Auckland Regional Council
TE RAUHITANGA TAIAO

Fish Passage in the Auckland Region – a synthesis of current research

June TR 2009/084

Auckland Regional Council
Technical Report No.084 June 2009
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-877528-96-5

Note: This report is a companion document to TP 131 – Fish Passage Guidelines for the Auckland Region, incorporating the latest research on fish passage requirements.

This document is available on the ARC website at the following location:

http://www.arc.govt.nz/plans/technical-publications/technical-reports/technical-reports-2009/technical-reports-2009_home.cfm

Reviewed by:

Name: Chris Hatton

Position: Principal Advisor Environmental Policy

Organisation: Auckland Regional Council

Date: 19 June 2009

Approved for ARC Publication by:

Name: Grant Barnes

Position: Group Manager – Monitoring and Research

Organisation: Auckland Regional Council

Date: 19 June 2009

Recommended Citation:

Stevenson, C.; Baker, C. (2009). Fish Passage in the Auckland Region – a synthesis of current research. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Report 2009/084.

Fish Passage in the Auckland Region – a synthesis of current research

Catriona Stevenson
Cindy Baker

Prepared for
Auckland Regional Council
Environmental Research

NIWA Client Report: HAM2009-059
May 2009

NIWA Project: ARC08227

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

Contents

Reviewed by:

Jacques Boubée

Approved for release by:

David Rowe

Formatting checked

A. Bartley

1 Executive Summary

Of the 35 indigenous freshwater species currently recognised in New Zealand, 18 are diadromous and undergo migrations between fresh and saltwater as part of their life cycle. Apart from the degradation of adult habitats, one of the most significant causes of the decline in freshwater fish populations in New Zealand is the construction of structures such as dams and culverts that prevent fish from accessing otherwise suitable habitats.

The distribution of freshwater fish in the Auckland Region was analysed using data recorded in the New Zealand Freshwater Fish Database. In total, 21 indigenous and 14 introduced fish species have been recorded in the Auckland Region. The majority of the indigenous species (14 species) are diadromous and fish migration barriers are therefore expected to have a major influence on their distribution in the Auckland Region. Potential migration barriers like waterfalls, rapids, chutes and debris jams are natural; however, the majority of in-stream obstructions are man-made. These include badly positioned or undersized culverts, fords, dams and diversion structures, weirs (including flow measuring weirs), diversion channels, bed erosion control devices and stream bed modifications.

This report provides guidance for the construction and retrofitting of in-stream structures to allow the upstream passage of fish. Although primarily aimed at road crossing culverts, solutions for the numerous low head weirs and artificial channels present in the Auckland Region are also discussed.

As each potential barrier is different, and the species to be catered for are not always the same, passage solutions will tend to vary from site to site. For culverts, four options are proposed. Firstly, the no-slope (stream slope) design option allows passage of all species, but requires the installation of a conservative structure. Secondly, the stream simulation design option recreates the natural channel within the culvert barrel and allows the passage of species present at the site. Thirdly, the hydraulic option is designed to meet the velocity and depth requirements of a target fish species. Finally, the climber design option makes use of the climbing ability of many indigenous freshwater species (e.g., elvers and koaro) to use the wetted margin to progress upstream. In terms of design, the climber design option is the least restrictive but is only useful in high gradient streams where fish diversity is already limited. With all four options, bed control devices designed to minimise the risk of erosion are essential, and potential solutions for this are therefore also discussed.

For barriers other than culverts, only general principles are described and potential solutions may need to be modified to suit the landscape features, the type of structure proposed or installed, as well as the habitat, and fish species present. Options for low head structures include natural and rock-cascade fishways. In all cases, it is recommended that only proven designs be used or that expert advice be sought. Inevitably, even with standard designs, adjustments and repairs will be required and a monitoring and maintenance schedule should always be adopted.

As additional information is gathered, concepts and guidelines developed in this report will need to be reviewed. Users are therefore encouraged to submit comments for incorporation into future reviews and updates.

2 Introduction

New Zealand possesses a relatively sparse fish fauna, with only 35 or so indigenous species, at least another 20 introduced, and half a dozen marine wanderers that periodically enter estuaries and lowland rivers. Of indigenous freshwater species, 18 are diadromous and undergo migrations between fresh and saltwater as part of their life cycle.

