsend and Simon, 2006) assessed 198 sites within the catchment for presence of trout and galaxias. The key findings were:

- Waterfall barriers at least 3m high were effective barriers against trout
- The presence of trout beneath these waterfalls suggest that trout had established themselves in most reaches until a waterfall blocked access further upstream
- Galaxias were found only upstream of one or more large waterfalls (i.e. in habitat protected from trout).

6.1.3 Akatore Creek Waterfall Barrier (pre-weir), Otago

Akatore Creek is a small, coastal stream (flow range of 3-167 L/s; average stream width of 3 m), which drains the coastal hills south of Taieri mouth. A 1.8 m high bedrock waterfall in Akatore Creek, Coastal Otago, had previously prevented brown trout from gaining access upstream of the waterfall (Figure 6-4). However, routine monitoring of Taieri flathead galaxias in the Creek in 2010 indicated brown trout had gained access above the waterfall and were reducing the galaxias population (Department of Conservation, 2012). The reasons for the breach in the barrier are unclear but are considered to be due to one or a combination of the following:

- High flows may have coincided with spawning trout
- High flows may have coincided with increased deposition of gravel in the pool immediately below the waterfall, reducing the barrier height
- A small depression up the waterfall face may have provided a ‘stepping stone’ for trout to use in scaling the barrier, reducing the height of each jump required to breach the barrier

The galaxiid population was observed to recover well following several trout removal operations, and therefore the site was selected for installation of a built barrier to prevent reinvasion of the trout (Campbell et al., 2013).

Figure 6-4: Akatore Creek Waterfall Barrier (pre-weir)

6.1.4 Cave Stream Waterfall, West Coast

Cave Stream (average stream width of 3 m) is a tributary of the Maruia River, and has an approximately 3 m high waterfall formed from large boulders that creates a barrier to introduced species (Collis, 2008). Annual monitoring is undertaken of galaxiids in the upper Maruia River catchment, and the 2007/2008 Annual Report records the existence of this natural barrier in Cave Stream. Large numbers of dwarf galaxias and a few long finned eels have been found in upstream of this waterfall, while trout were confirmed in the waterway downstream of the waterfall. Only a few dwarf galaxias and upland bullies were found below the waterfall. The comparative increase in native fish numbers and the absence of brown trout upstream of the waterfall confirm that it is an effective barrier.

6.1.5 Shingle Creek, West Coast

Shingle Creek (average stream width of 1 m, with a 10km long catchment) is also in the Maruia catchment. Aside from the Cave Stream waterfall barrier, its 5 m high waterfall is considered to be the only other barrier within the Maruia catchment that would exclude introduced species from its upper reaches (Collis, 2008). However, as of 2007/2008 the barrier had not been surveyed and no further information has been recorded about this barrier.

7 Built Barrier Case Studies

As part of this review, a database has been developed of known built barriers within New Zealand and of some examples of overseas use of built barriers. The database allows for comparison and analysis of barriers, including installed barriers, those still in the design phase and laboratory trials. Analysis of the range of barrier types and their recorded effectiveness reflects both the lack of data available and the fact that many intentional barriers that have been installed for protection of native aquatic values are relatively new and further monitoring is needed to confirm their effectiveness. Table 7-1 shows the spread of barrier types and their recorded effectiveness. It should be noted that while there is a majority of barriers with unconfirmed effectiveness, only 3 have been confirmed as ineffective while 10 have proven effective, some for a period of 5 years or more.

Table 7-1: Summary of Barrier Type and Observed Effectiveness

Effectiveness of Barrier	Barrier Type				Total
	Weir	Screened Barrier (includes gabions)	Culverts	Other	
Barrier effective	5	3	1	1	**10**
Not effective	1	2	0	0	**3**
Unspecified or unconfirmed	11	4	2	2	**19**
Total number of each type	**17**	**9**	**3**	**3**	**32**

Weir barriers were the most common type of built barrier and typically had the most recorded design information available. Key findings from the database for characteristics of effective physical drop (weir) barriers are summarised in Table 7-2.

Table 7-2: Summary of Design Considerations for Physical Drop (Weir) Barriers

Design Feature	Design Criteria	Design Considerations
Barrier location	• Barrier placed in a stable section of streambed, with a moderate slope	• Minimise upstream backwater effects including loss of riffle zones, flooding by placing barrier in section of reasonable gradient
Barrier height	• Drops ≥1.5 m are effective exclusion barriers. Smaller drops (1.5-2.5 m) should be used in combination with other barrier types, such as a shallow, high velocity chute.	• 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 to maintain a concentrated, high-velocity body of flow under low flow conditions • Existing barriers have used ≥500 mm overhangs to inhibit jumping	• Minimise upstream backwater effects by using a shallower upstream face profile • Grated overhangs have been used to allow climbers to pass up through barrier

Design Feature	Design Criteria	Design Considerations
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, scour • Protection of abutments
Downstream zone	• Downstream apron (>2 m length) to create a high velocity and shallow water zone that inhibits jumping and swimming	• Scour protection on sides of apron • Scour protection downstream of apron

The following sections provide overviews of New Zealand and international built barrier case studies to supplement the information captured in the database tables. Note that the barriers described in these case studies are all included within the database.

7.1 New Zealand Case Studies

7.1.1 Maruia Tributary Gabion Barrier, West Coast

A gabion barrier was installed prior to 2007 at one of the tributaries of the Maruia River (at the Lake Daniells carpark; average stream width of 2-3 m) (Figure 7-1). Routine monitoring had shown this tributary to be a key habitat for dwarf galaxias (Collis, 2008). As of 2007, annual monitoring had shown that the barrier was successful at preventing further introduced species from gaining access to upstream of the barrier. The barrier is comprised of large rocks, up to 250 mm in diameter, held with gabion wire mesh. The intention of the design is to prevent access for introduced species while allowing dwarf galaxias to migrate past the barrier via the spaces between the rocks within the barrier. Trout were in low to moderate numbers upstream of the gabion barrier as they have not been removed. Unfortunately, due to lack of maintenance and the location at which the barrier was installed, flood flows have breached the barrier and repeated flooding has washed away the barrier (Gavin Collis, pers. comm.).

Figure 7-1: Maruia River Tributary gabion barrier, soon after installation

7.1.2 Orokonui Gabion Barrier, Otago

A gabion barrier was installed in Orokonui Creek in 2000 (Campbell, 2010) with the multiple objectives of:

- To allow native juvenile fish upstream passage as well as allowing adult migratory fishes passage out to sea.
- To obstruct and prevent the upstream passage of spawning brown trout,
- To test the effectiveness of a gabion basket as a method of allowing native fish passage and preventing brown trout passage.

Several diadromous native fish species have been found in this catchment, and the only species of concern is brown trout. The gabion basket was therefore intended to work by allowing juvenile native fish to move upstream through the interstitial spaces within the gabion, while brown trout would be unable to pass through these small spaces. A perched culvert was installed within the gabion to allow adult migratory fish passage out to sea, while preventing brown trout from being able to jump upstream past the gabion (Figure 7-2).

However, the subsequent monitoring results show that the overall abundance of native fishes above the gabion basket is declining. This is an indication that the barrier does not allow sufficient numbers of juvenile fish to pass through. The loss of two species of bully and the apparent decline of banded kokopu provides further indication that the gabion basket does not effectively allow for migration of juveniles. In addition to not providing access to fish, the gabion weir needed regular maintenance to clear it of debris that would build up in higher flows. The plant, Monkey Musk (*Mimulus guttatus*), also established on the weir such that the interstitial spaces in the gabion became clogged (Pete Ravenscroft, pers. comm.).

The report recommended the removal of the gabion barrier as it had not been effective in achieving the goals for fish passage management in the Creek.

Figure 7-2: Orokonui Creek "permeable" Gabion Barrier

7.1.3 Upper Waipori Barrier, Otago

A v-notch weir on the Upper Waipori River (Figure 7-3) has been modified to create a barrier to exclude köaro as they were thought to be adversely impacting the upstream population of dusky galaxias. As of 2012, the effectiveness of this barrier was uncertain (Bowie and West, 2012), both in terms of whether total exclusion of köaro is achieved and whether this barrier enhances the dusky galaxias population as monitoring was not showing a response in the dusky galaxias population to the removal of köaro and installation of the barrier.

Figure 7-3: Upper Waipori River gauging weir with added stainless steel barrier apron

7.1.4 Fraser Spring Barrier, Mackenzie Basin

A population of two threatened galaxiids, the Nationally Critical endangered lowland longjaw galaxias and the National Vulnerable bignose galaxias are found in small spring associated with the Fraser Stream near Twizel (Ravenscroft et al., 2013). These species were severely put at risk by an invasion of brown trout in 2006. Trout removal operations limited trout numbers, and a temporary barrier was installed in 2008 to assist in limiting numbers in the periods between trout removal operations and while approvals were being gained for the permanent barrier. This temporary barrier was effective for its purpose, however a permanent barrier that excluded (not just limited) trout was required.

A permanent concrete weir barrier was installed in 2010 (Figure 7-4). The specific design decisions and features of the barrier are:

1) Precast concrete to minimise on-site construction
2) Concrete apron on downstream side to prevent formation of a plunge pool that could enable trout to jump past the barrier
3) A galvanised steel lip was attached to the downstream side of the weir – extending 150mm out from the wall face, with a turned down piece of 70mm length – to create an overhang to prevent köaro from climbing over the barrier and accessing the upstream habitat.
4) V-notch weir crest to ensure concentrated, fast water flow over the crest under varying flow conditions
5) Concrete side walls and raised earth stop banks to prevent overland flows and scouring around the weir sides during periods of high flows
6) The weir has a buried culvert off to the one side to aid in the lowering of upstream water levels, if trout removal from the pool on the upstream side of the weir is required. This also allows the upstream habitat to be managed to ensure large deep pools are avoided and non-migratory galaxiids are provided with optimal habitat.

Figure 7-4: Fraser Spring Weir Barrier (Constructed by DOC)

Lessons learnt relating to the installation of this barrier are summarised in Table 7-3.

Table 7-3: Fraser Spring Barrier Assessment of Strengths, Weaknesses and Improvement Options

Strengths	Weaknesses	Improvements to Address Weaknesses
Concrete apron downstream of the weir has been successful in preventing plunge pool formation.	When the precast barrier weir was lowered into the bed of Fraser spring, the seal between the barrier apron and the spring bed was insufficient and water flowed under the barrier from the upstream side to downstream.	The underflow was remedied by pouring additional concrete in front of and under the apron to ensure a perfect seal was formed. Ravenscroft et al. (2013) suggests for future such installations, it would be preferable to pour the whole concrete pad on site and then add the precast upright parts of the barrier later.
The galvanised steel lip has been successful in inhibiting fish ability to jump past the barrier.	Too much splashback was created on the galvanised steel lip which allowed köaro to climb past the barrier on the wetted surfaces.	A wider overhang should be installed.
	Bypass culvert was not actioned as this was not as straight forward to construct as first thought.	A weir created by wood planks may have been more effective as it would allow for changing the height of the barrier.

Some changes are proposed to be made to this barrier soon including changing from a solid concrete barrier face to a drop log structure this will enable better manipulation of flows (Pete Ravenscroft pers comm.). The culvert will be opened up to allow the flows to be dropped to allow this work to be undertaken.

Monitoring has shown that trout are excluded by the barrier, a pool created upstream of the barrier is larger than predicted, and further work is needed within the spring to manage macrophyte establishment and silt (Bowie and West, 2012). It is uncertain whether climbing fish are excluded by the barrier. Regardless, the two galaxias species upstream of the barrier are showing a recovery in population numbers.

7.1.5 Haumurana Stream Tributary Barrier, Bay of Plenty

A spring-fed tributary of the Haumurana Stream is habitat for köaro, common bully and koura. A permanent trout exclusion barrier has been installed 10 m upstream from the tributary's confluence with Haumurana Stream. The tributary is considered to be a very stable catchment, with low fluctuations in flow rate due to its spring-fed nature (Bay of Plenty Regional Council, 2013) and established vegetation corridor.

The specific design decisions and features of the barrier are:

1) Concrete apron on downstream side
2) Wingwalls cut into bank and protected with gabion baskets
3) V-notch weir profile to ensure concentrated, fast water flow over the crest under varying flow conditions, and allows climbing species to negotiate the weir
4) A metal grate extends out over the weir crest to inhibit trout from jumping
5) The presence of the weir will raise upstream water depth by 100-120 mm, however, this is not considered a flooding issue as the stream banks at the proposed barrier location are high, the inset wingwalls will protect against side scour and the spring source means flows are generally stable.

Figure 7-5: Haumurana Stream Tributary weir and grate barrier

7.1.6 Haldon Pastures Barrier, Canterbury

Several spring-fed streams (average stream widths of 1-3 m) at Haldon Pastures provide habitat to the endangered Canterbury mudfish, as well as Canterbury galaxias, upland bully and shortfin eel. A weir and grate barrier is proposed (see example of barrier type in Figure 7-6) to exclude trout from a 3 km length of one of the streams as it is a key location of Canterbury mudfish and this species does not cope well when co-occurring with other species (McCaughan and Spencer, 2012). Design considerations and features include:

1. Measured channel width of 2 m at the proposed barrier site

2. Limited hydrological monitoring has been undertaken at the barrier site (including water flow, velocity and depth)
3. A concrete barrier is to be constructed off-site then brought to site for installation
4. The surrounding land and stream bed is low gradient, therefore a 1 m barrier will likely cause unacceptable upstream flooding. A 0.5 m barrier was selected in combination with other mechanisms to create an exclusion barrier.
5. The other mechanisms include:
    a. An anti-jump screen which protrudes horizontally from the downstream face
    b. A 2 m long downstream concrete apron for scour protection and to prevent a downstream pool forming (and thereby inhibiting jumping)
6. Gabion baskets, reno blankets and rip-rap will be used to provide scour protection on the stream banks and bed.
7. The water level fluctuates seasonally and is lowest in late summer/autumn. It is hoped that the increase in water depth created by the barrier may provide more habitat for the mudfish in the drier periods.
8. The only migratory native fish in the stream are short-finned eels. The eels are strong climbers and should be able to cross the barrier by climbing the wetted concrete surface or wetted grass adjacent to the barrier. Eels are not in large numbers in this system and if they were excluded from upstream of the barrier, this would not be considered a significant issue as there is large habitat available elsewhere. Furthermore, mudfish cannot handle large abundances of eels as they are a predator, so limited eel numbers are beneficial for the health of the mudfish population.

This proposal is still working through approval processes and is not yet installed.

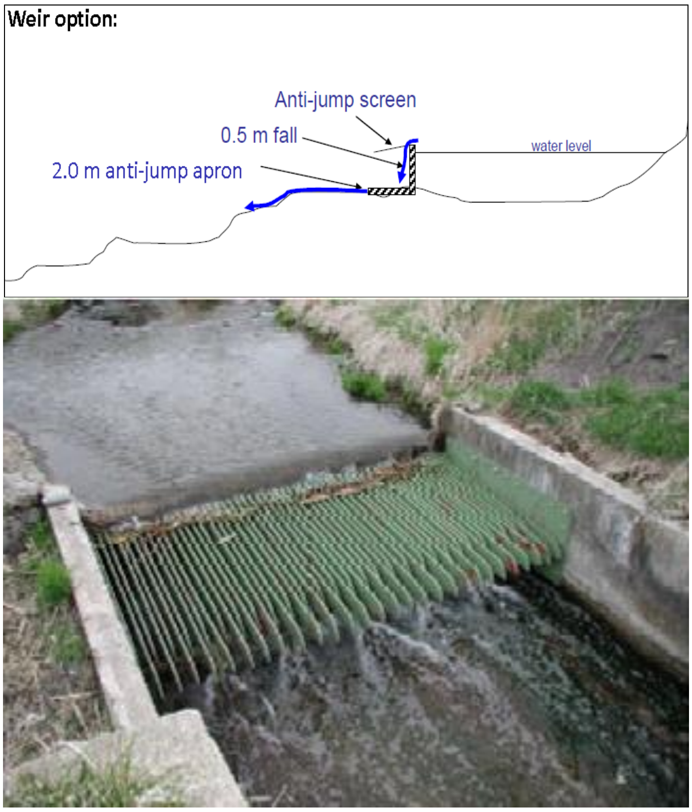


Figure 7-6: An US example of a weir and grate barrier design similar to proposed Haldon Pastures Barrier

7.1.7 Coach Stream Barrier, Canterbury

Modifications are to be made to an existing culvert apron to create a barrier that prevents trout from accessing upstream Canterbury galaxias habitat. Design considerations and features include:

1. A new section of wingwall is to be added downstream of the existing wing wall to contain flow within the apron
2. A 1.6 m horizontal step is to be created at the end of the existing downstream wing wall to create an zone of shallow water
3. A new ‘fish deflector’ is to be attached to the downstream edge of the step to create a barrier against jumping while enabling climbers to pass upstream. The deflector is comprised of 500 mm long metal fins centred 35 mm apart.
4. The scour pool is to be extended and lined with ~400 mm diameter rocks to limit erosion and water depth in the downstream pool.

This barrier is in the preliminary design phase only and therefore there is no data available on the effectiveness of this barrier design.