Apart from degradation of the adult habitats, one of the most significant causes of the decline in freshwater fish populations in New Zealand is the construction of structures such as dams and culverts that prevent fish from accessing otherwise suitable habitat.

This report was commissioned by the Auckland Regional Council to provide users with guidelines for the construction and operation of in-stream structures. It provides an update to an earlier fish passage guideline for the Auckland region (Boubée et al. 2000). As each potential barrier is different, solutions will also vary. Consequently, only general principles are described here and these will need to be modified to suit the landscape features, the type of structure proposed or installed, as well as the habitat and fish species present. In most cases it is recommended that only proven designs be used or that expert advice be sought. Inevitably, even with standard designs, adjustments and repairs will be required and a monitoring and maintenance schedule should always be adopted.

3 Distribution of freshwater fish in the Auckland region

The distribution of freshwater fish in the Auckland region was assessed by Boubée et al. (2000) using data from the New Zealand Freshwater Fish Database (NZFFD). In 1999, 608 records had been collected, which indicated that 15 indigenous fish species and eight introduced fish species were present. In the past decade, the number of NZFFD records for the Auckland region has quadrupled, with 2486 records present by August 2008 (Figure 1). Of these, 120 sites contained no fish. Currently, 21 indigenous and 14 introduced fish species have been recorded from the Auckland Region (Table 1). Banded kokopu were the most abundant species followed by shortfin and longfin eels. Common bully, inanga and redfin bully were all frequently recorded, occurring at over 10% of all sites sampled. The mosquito fish was the most common introduced species occurring at close to 10% of all sampling sites. All other introduced species were found at less than 2% of the sampling sites.

Since 1999, six additional indigenous fish species have been entered as present in the Auckland region; these are the estuarine triplefin, flounder, black mudfish, bluegill bully, shortjaw kokopu and lamprey. In addition, six introduced fish species have been recorded for the first time (grass carp, silver carp, catfish, the Australian longfin eel, golden orfe and the dart goby). However, their frequency of occurrence is low. Although the number of exotic fish species has increased since 1999, the frequency of occurrence of species recorded prior to 1999 has changed very little. This report does not address the passage requirements of exotic fish species and is confined to native freshwater fish. More information on fish species and their distribution is available on the NZFFD website at http://www.niwa.cri.nz/services/free/nzffd .

Figure 1.

Location of sites within the Auckland region where freshwater fish information was available on the New Zealand Freshwater Fish Database in August 2008.