7.1.8 Lake Rotopiko Barrier, Waikato

A V-notch weir barrier was installed at the outlet from the Serpentine (Rotopiko) Lakes complex in Waipa District, with the objective of preventing upstream reinvasion of rudd into the lakes (Rowe and Dean-Speirs, 2009). Design considerations and features include:

1. A V-notch weir forms the centrepiece of the barrier, with a drop of 1.3 m from the centre of the notch to the base of the downstream face
2. The main weir piece is constructed from 200 mm SED (Small End Diameter) timber, with full-round posts and tongue and groove horizontal boards. There is a 1 m wide central section of removal timber retaining boards allows the upstream water level to be reduced as required.
3. A downstream concrete apron, laid at 1:12 slope (8%) extends 2 m away from the downstream face of the weir. The apron is set up a minimum of 500 mm from the stream bed
4. 200-300 mm diameter rocks are used to protect the stream bed from scour off the end of the apron
5. A Reno mattress is used to provide downstream bank protection
6. 15 mm diameter fish barrier bars extend 950mm in a downstream direction from the weir crest, set on a 30° angle down from horizontal. The bars are set with a 40 mm gap between each one.
7. A facing of nylon bristles is set against the downstream side of the timber boards to create a climbing eel passage.
8. The weir foundations (i.e. the full-round posts) are set in concrete to a minimum depth of 2 m below surface.

Figure 7-7 shows the completed installation, however, no data on the effectiveness of this barrier is available yet.

Figure 7-7: Lake Rotopiko outlet barrier, immediately after installation

7.1.9 Lake Ohinewai Barrier, Waikato

Coarse screens have been installed over drain entrances at Lake Ohinewai to prevent koi carp entering the drains from the lake (Bowie and West, 2012). These barriers have proven to be effective at controlling the spread of carp and are low cost. This type of barrier may be suitable in environments where little debris is expected from the piped drains, and only large spawning fish need to be excluded.

Figure 7-8: Left: One way barrier installed on outlet of Lake Ohinewai, Waikato River. Right: Close up of one-way hinged grate through which large fish can pass in one direction only.
(Photo credits: Adam Daniels)

7.1.10 Akatore Creek Barrier (post-weir)

As detailed in Section 6.1.3, the Akatore Creek natural waterfall barrier was breached by brown trout and as a result a concrete and wood slat weir was installed in 2013. Subsequent surveys suggest there are no brown trout remaining above the barrier, and observations suggest a positive response by Taieri flathead galaxias to the removal of brown trout (Campbell et al., 2013).

Figure 7-9: Akatore Creek Built Barrier

The key design features of the enhanced barrier are:

- The main structure is concrete, keyed into the underlying greywacke bedrock with rebar and grout, with treated timber slats forming the central overflow crest
- The crest height over the timber slats is 700 mm above the bedrock, so the combined vertical drop of the enhanced barrier has become 2.5 m.

- The top of the timber slats is set down 150mm from the top of the surrounding concrete walls, to ensure flow is concentrated and directed over the timber slats, not the whole crest length
- The timber slats can be removed and the upstream pond level dropped if required

7.1.11 Important Water Intake Design Criteria

Water intakes are a screen barrier, however their purpose is quite different to installing a barrier in stream to prevent passage upstream to protect a specific species location. This brief section on water intake design has been included in this review to provide some design knowledge that can also be considered in other barrier types, for example, for downstream barriers intended to prevent invasion of species into riverine environments from lakes.

Water intakes need to be designed to exclude fish where possible to avoid impingement or entrainment, which would result in them being lost to the fishery. A multi-agency working party (Irrigation NZ, Environment Canterbury, DOC and Fish & Game) undertook a number of reviews to determine seven key criteria that are important to ensure water intakes are designed to prevent impingement and entrainment of fish at water intakes (Jamieson et al., 2007), as follows:

1. **Location** – the location of the intake needs to minimise the exposure of the fish to the fish screen structure and the best way to do this is often to ensure it is as close as practical to the take
2. Water velocity through the screen (**approach velocity**) is slow enough to allow fish to escape entrainment or impingment (maximum approach velocity = 0.12 ms^{-1})
3. Water velocity across the screen (**sweep velocity**) is sufficient to sweep the fish past the intake promptly (i.e. sweep velocity > approach velocity)
4. A suitable **bypass** is provided so that fish are taken away from the intake and back into the source channel
5. There needs to be “**connectivity**” between the fish bypass and somewhere safe for the fish (e.g. usually an actively flowing main stem of a waterway)
6. Screening material on the screen needs to have openings small enough to exclude fish and a surface smooth enough to prevent any damage to fish (**2-3 mm** optimal for exclusion of NZ fish species)
7. The intake needs to be kept operating to a consistent, appropriate standard with appropriate **operation and maintenance**

Figure 7-10: Fish screen at intake to irrigation water race

As part of this work, a collation of specific native fish requirements was established (Charteris and Hamblett, 2006) and this was combined with sports fish requirements (Bejakovich, 2005) to form the overall guidelines (Jamieson et al., 2007). An example of native fish requirements was that by using the known swimming ability information, it was determined that velocities need to be maintained at water intakes <0.3 ms^{-1} and this would minimise involuntary entrainment of most juvenile and adult native fish. In contrast, sweep velocities past a water intake needed to be >0.5 ms^{-1} (Charteris and Hamblett, 2006).

7.2 International Case Studies

7.2.1 Shaw Creek Barrier, Victoria, Australia

Within the Alpine National Park, Victoria, Australia, a newly discovered galaxias species, the Shaw Galaxias (*Galaxias sp. 7*), have inhabited a small area of alpine stream, upstream of a natural waterfall that creates a barrier against migration of trout (Parks Victoria, 2013) (Figure 7-11). However, storms and floods over the summer period of 2010-11 compromised the integrity of this barrier and enabled trout to start colonising upstream of the waterfall. Subsequent monitoring showed a drastic reduction in galaxiid numbers until their habitat was reduced to a 300 m length of 0.3 m wide stream and the population was in imminent threat of extinction (Parks Victoria, 2013).

A multi-stage approach was developed:

1. A temporary barrier was installed at the downstream end of the existing small habitat
2. A permanent barrier (concrete weir) was then installed near the existing waterfall
3. Trout removal was carried out for the catchment upstream of the permanent barrier
4. Monitoring is now ongoing

The permanent weir is a 1.3 m high cast-insitu concrete weir with a shallow v-notch crest profile, as shown in Figure 7-11. It includes a downstream concrete apron and pools both directly upstream and downstream of the weir have been infilled as part of the construction.

Figure 7-11: Shaw Creek Barrier, before and after installation in 2012 (Source: Raadik, 2012)

Experience gained to date through this project (Tarmo Raadik, pers. comm.) can be summarises as follows:

1) A barrier **crest height of 1.3 m** was selected to provide a sufficient height barrier against jumping when in combination with other barrier mechanisms such as the shallow water zone created beneath the weir.
2) The barrier was located where the **stream bed gradient was steep** to limit pooling downstream of the barrier.
3) Rocks were 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).
4) A **pool directly upstream of the weir was eliminated** through infilling, providing two benefits:
   a) Increased stability of the structure (greater mass to prevent overturning)
   b) Trout no longer have a pool to jump into
5) An apron was installed to **eliminate pooling** directly downstream of the weir.
6) Large rocks were placed on the floodplain of each bank to direct overland flows into the main channel, to **eliminate any opportunity for trout to bypass** the barrier.
7) The barrier site was also selected in a section of the catchment with the **smallest floodplain area** on each bank.
8) The weir profile was a **shallow V-notch to concentrate flows** towards the centre of the weir
9) Precast headwalls were considered for the barrier structure, but were discounted because:
   a) unavailable at the large size required, and
   b) came with a pre-formed hole for a culvert pipe, which would have required blocking at increased cost.

7.2.2 Lees Creek Barrier, ACT, Australia

An existing v-notch weir in Lees Creek, ACT, Australia has been augmented to prevent re-invasion of rainbow trout (*Oncorhynchus mykiss*) into *Galaxias olidus* habitat (Figure 7-12). Lees Creek is a perennial stream with a stream width of 1-2 m and average water depth of 100-300 mm (Thomas et. al, 1989, in Lintermans and Raadik (2001)).

The weir was augmented by addition of a metal grill to provide a vertical drop of 1.75 m. Rotenone treatment, a type of ichthyocide (fish poison), was then undertaken to eradicate trout upstream of the barrier. Prior to the augmentation of the weir, a road crossing culvert 2.4 km upstream of the weir was found to have successfully prevented upstream movement of trout, due to its 15 m length of relatively fast, unbroken flow with no cover available to provide respite from the current for trout.

Figure 7-12: Lees Creek Weir Barrier, before and after augmentation
(Source: Lintermans and Raadik, 2001)

This case study is the first documented case in Australian streams of recovery of a native species following eradication of an exotic fish species ((Lintermans and Raadik, 2001)). As of 2001, the treated stream section upstream of the barrier remains trout-free (i.e. over 6 years since treatment). This provides approximately 9 km of predator-free habitat for *G. olidus*.

Lintermans and Raadik (2001) note that the success of the augmented weir in Lees Creek and effectiveness of the road culvert as a long-term barrier to trout movement both demonstrate that only relatively small structures are required for trout exclusion.

7.2.3 Constructed Trout Barriers, Victoria, Australia

Three barriers have been constructed in the Goulburn River catchment, Victoria to prevent re-invasion of trout into barred galaxias (*Galaxias fuscus*) habitat (Lintermans and Raadik, 2001), in Morning Star Creek, Perkins Creek and Godfrey Creek (which flows into Raspberry Creek). Barred galaxias are considered to be one of Australia's most endangered fish species.

Each barrier includes:

1) Vertical drops ranging from 1.5 m to 1.8 m (the design criteria was a minimum of 1.5 m) were achieved by creating each barrier out of two hardwood logs stacked on top of each other, keyed into each bank by 1.5 m (Figure 7-13).

2) In higher flows, flow is to directed towards the centre of the stream channel, via a notch cut into the upper log at stream centre

3) Slower overland flow and erosion around the sides is prevented by crushed rock places along the stream edges

4) Any pooling below the barrier was filled in to help prevent trout from jumping past barrier

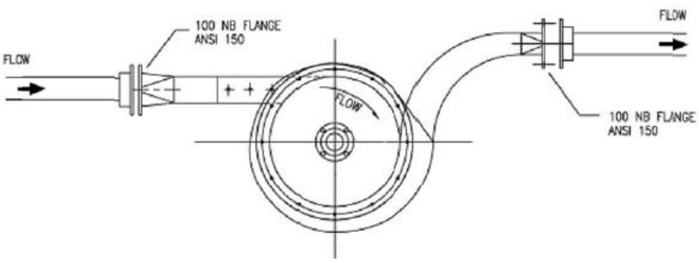
5) The upstream weir faced was infilled with crushed rock to reduce the hydraulic pressure on the face and eliminate any upstream pool. Initially there was flow through the crushed rock and seepage out the gaps between the logs, but migration of fines plugged these gaps up over time. The water now consistently flows over the top of the log weir structure.

Figure 7-13: Godfrey Creek constructed trout barrier

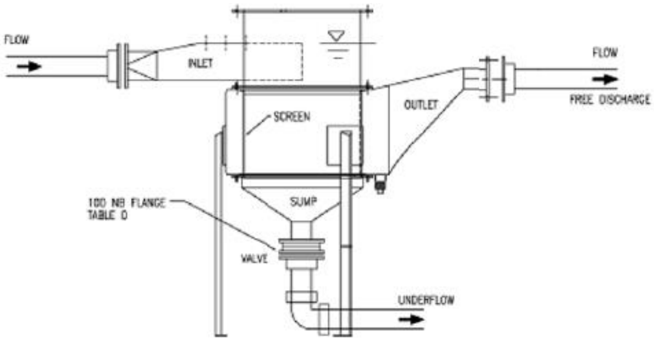
The barriers were constructed prior to successful treatment with rotenone to eradicate trout from areas upstream of the barriers (note, no barred galaxias were poisoned in this operation (Lintermans and Raadik, 2001)). As of 2000, the barred galaxias had re-established in approximately 4 km of the 20 km of stream habitat protected by the three barriers (Raadik, 2000, in Lintermans and Raadik (2001)). While trout had re-established in Raspberry Creek and in Morning Star Creek, this was thought to be due to deliberate re-introduction by anglers and the barriers themselves had not been compromised.

7.2.4 Continuous Deflective Screening, Murray-Darling Basin, Australia

Continuous Deflective Screening (CDS) is a form of indirect screening previously used successfully in stormwater applications (Schwarz and Wells, 1998). In the CDS unit, the inflow is deflected away from the main flow stream into a separation chamber. The chamber has a sump at the bottom and a screen in the upper section. Coarse particulates are captured in the sump, while filtered water passes through the screen and re-enters the main flow stream.



(a) Plan view



(b) Elevation

Figure 7-14: Schematic of CDS unit (Source: Keller, 2012)

A CDS barrier was installed at the outlet of a reservoir in the Glenelg River system (Keller, 2012) (Figure 7-15). The objective of preventing carp from moving downstream from the carp-infested reservoir waters into the river. The barrier needed to be able to pass high flows at all times. A model study, followed by a prototype field trial, was conducted with carp eggs and hatchlings to record the success rate of the CDS in preventing their passage back into the stream. The model studies demonstrated 99.7% effectiveness at removing carp eggs and hatchlings, while five years of field monitoring has shown no evidence of establishment of carp populations in the river beyond the barrier.

Figure 7-15: Prototype Carp Extraction System in operation (Source: Keller, 2012)

7.2.5 German Gulch Barrier, Montana, USA

German Gulch is a tributary of Silver Bow Creek which then flows into the Clark Fork River. Mining in the Silver Bow Creek catchment has previously prevented migration of invasive species such as rainbow trout and brown trout into German Gulch from the Clark due to the toxicity of the water (Montana Water Center, 2007). However, westslope cutthroat trout and brook trout populate German Gulch and the westslope cutthroat trout is considered a valuable fishery. Remediation of the mining area will improve the Silver Bow Creek water quality in the future and a weir barrier was designed to ensure the downstream invasive species cannot enter German Gulch once the Silver Bow Creek water quality no longer poses a barrier.

Hydraulic analysis was done (using HEC-RAS, internationally-available hydraulic modelling software) for the proposed barrier profile, assessing the peak flows across the barrier crest at various flood scenarios (i.e. 2 year return event up to a 100 year return event). A design minimum velocity of 15 ft/s (4.6 m/s) was selected based on the maximum burst speed of the downstream species, and the water velocity for each flood scenario was checked and found to exceed the design minimum velocity. A range of crest heights were modelled, from 4 to 7 ft (1.2-2.1 m), and the resultant backwater profile of the channel upstream from the weir was also modelled to check for flooding and overtopping of banks. With an average stream bed slope of 1.8% and bank height of 2 ft (0.6 m), the backwater length ranged from 300 ft to 500 ft (90-150 m) under the range of crest heights and up to 5 year return event flows. Based on these findings, a final barrier design with 6 ft (1.8 m) crest height was selected, as shown in Figure 7-16.

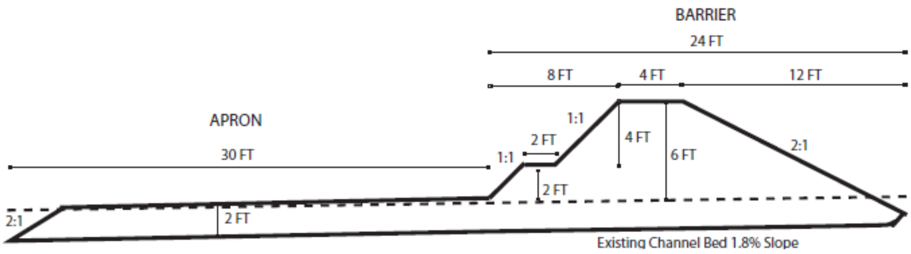


Figure 7-16: Selected Profile of German Gulch Barrier (Source: Montana Water Center, 2007)

A revised hydraulic analysis was done of the final design under low flow conditions (i.e. when water velocity would also be low) to check whether the water depth would be sufficiently low enough to inhibit swimming over the barrier. It was concluded that the combination of very low water depth and compound face profile (i.e. a stepped downstream face, not a single slope) would be an effective barrier when water velocity was below design velocity.

The barrier is to be constructed from rocks, with a geotextile fabric to minimise flows through the structure. No information is yet available about the effectiveness of this barrier.

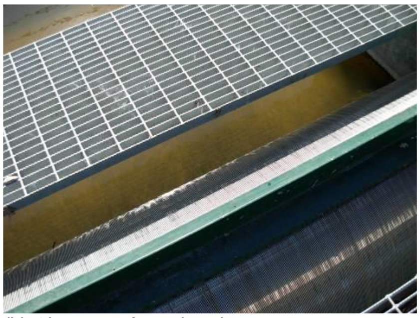
7.2.6 Shallow Lakes Barriers, Minnesota, US

A range of barrier types have been installed as part of the Shallow Lakes Program in Minnesota, US, to control carp populations (Minnesota Department of Natural Resources (2010), West (2009)). These shallow lakes (i.e. less than 15 ft deep (4.5 m)) are typically dominated by wetland habitat. The barriers (as shown in Figure 7-17) include:

- Electric and flow-powered rotating drum barriers, which provide screening of the outlet
- A velocity culvert, which uses velocity as the sole barrier against upstream fish movement (i.e. the culvert is not significantly perched above the downstream streambed level)
- Vertical and grated weirs that prevent upstream movement by providing a barrier against jumping, while allowing significant flows to pass downstream. The grated weir design is similar to the design adopted for the Coach Stream modifications (see Section 7.1.7) .
- An electric barrier

The individual effectiveness of each barrier is not recorded.