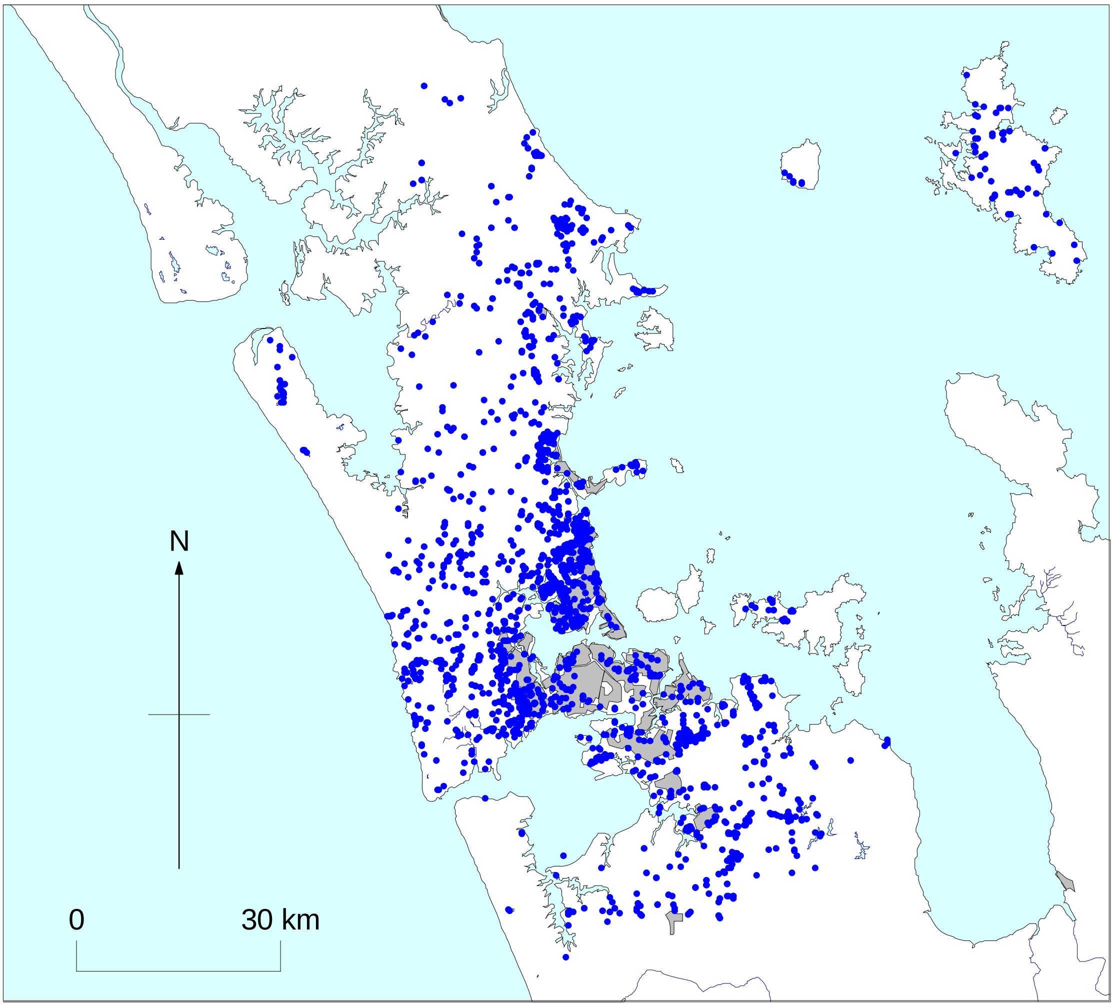


Table 1.

Freshwater fish species recorded on the New Zealand Freshwater Fish Database for the Auckland Region. The total number of sites dating from 1980 to the present that contained fish was 2486. * represents diadromous species. † denotes marine wanderers.

Common name	Scientific name	Frequency of occurrence (%)
INDIGENOUS		
Banded kokopu*	Galaxias fasciatus	38.54
Shortfin eel*	Anguilla australis	37.29
Longfin eel*	Anguilla dieffenbachii	32.50
Common bully*	Gobiomorphus cotidianus	20.47
Inanga*	Galaxias maculatus	16.77
Redfin bully*	Gobiomorphus huttoni	12.63
Cran's bully	Gobiomorphus basalis	9.98
Giant bully*	Gobiomorphus gobioides	3.06
Common smelt*	Retropinna retropinna	2.49
Torrentfish*	Cheimarrichthys fosteri	1.97
Yelloweyed mullet†	Aldrichetta forsteri	1.73
Koaro*	Galaxias brevipinnis	1.29
Giant kokopu*	Galaxias argenteus	0.96
Estuarine triplefin†	Grahamina sp.	0.56
Dwarf inanga*	Galaxias gracilis	0.32
Grey mullet†	Mugil cephalus	0.32
Black mudfish	Neochanna diversus	0.32
Bluegill bully*	Gobiomorphus hubbsi	0.20
Shortjaw kokopu*	Galaxias postvectis	0.08
Lamprey*	Geotria australis	0.04
Flounders†	Rhombosolea sp.	0.04
INTRODUCED		
Mosquito fish	Gambusia affinis	9.45
Goldfish	Carassius auratus	1.65
Grass carp	Ctenopharyngodon idella	1.49
Rudd	Scardinius erythrophthalmus	1.33
Perch	Perca fluviatilis	1.21
Tench	Tinca tinca	1.17
Koi carp	Cyprinus carpio	0.80
Rainbow trout	Oncorhynchus mykiss	0.68
Silver carp	Hypophthalmichthys molitrix	0.53
Catfish	Ameiurus nebulosus	0.36
Australian longfin eel*	Anguilla reinhardtii	0.24
Brown trout	Salmo trutta	0.16
Golden orfe	Leuciscus idus	0.04
Dart goby†	Parioglossus marginalis	0.04

4 Passage requirements of fish

4.1 Migration and habitat requirements

Most of the indigenous fish species that occur in New Zealand's waterways have a juvenile migrant stage, therefore their adult populations are dependent upon the success of the annual upstream migrations of juveniles. The migration times of some of the most important freshwater species found or expected in the Auckland Region are presented in Table 2.