(a) Electric rotating drum barrier


(b) Close up of rotating drum


(c) Chamber cover for flow-powered rotating drum barrier


(d) High velocity culvert outlet


(f) Vertical weir barrier (overflow weir)


(g) Grated weir


(h) Low head weir with grated overhang and downstream apron

(j) Electric barrier (switchboard building to back left). Inset: warning sign on switchboard building.

Figure 7-17: Minnesota Shallow Lakes Barriers (Source: West, 2009)

7.2.7 United States Bureau of Reclamation (USBR) Manual

Chapter 3 of the USBR manual on fish protection at water diversions (USBR, 2006) includes a review of built barrier types and examples of where each type of barrier has been installed. However, the application of these barriers is primarily for preventing fish movement in a downstream direction (i.e. keeping fish clear of water intakes), instead of preventing upstream movement as is the most common scenario in New Zealand. The manual can be referred to for specific examples of implementation of each barrier type, but the recorded design details in the manual for the examples are minimal.

8 Discussion

8.1 Barrier Effectiveness

Clarkson (2004, cited in Carpenter and Terrell (2005)) argued that any fish barrier that is not 100% effective could be considered a failure. However, the success of the barrier can only be measured in terms of its objectives. There is value in having a partial barrier, as demonstrated by the temporary barrier used at Fraser Springs prior to a permanent installation, as it can limit the numbers and size of invasive fish in between fish removal programmes.

As trout species are one of the primary threats to New Zealand native species, full exclusion barriers are likely to be required that impede the strong swimming and jumping ability of trout in some key threatened native locations. The key compromise with moving to a full exclusion barrier is the risk that the isolation imposed on the upstream species will put it at risk of localised extinction. However, healthy isolated galaxiid populations are evident upstream of barriers in key non-migratory galaxiid locations (either as a result of a natural barrier or built barrier).

In understanding why a barrier may fail, Carlson (1994, cited in Bullen and Carlson (2003)) suggested the most common reason for fish control (barrier) systems failing to achieve their objectives is where the response of the fish to the water flow conditions is overridden or superseded by their response to other stimuli (such as food). This is evident from the variability in effectiveness found in non-physical barrier field studies. For example, two different infrasound (low frequency) studies found effectiveness levels of 57% and 80% (Sonny et. al, 2006 and Sand et. al, 2000, in Noatch and Suski (2012)), while a study of an air bubble curtain combined with strobe lighting found a range of effectiveness (70% up to 95%) in part due to acclimation of fish to the strobe over time (Patrick et. al, 1985, in Noatch and Suski (2012)). In contrast, physical barriers are primarily at risk to changes in water flow conditions only.

8.2 Upstream Effects of Physical Barriers

The upstream effects on stream hydrology from the installation of a weir need to be considered, including (Salant et al., 2012):

- Siltation against the upstream face of the weir as the water is slowed. The loss of energy means particles drop out of suspension.
- The backwater effects upstream of the weir can cause loss of riffle zones and creating of deeper pool areas, which may enhance or reduce the available habitat of the upstream species.
- A shallow stream grade results in an extensive area of backwater.
- The backwater effects may cause flooding of an area beyond the original stream channel, changing availability of habitat and balance of aquatic fauna and flora.

Land use is an important factor in the likelihood of siltation at barrier sites. There may be a reduced risk of siltation in the higher-altitude reaches of streams, due to the limited amount of finer, more weathered soils. However, at sites surrounded by modified landscapes (e.g. farming catchments), silt is contributed to the stream by surrounding landuse activities as well as via concentration by macrophytes in the stream. Siltation issues are evident at the Fraser Spring Barrier in Canterbury (Section 7.1.4).

Research by Goodarzi et al. (2012) into the effects on the backwater profile from different upstream slopes of broad-crested weirs found that a shallower upstream slope reduced the increase in water depth upstream and therefore reduced the length of the backwater. Crowder (2009) found the backwater length could be approximated when the depth of water at the weir and streambed slope were known, as shown in Equation 1:

$$\text{Backwater length (km)} = 0.7 * \text{depth (m)} / \text{gradient (m/km)} \qquad (1)$$

This equation assumes a 90° (i.e. vertical) upstream face, with no confluences, loops, spills etc. in the reach above the weir and steady-state, subcritical flow. This relationship can provide a useful means of estimating expected backwater length with a vertical upstream face, which could then be reduced by creating a shallower-sloped upstream face.

9 Conclusions

Conclusions that can be drawn from reviewing the available literature on waterways barriers for the purpose of protecting native fish species from invasive ones are:

1. In New Zealand, there are a few invasive fish species that are impacting some of our key native sites. Invasive fishes', e.g. brown trout, predation of native fish species, the invasive species' strong swimming ability and strong jumping ability indicate that a full exclusion barrier is required to provide adequate protection for the native species. This is especially true for non-migratory galaxiids that are at risk of extinction without control or eradication of brown trout in select places.
2. Because trout are unable to climb while several of our native species are moderate to strong climbers, this can be exploited by using grates and overhangs that inhibit jumping but allow

climbers to pass upstream through the barrier. However this is not essential for our non-migratory galaxiids as they recruit from upstream of barriers and are not strong climbers.

3. The design of the barrier is directed by the objectives of the barrier e.g. whether the barrier is for full exclusion, limitation of numbers, allowance for migratory native fish, to prevent upstream movement or to prevent downstream movement. There is no one design that fits all.
4. Barriers are typically needed to prevent upstream movement, as the species of concern are established in lower reaches (they have a diadromous lifecycle) and for many at risk species, headwaters are the only remaining strongholds. However, where invasive species have been introduced into a lake environment, a barrier to prevent the invasive species establishing a downstream population may be desired.
5. The Otago Barrier Assessments indicate that many non-migratory galaxias species are able to maintain a self-sustaining population upstream of full exclusion barriers. For a few specific species there is also evidence of some migratory species successfully developing non-migratory lifecycles, which would allow them to maintain a self-sustaining population if they were to be isolated. If protecting diadromous native species from exotic species then partial barriers are important to ensure connectivity and access of young to protected upstream habitats.
6. Non-physical barriers cannot be relied upon as full exclusion barriers against species such as trout and salmon. They are more effective when a combination of barrier mechanisms is used.
7. Physical barriers have been demonstrated to be effective full exclusion barriers, particularly when the following design elements are incorporated:
    a. A downstream apron (>2 m length) creates a zone of high velocity and low water depth under the barrier that inhibits jumping
    b. Drops ≥1.5 m are effective exclusion barriers. Smaller drops (<2.5 m) should be used in combination with other barrier types, such as a shallow, high velocity chute and overhang grate.
    c. Scour protection is required downstream of the apron where the hydraulic jump will occur as the water is turbulent
    d. Wingwalls set into the sides of the bank to help avoid side scour
    e. Wingwalls are sloped up away from the weir crest to provide protection during higher flows
    f. Existing weir barriers use V-notch profiles to maintain a concentrated, high-velocity body of flow under low flow conditions or drop log structures so that upstream water levels can be better managed.
    g. The upstream backwater effects can be minimised by setting the barrier in a stream reach with moderate slope and having a low angle on the upper face of the barrier and adding substrate or other to establish shallow habitat (e.g. add large rocks or concrete pad)
    h. Cohesive soils (e.g. clays) and steep stream beds should be avoided due to high erodibility (i.e. place barrier in a stable section of streambed, with a moderate slope)

The importance of different design criteria is varies depending on species being excluded and environment.

8. The length upstream that backwater effects extend from a barrier can be estimated from: Backwater length (km) = 0.7 * water depth at barrier (m) / gradient (m/km)
9. Gabions installed to date have not been found to consistently form a full exclusion barrier as they have degraded and changed shape over time. However, as the ones installed to date have been designed as permeable barriers, it is likely that trying to create a gabion with adequate interstitial spaces also leaves it vulnerable to consolidation of the cobbles and reshaping over time. Gabions are by their nature more vulnerable to defects in installation. It is considered that future gabions, if designed more compactly and installed correctly, could provide more robust long term exclusion barriers that evidenced to date. It should also be noted that the installed gabions barriers to date have been successful at limiting the number of fish entering the upstream area and have been effective as temporary fish limiting barriers.
10. Overhangs are likely effective at inhibiting jumping fish, while they still provide opportunity for allowing climbers over the barrier if grated. A solid plate can be used where both jumping fish and climbers such as köaro are to be excluded, as the köaro cannot climb the overhang. Existing barriers have used ≥500 mm overhangs to inhibit jumping.
11. Existing barriers (in the US) have used 1:100 year flood flows as the maximum design flow for full exclusion. The key design considerations associated with the design flow are the hydraulic profile over the weir crest under varying flows, anchoring of weir structure to prevent overturning, sliding, scour during high flows and protection of abutments.