4.2 Fish swimming ability

There are three dominant swimming modes that are accepted by most researchers: (1) sustained swimming, (2) prolonged swimming and (3) burst swimming (Beamish, 1978; Hammer, 1995). Sustained swimming is aerobic, can be maintained for an indefinite period and does not involve fatigue. In operational terms it is agreed that this swimming mode can be sustained for at least 200 min. The burst mode represents another extreme of short (15–30 secs), but high-speed anaerobic motion. The prolonged swimming mode occupies an intermediate range (from 30 secs to 200 min) between burst and sustained modes and involves both aerobic and anaerobic processes.

The ability of fish to migrate upstream is influenced by several factors including swimming ability, water temperature and behaviour (Boubée et al. 1999). Fish swimming ability increases with size (Behlke et al. 1991; Clay 1995) and because indigenous New Zealand fish species migrate upstream at a small size, they have an even lower swimming ability than larger sized species considered weak swimmers overseas (Table 3). Therefore, New Zealand species are not able to negotiate velocities as high, or distances as long, as most Northern Hemisphere species. A comparison of the swimming ability of New Zealand indigenous fish with overseas species is provided in Figure 2. In addition to swimming, several indigenous New Zealand fish species have the ability to climb moist surfaces (Table 4). These species can negotiate obstacles that appear to be insurmountable as long as a continuous wetted margin is provided.

Although knowledge of the swimming performance of fishes has been significantly advanced in the last 30 years, there are still many specific questions awaiting clarification. These questions relate to both environmental factors (e.g., water temperature, turbulence, sediment concentration, pollutants, light and food) and to physiological factors (e.g., scale, age, sex, oxygen debt and fatigue), which may have varying effects on performance dependent upon the mode of swimming and species.

Table 2.

Upstream and downstream migration times of some of the most important freshwater species found in the Auckland Region. ⇑, Upstream migration; ⇓, Downstream migration. L, Larvae; J, Juvenile or whitebait; A, Adult; S, Spawning adults; ?, indicates that further research is required.

Species	Life	Summer			Autumn			Winter			Spring		
	Stage	D	J	F	M	A	M	J	J	A	S	O	N
Eels (adult)	J	⇑	⇑	⇑	⇑								⇑
Anguilla australis and *A. dieffenbachii*	A	⇓	⇓	⇓	⇓	⇓	⇓						
Eels (glass eels) *A. australis* and *A. dieffenbachii*										⇑	⇑	⇑	
Grey mullet	J	⇑	⇑	⇑	⇓	⇓	⇓					⇑	⇑
Mugil cephalus	A	⇑	⇑	⇑	⇓	⇓	⇓					⇑	⇑
Trout	J	⇑			⇓	⇓	⇓					⇑	⇑
Salmo trutta and	A	⇑				⇓	⇓	⇓	⇓	⇓	⇓	⇑	⇑
Oncorhynchus mykiss	S					⇑	⇑	⇑	⇑	⇑	⇑		
Lamprey	J							⇓	⇓	⇓			
Geotria australis	A						⇑	⇑	⇑?	⇑?	⇑?		
Torrentfish	J	⇑	⇑	⇑									⇑
Cheimarrichthys fosteri	A	⇑				⇑	⇑	⇑	⇑	⇑	⇑		
	S	⇓				⇓	⇓	⇓					⇓
Smelt	L				⇓	⇓	⇓	⇓				⇓	⇓
Retropinna retropinna	J	⇑	⇑	⇑								⇑	⇑
(riverine stock)	A	⇑	⇑	⇑	⇓	⇓	⇓						⇑
Inanga	J	⇑	⇑							⇑	⇑	⇑	⇑
Galaxias maculatus	A	⇑	⇑							⇑	⇑	⇑	⇑
	S				⇓	⇓	⇓ ⇑	⇑	⇑				
Giant kokopu	L						⇓	⇓	⇓	⇓			
G. argenteus	J	⇑										⇑	⇑
	S						⇓⇑	⇓⇑	⇓⇑	⇓⇑			
Koaro	L						⇓	⇓	⇓				
G. brevipinnis	J									⇑	⇑	⇑	⇑
	S					⇓⇑?	⇓⇑?	⇓⇑?	⇓⇑?				
Banded kokopu	L						⇓	⇓	⇓				
G. fasciatus	J									⇑	⇑	⇑	⇑
	S					⇓⇑	⇓⇑	⇓⇑	⇓⇑				
Common bully	L				⇓	⇓	⇓	⇓		⇓	⇓	⇓	⇓
Gobiomorphus cotidianus	J	⇑	⇑	⇑								⇑	⇑
Redfin bully	L									⇓	⇓	⇓	⇓
G. huttoni	J	⇑	⇑	⇑?								⇑?	⇑
Shrimp	L			⇓	⇓						⇓	⇓	⇓
Paratya curvirostris	J		⇑	⇑	⇑	⇑			⇑				

Table 3.