10 Future Research

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Further research would be beneficial in a number of aspects of barrier design, including:

1. Laboratory trials of key design parameters, including:
    a. The concluded minimum 1.5 m vertical drop versus invasive species jumping abilities
    b. Flow velocities versus invasive species jumping abilities
    c. Effects of weir geometry on backwater profile
    d. Effects of screen size of intake structures on backwater profile
2. Extension of natural barrier assessments to other areas in New Zealand (e.g. Canterbury, where there are rare non-migratory galaxiid locations). The assessment results would be recorded in a similar form to the Otago Barriers Assessment spreadsheet.

11 Your Role in Enhancing the Waterway Barriers Design Database

The Waterway Barrier Design files are intended to be live documents and it is essential that the information in the database is updated as more barriers are established and more monitoring information on existing barriers is gathered. **Please contact Sjaan Bowie** and **Dave West** at the Department of Conservation (details below) with any information you have gathered about the design and performance of waterway barriers. This information will help continue to build the database of information on the effective design of waterway barriers for protection of New Zealand's aquatic values.

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Appendix A Waterway Barrier Design Companion Files

Waterway Barriers Database

This database collates information known to date about the design and effectiveness of natural and built waterway barriers that prevent or inhibit fish movement. The summary below describes the contents of each table.

This database is intended to be a live document - the user can add details to the existing entries or create new entries within Table A.

Sheet A - Barriers Master

This table records the known details of waterway barriers, for both natural and built barriers. It allows the user to filter by column search, compare and analyse the known information about barrier design and effectiveness.

Note that this Master Table includes the details of the Non-Physical Barriers (Table B). However, it does not include the Otago natural barrier details, except where there is a separate report (i.e. in addition to a Barrier Assessment file) about that barrier (e.g. Akatore Creek waterfall).

Barrier Name	Barrier name and lead organisation involved with barrier assessment and implementation
Barrier Location	Regional Council and country, mapping references, elevation
Barrier Type	Divided into natural, physical (built) and non-physical (built), includes a brief summary of the key barrier features
Objectives	The primary objectives for having the barrier in place, including whether its is to be a full exclusion barrier or not and if it is permanent or temporary only.
Design Criteria	The set criteria that the design needs to achieve (often associated with allowable flows, flooding prevention, creation of particular flow regimes (e.g. shallow, fast flow (supercritical flow))
Design Features	The design features that are included to address the design criteria and barrier objectives. Typically these are physical features such as downstream aprons, overhangs, and wingwalls.
Barrier Dimensions	All known physical dimensions of the barrier: height, width, length, gabion material diameter, grate spacing, screen aperture etc.
Species to be Protected	The particular (native) fish species that are to be protected by the barrier
Species of Concern	The species that are threatening the native fish populations or their habitat. Note that koaro can be considered a species of concern as they can dominate that habitat of other galaxias species, and there are examples where barriers have been installed to prevent their estblaishment in habitat of more vulnerable galaxias.

Catchment Details	The hydrological characteristics of the stream where the barrier is located. This includes contributing catchment area, stream width, gradient and water depth under seasonal flow conditions.
Construction Details	The most up-to-date status of the barrier (e.g. design, consenting, under construction, in place) and the date of that information. Also records construction date and cost where known.
Barrier Effectiveness	Measure of how effective the barrier has been at meeting its objectives. Where possible a percentage is given to indicate the percentage of fish prevented from negotiating the barrier. Also, the reasons why the barrier has or has not met its objectives.
Maintenance and Monitoring	Indicates the barrier's maintenance requirements and the monitoring programme in place (including direct performance monitoring of the barrier or monitoring of the upstream and downstream fish populations as an indicator of its effectiveness).
References	Links to literature about the barrier and contact organisations.

Sheet B - Non-physical Barriers

This small table summarises the known details of non-physical barriers in the US. While the details are also included within the Master Table (Table A), the available information on these barriers is light. Therefore they are also presented here in their own table for ease of reading, with a trunctated number of columns to reflect the limited details.

Sheet C - Natural Barrier Assessment

This table records the information captured in the Barrier Assessment worksheets produced by Department of Conservation.

By entering this data into a database, the data can be searched, filtered and analysed (see discussion of analysis in the Literature Review report).
See Tab "Natural Barriers Ranking' for details on the evaluation matrix used by DOC to assess the risk of each barrier not being effective at protecting upstream vulnerable species.

Summary of Barrier Information
A - Barriers Master

Barrier Name	Organisation	Region, Country (by Regional Council)	Projection	Northing	Easting	Elevation at Barrier (m asl)	Category	Waterfall	Weir	Screened	Culvert	Other	Material	Natural Barrier	Protection of upstream native fish	Protection of aquatic habitat	Prevention of movement of invasive species	Prevention of downstream movement	Prevention of upstream movement	Maintain diadromous movement	Deter fish from entering harmful environment	Exclude climbers	Permanent	Temporary/Trial	Shallow water zone
BARRIER NAME		BARRIER LOCATION					BARRIER TYPE							BARRIER OBJECTIVES											DESIGN
Akatore Creek Waterfall	DOC	Otago, NZ					Natural	X					Bedrock	X					X				X		
Cave Stream Waterfall, Maruia catchment	DOC	West Coast, NZ					Natural	X					Bedrock	X					X				X		
Shingle Creek Waterfall	DOC	West Coast, NZ					Natural	X					Unspecified (likely waterfall)	X					X				X		
Taieri River Barriers	University of Otago	Otago, NZ					Natural	X				X	Unspecified	X											
Akatore Creek Built Barrier	DOC	Otago, NZ	NZMG	5454914	2287836	78	Physical		X				Concrete and stop logs		X				X				X		
Maruia Gabion Barrier	DOC	West Coast, NZ					Physical			X			Gabion		X				X	X			X		
Orokonui Gabion Barrier	DOC	Otago, NZ				Near sea level	Physical			X			Gabion with PVC pipe running through gabion to convey main flow through barrier		X					X				X	
Upper Waipori Barrier	DOC	Otago, NZ					Physical		X				Modification to existing V-notch weir with metal grill		X				X			X	X		
Fraser Spring Permanent Barrier	DOC	Canterbury, NZ					Physical		X				Concrete and overhanging steel plate, bypass culvert		X				X				X		X
Fraser Spring Temporary Barrier	DOC	Canterbury, NZ					Physical			X			Pea straw bales wrapped in chicken wire		X				X					X	
Haldon Pastures Barrier	DOC	Canterbury, NZ					Physical		X				Concrete weir with anti-jump screen		X	X			X				X		X
Coach Stream Barrier	Environment Canterbury	Canterbury, NZ					Physical				X		Modification of concrete apron of existing culvert, and new fish deflector		X				X				X		X

Introduction | EndNote Library Keywords | A - Barriers Master | B - Non-physical Barriers | C - Natural Barrier Assessments | Natural Barriers Ranking

Summary of Barrier Information
B - Built Non-Physical Barriers

	BARRIER TYPE						LOCATION	BARRIER OBJECTIVES										SPECIES OF CONCERN									BARRIER EFFECTIVENESS				REFERENCES	
	Electric	Acoustic	Air Curtain	Chemical	Light	Barrier Details	Country	Protection of upstream native fish	Protection of aquatic habitat	Prevention of movement of invasive species	Prevention of downstream	Prevention of upstream movement	Maintain diadromous movement	Deter fish from entering harmful environment	Permanent	Temporary	Trial (Laboratory or field)	Salmonids	Carp - Grass	Carp - Silver	Carp - Asian	Carp - Species unidentified	Sea lamprey	Estuarine species unidentified	Species not occuring in NZ	Other/Unspecified	% reduction in movement	Unspecified	Unknown	Details	Base Reference	R
1	X					Electric pulsator was set to 276 volts and 2 Hz	US							X	X			X									100%				Johnson and Hoffman, 2000	Johnson ar
2	X					Unspecified	US			X					X							X			X			X		Carp observed to cross barrier when water depth at barrier increased from 0.5m to 2m.	Carpenter and Berrell, 2005	Verrill and E
3	X					2ms pulse width	US			X					X								X				100%				Carpenter and Berrell, 2005	Swink, 199
4	X					Unspecified, but monitored over long time period to include periods of power outages	US			X					X				X							X		X		Evidence of grass carp moving through working barrier; power outages allowed non-native fish to cross barrier.	Carpenter and Berrell, 2005	Clarkson, 2
5		X				20-600Hz sound barrier	US							X	X									X			60%				Noatch and Suski, 2012	Maes et al,
6		X				High frequency - 122-128 kHz	US							X	X											X	87%				Noatch and Suski, 2012	Ross and D
7		X				Infrasound - 16 Hz	US							X	X							X					80%				Noatch and Suski, 2012	Sonny et al
8		X				Infrasound	US							X	X											X	57%				Noatch and Suski, 2012	Sand et al,
9		X				Unspecified	US			X					X						X						95%				Noatch and Suski, 2012	Pegg and C
10			X			Air bubbles under 'adequate lighting'	US			X							X					X				X	70-95%				Noatch and Suski, 2012	Patrick et a
11			X			Bubble barrier	US			X							X									X	100%				Noatch and Suski, 2012	Stewart 198
12				X		Supplemental nitrogen and carbon dioxide gas in addition to hypoxia that occurs due to anthropogenic discharges into canal	US			X					X											X			X		Noatch and Suski, 2012	Suski et al,
13				X		100mg/L CO_2 concentration zone	US			X							X			X						X	100%				Kates et al, 2012	Kates et al,
14				X		Pheromones (necromones)	US			X							X									X			X		Noatch and Suski, 2012	Wagner et a
15					X	Unspecified	US							X	X			X										X			Noatch and Suski, 2012	Johnson et al 2008
16					X	Strobe	US							X	X											X		X			Noatch and Suski, 2012	Brown, 200
17					X	Strobe and mercury lights	US										X	X										X			Noatch and Suski, 2012	Nemeth an
18			X		X	Air bubble curtain plus acoustic field	US										X				X						95%				Noatch and Suski, 2012	Pegg and C

Introduction | EndNote Library Keywords | Natural Barriers Ranking | A - Master | **B - Non-physical Barriers** | C - Otago Natural Barrier

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Summary of Barrier Information

C - Inventory of Otago Natural Barrier Assessments

STREAM AND LOCATION DETAILS							BARRIER TYPE												
							Waterfall			Culvert				Weir/dam		Swamp	Dry Stream Bed		
Entry	Code	Stream	Date	Observers	Map Reference	Photo?	Type	Height (m)	Overhanging? If yes, dimensions (m)	Height (m)	Width/Diameter (m)	Overhang (m)	Type	Height (m)	Material	Length (m)	Length (m)	Is dry section perm?	Timing of dry periods
1	31419	Munro's Creek Tributary	24/07/2006	SM, DJ	H44	Y	Bedrock and boulders	2	N										
2	31551	Munro's Creek Tributary	25/07/2006	SM, DJ	H44	Y	Bedrock and boulders	1.2	N										
3	31551	Munro's Creek Tributary	25/07/2006	SM, DJ	H44	Y	Bedrock and boulders	0.9	0.45										
4	31567	Munro's Creek Tributary	24/07/2006	SM, DJ	H44	Y	Bedrock and boulders	4-5											
5	31734	Munro's Creek	24/07/2006	SM, DJ	H44	Y	Bedrock and boulders	6-8											
6	31968	Shag River un-named tributary	12/12/2005	SM	I42	Y	Bedrock	1.7											
7	31968	Shag River un-named tributary	12/12/2005	SM	I42	Y	Bedrock	3											
8	175740	Garden Bush Stream	12/09/2005	SM, MH	I43	Y								3	Unspecified				
9	175742	Deighton Creek	13/09/2005	SM, MH	I43	Y	Bedrock	6-8											
10	175745	Barbours Stream	01/04/2005	PR	H44	Y	Bedrock	1.5											
11	175808	Pigroot and Siberia Creeks	23/11/2005	SM, MH	I42	Y	Bedrock	1.5											
12	175879	Tributary of Dip Creek	01/12/2011	DJ, FG	CA14	Y				1			Velocity						
13	175974	Sow Burn	08/04/2005	RD	H42	Y	Boulder	2											
14	176021	Coal Creek	13/4/2005	SM, PR	G40	Y	Earth	0.6								400			
15	176035	Roadmans Creek	14/4/2005	SM, PR	F41	Y				0.75	1.2								
16	176046	Sheepskin Creek	04/07/2004	PR, AM	G40	Y											600	Y	
17	176061	White Burn	18/2/2004	PR, AM	E42	Y				0.75	1								
18	176061	White Burn	18/2/2004	PR, AM	E42	Y				0.75	2								

Entry	FISH SPECIES DOWNSTREAM OF BARRIER												
	Flathead galaxia	Dusky galaxias	Galaxias species 'D'	Canterbury galaxias	Eldon's galaxias	Brown Trout	Rainbow Trout	Brook Char	Perch	Upland Bully	Redfin Bully	Longfin eel	Koura
1		X											
2								X					
3								X					
4		X											
5													
6	X					X							
7	X					X							
8						X				X		X	
9	X					X							
10						X							
11	X					X							
12						X							
13						X							
14						X							
15						X							
16						X	X						
17							X						
18							X						

EndNote Library Keywords | Natural Barriers Ranking | A - Master | B - Non-physical Barriers | C - Otago Natural Barriers

EndNote Library

Author	Year	Title	Keywords	Reference Type
Adams, S. B.; Fris...	2001	Geography of invasion in mountain streams: Consequences ...	International	Journal Article
Allibone, R. M.	1999	Impoundment and introductions: Their impacts on native fis...	NZ	Journal Article
Allibone, R. M.	2000	Assessment techniques for water abstraction impacts on no...	NZ	Report
Allibone, R.M.	2000	Fish population and fish passage monitoring for Orokonui C...	NZ	Report
Amoser, Sonja; L...	2005	Are hearing sensitivities of freshwater fish adapted to the am...	Europe	Journal Article
Baker, C. F.	2003	Effect of fall height and notch shape on the passage of inan...	NZ	Journal Article
Barnes, G.	2004	Barriers to Fish Passage in the Hunua Ranges and Waharau R...	NZ	Report
Barrett, Jim	2001	Australia's national management strategy for carp control	Australia	Conference Proceedings
Barrier, R.; West, ...	1995	Fish passage over the Whangamarino weir	NZ	Report
Baxter, J. S.; Birch,...	2003	Assessment of a constructed fish migration barrier using rad...	Canada	Journal Article
Bay of Plenty Reg...	2013	Application for Dispensation from Freshwater Fisheries Regu...	NZ	Unpublished Work
Bejakovich, D	2005	Biological Criteria for Fish Screen Design in Canterbury	NZ	Web Page
Bleackley, N.	2008	Biology of common bully (Gobiomorphus contidianus) pop...	NZ	Thesis
Bloxham, M.	2010	Rotorua Lakes Koaro Restoration Project (Appendix 4)	NZ	Unpublished Work
Boubée, J.; Jowett...	1999	Fish passage at culverts: a review, with possible solutions for ...	NZ	Report
Boubée, J.; Willia...	2000	Fish passage Review and Guidelines for the Auckland Region	NZ	Report

Within the EndNote Library, the 'Keywords' field for each reference has been populated with a selection from the following keywords list, describing the focus and content of that particular reference document. Note that in the main page view (as shown in screen shot above), only the first keyword shows, however, opening a particular reference will show all the keywords that have been entered for that reference.

Use the following list to assist with choosing keywords to search with, or as a guide to setting consistent keywords when adding in further references to the library in the future.

Location	Study Type	Study Subtype	Barrier type	Barrier subtype	Fish species	Other
NZ	Laboratory	Performance evaluation	Natural barrier	Waterfall	Galaxias	Downstream movement
Australia	Pilot-scale	Design	Built barrier	Weir	Kōaro	Upstream movement
US	Constructed	Application	Physical barrier	Acoustic	Trout	Invasion
Canada	Thesis	Fish response	Non-physical barrier	Air bubble	Salmonids	Lake
Europe	Guidelines			Electric	Carp	Non-migratory
International				Water abstraction	Rudd	Migratory
				Gabion	Native species	Population distribution
				Screens		

Photo and Drawings Library

Hyperlinks have been set up in the Database to link the user to the relevant photo in the Photo Library. The photo opens up in a new window. The library folder also contains construction and design drawings for reference.