Swimming speeds, migration rates and velocity preferences of indigenous New Zealand freshwater fish species, including a comparison with some North American data for weak and strong swimmers. Sustained speed = the velocity that can be maintained for long timeframes; Steady speed = the velocity that can be maintained for minutes; Burst speed = the velocity that can be maintained for seconds. LCF = length to caudal (tail) fork.

Species		Speed (m s^{-1})	Comments	Source
New Zealand				
Inanga (whitebait)				
	47-50 mm	0.2-0.21	Maximum sustained swimming speed under hypoxic (low oxygen) conditions, at thermal optimum of 13.9ºC	Bannon 2006
	47-50 mm	0.24 – 0.26	Maximum sustained swimming speed under normoxic (normal oxygen) conditions, at thermal optimum of 17.7 ºC	Bannon 2006
Inanga (post-whitebait)				
		0.01–0.03	Upstream migration gain in the Waikato River	Stancliff et al. 1988
	39-40 mm	0.22	Maximum sustained swimming speed under normoxic (normal oxygen) conditions, at thermal optimum of 9.4 ºC	Bannon 2006
Inanga (adult)				
	52-73 mm	0.19	Mean velocity for sustained swimming	Mitchell 1989
	52-73 mm	0.36	Mean velocity for steady swimming	Mitchell 1989
	52-73 mm	0.47	Mean velocity for burst swimming	Mitchell 1989
		<0.15	Water velocity which fish select and can easily negotiate	Mitchell and Boubée 1995
		≈0.07	Preferred velocities	Mitchell and Boubée 1995
		0.30–0.34	Maximum water velocities in which the fish will swim freely	Mitchell and Boubée 1995
	55-68 mm	0.22 – 0.27	Maximum sustained swimming speed under normoxic (normal oxygen) conditions, at thermal optimum of 18.3º C	Bannon 2006
Smelt	56-67 mm	0.19	Mean velocity for sustained swimming	Mitchell 1989
	56-67 mm	0.27	Mean velocity for steady swimming	Mitchell 1989
	56-67 mm	0.50	Mean velocity for burst swimming	Mitchell 1989
Common bullies (juvenile)		0.24	Sustained swimming	Mitchell 1989
	30-42 mm	0.6	Burst swimming	Mitchell 1989
Banded kokopu (whitebait)		0.05	Upstream migration gain in the Waikato River	Stancliff et al. 1988
Elver	55–80 mm	0.20–0.34	Sustained speed	Mitchell 1989
Grey mullet	85–96 mm LCF	0.12–0.20	Sustained speed	Mitchell 1989
Overseas				
Elvers	100 mm	0.0–0.15	Sustained speed	Bell 1986
Arctic grayling	50–100 mm	0.46–0.76	Steady speed	Bell 1986
Arctic grayling (adult)		0.81–2.1	Steady speed	Bell 1986
Grey mullet	13–69 mm	0.14–0.46	Burst speed	Bell 1986
Brown trout		0.76–2.14	Steady speed	
		2.14–3.97	Burst speed	Bell 1986

Figure 2.

Swimming speeds of New Zealand fish compared to swimming speeds calculated for North American fish species (redrawn from Boubée et al. 1999). Lengths of fish are detailed in the key below the figure. Two red lines show the swimming speeds of inanga, 48 mm and 92 mm in length respectively (Nikora et al. 2003).