Name	Date modified	Type	Size
31419 Munro Creek.jpg	7/26/2013 12:43 PM	JPEG image	811 KB
31551 Munro Creek Trib 1.jpg	9/11/2013 5:57 PM	JPEG image	890 KB
31551 Munro Creek Trib 2.jpg	9/11/2013 5:58 PM	JPEG image	669 KB
31567 Munro Creek Trib.jpg	9/11/2013 5:58 PM	JPEG image	577 KB
Akatore Creek Waterfall - depression in w...	7/26/2013 2:29 PM	JPEG image	406 KB
Akatore Creek Waterfall.jpg	7/26/2013 2:28 PM	JPEG image	397 KB
Maruia Gabion Barrier.jpg	7/26/2013 2:28 PM	JPEG image	111 KB
Orokonui Gabion Barrier.jpg	7/26/2013 2:29 PM	JPEG image	63 KB

Summary of Barrier Information

C - Inventory of Otago Natural Barrier Assessments

STREAM AND LOCATION DETAILS							BARRIER TYPE				
							Waterfall			Culv	
Entry	Code	Stream	Date	Observers	Map Reference	Photo?	Type	Height (m)	Overhanging? If yes, dimensions (m)	Height (m)	Width/Diameter (m)
1	31419	Munro's Creek Tributary	24/07/2006	SM, DJ	H44	Y	Bedrock and boulders	2	N		
2	31551	Munro's Creek Tributary	25/07/2006	SM, DJ	H44	Y					
3	31551	Munro's Creek Tributary	25/07/2006	SM, DJ	H44	Y					
4	31567	Munro's Creek Tributary	24/07/2006	SM, DJ	H44	Y	boulders	[illegible]			

file:///E:\Files for DOC Comment\Photos\31419 Munro Creek.jpg - Click once to follow. Click and hold to select this cell.

Design Review Checklist

Waterway Barriers - Design Review

BASIS OF DESIGN

Define the objectives of the barrier:

- [ ] Full exclusion
- [ ] Reduction in numbers of fish
- [ ] Reduction in size/maturity of fish able to pass barrier
- [ ] Other: specify ___________________

Define the species of concern:	Strong swimmers	Strong jumpers	Climbers	Sound sensitive
[ ] Trout	X	X		
[ ] Salmonids	X	X		
[ ] Carp				X
[ ] Koaro			X	
[ ] Other: specify ___________________				

Define the species to be protected:

- [ ] Non-migratory galaxias
- [ ] Migratory galaxias
- [ ] Non-migratory other natives
- [ ] Migratory other natives

--> Go to Design Considerations on next tab

Basis of Design | Design Considerations

Waterway Barriers - Design Review

DESIGN CONSIDERATIONS

This spreadsheet provides a checklist of factors that should be considered in the design of a physical built waterway barrier.
Also included is a checklist of hydrological field data, which, if it can be obtained, will help focus the design decisions and reduce the risk of the barrier not performing as expected.

Waterway Hydrology

	Define the design flood that the barrier is required to pass without being compromised	*Need to ensure barrier will not be compromised at higher flows, through undermining of barrier, overturning, scour and washout of the abutments*
	Define expected flood characteristics at this design flood: stream flow, stage height, flow paths in vicinity of barrier, level of debris	
	Is barrier location in hydrologically stable reach?	*Minimises the effects of the barrier on the sediment transportation within the stream, i.e. a hydrologically stable reach will not alter its profile, aggrade or degrade over time*
	What is the expected profile of the upstream backwater, i.e. how much ponding is expected upstream of barrier and what area will this cover?	*This can be positive in terms of providing addiitonal upstream pool habitats, or can be negative due to desired riffle habitat being drowned out, stagnation of water (reduced DO levels), raising of localised groundwater table (in neighbouring land) and flooding of dry land.* *Consider if barrier is at outlet of lake, then will raising effect of water level create an alternative outlet at another low point along the lake edge?*
	Is there possibility of the barrier being drowned out due to downstream obstruction or flooding?	*Consider the barrier's proximity to other obstruction features*
	What is the expected reduction in water flow downstream of barrier?	*May cause degradation of habitat during low flow periods*
	Define the cross-sectional profile of the stream at barrier site	*How does the waterway behave at different flow levels? What physical features need to accounted for in the design of the barrier abutments and base?*
	What is the expected sediment load in the stream?	*Settling out of sediment in upstream pool created by barrier will need to be managed in the long term. Also, consider whether silt or coarser sediments filling in gaps in barrier surfaces could creating issues (e.g. increased splash zone allowing climbers more access, smoother surfaces (changing surface texture))*
	How will expected hydrological changes affect the wider community balance, including macrophytes?	*Invasion of macrophytes, for example, could be detrimental to the species to be protected*
	Include in the design criteria any expected future change in hydrological regime	*Designing for the future. Historical data provides a baseline but expected future changes must also be incorporated into the design criteria.*

Species to be Protected

	Do they need to be able to climb past barrier as part of their migratory lifecycle?	*These factors contribute to design choices for overhang details and upstream face slope (affecting upstream pooling and riffle habitat)*
	Availability of habitat that species require	
	Interchange/connectivity needed to maintain healthy population	*Consider whether isolation of species may contriubte to inbreeding effects or decline in numbers*

Basis of Design | Design Considerations

Appendix B Fish Risk Assessment Model

The Fish Risk Assessment Model was developed by Wilding and Rowe (2008) to provide a measure of the potential ecological risk of introducing a new species to New Zealand. It is divided into two parts – risk of establishment and risk of causing ecological impact. The risk scores for each part are developed from a series of questions with weighted values for each yes/no/unsure response.

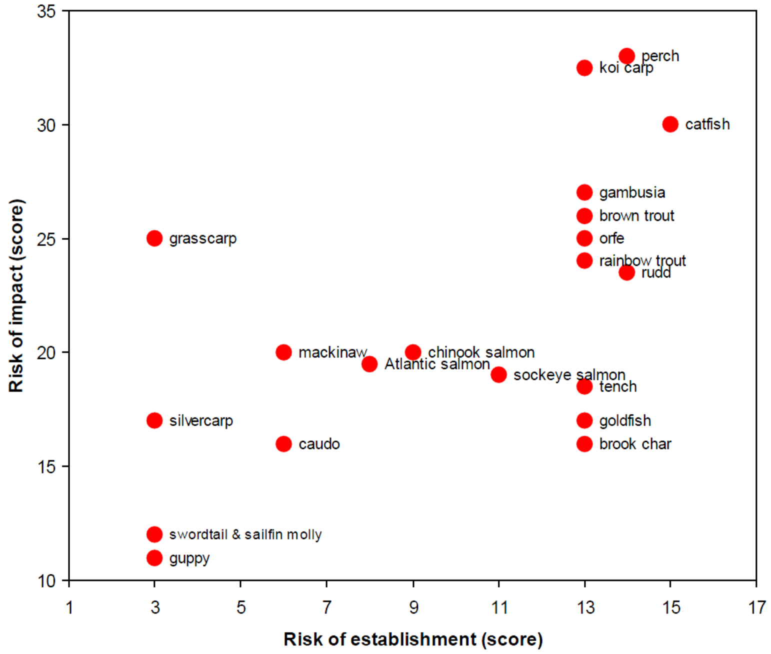

Figure B 1: Relationship between the risk of establishment and the risk of causing an ecological impact for alien freshwater fish species in New Zealand

Appendix C Evaluation Matrix for Barrier Risk Factors

Sourced from Department of Conservation Barrier Assessments

Note, highest value indicates highest risk of barrier being ineffective at protecting upstream species

Barrier Risk Factor		Assigned Risk Value							
		0	1	2	3	4	5	6	7
Fish factors	Threatened species upstream [1]	Not threatened	Sparse	Range restricted	Gradual decline	Serious decline	Nationally vulnerable	Nationally endangered	Nationally critical
	Length of habitat / size of fish population upstream	NA	10 km / ≥50,000	5-10 km / 10,000-50,000	2-5 km / 1,000-10,000	500 m - 2 km / 500-1,000	500 m / ≤500	NA	NA
	Invasive species downstream	NA	Others	Köaro	NA	NA	Perch, salmonids	NA	NA
	Spawning habitat upstream	No, or spawning habitat not required (e.g. eels)	NA	NA	Yes, rare	NA	Yes, plenty	NA	NA
	Coexistence downstream	Upstream fish abundant downstream	NA	Upstream fish occasional to common downstream	NA	Upstream fish rarely occur downstream, no indication of spawning success	No coexistence	NA	NA
Barrier factors	Distance to next barrier	Next barrier <50m upstream	Next barrier <10% of stream length upstream	Next barrier <25% of stream length upstream	Next barrier <50% of stream length upstream	Next barrier >50% of stream length upstream	No other barrier	NA	NA
	Barrier construction	Bedrock waterfall >3 m high, large dam or weir	Small dam or weir, small culvert	Bedrock waterfall 1-3 m high, dry stream section	Boulder waterfall >3 m high, bedrock waterfall <1m high	Boulder waterfall 1-3 m high	Boulder waterfall <1m high, swampy stream section	NA	NA

1 If more than one non-migratory galaxiid is present in the stream, each species should be scored and a cumulative total used to give the assigned risk value
2 If more than one species is present downstream of a barrier, use only the highest scoring species as the assigned risk value