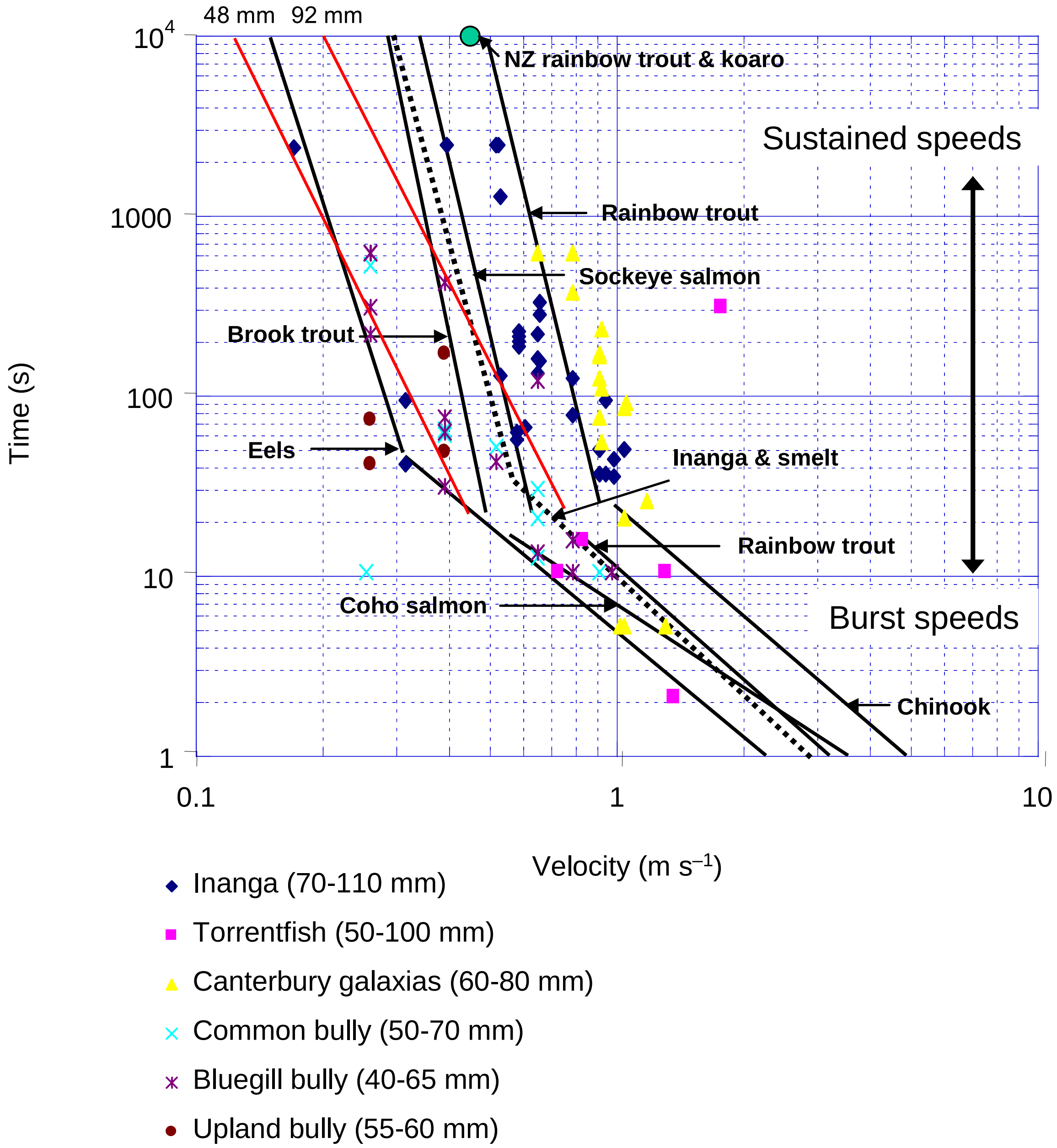


Table 4.

Locomotory classification of some New Zealand freshwater fish species (modified from Mitchell and Boubée 1989).

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

In situations where a range of fish are present in a catchment, the individual fish passage needs of all species, whether they progress by anguillid movement, climbing, jumping or swimming, should be considered. However, it can be useful to base passage requirements for a particular locomotory group upon a specific fish species - for example, basing a design for swimming species upon a 'typical' swimming species that migrates at a small size, such as the inanga. In this situation, by ensuring that the inanga can negotiate the in-stream structure, it is assumed that all other swimmers will also be able to pass the structure successfully.

4.3 What constitutes a barrier to fish passage?

4.3.1 Fall height

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

Energy requirements for fish negotiating impediments increase with fall height, and the ability of different fish species to surpass obstacles will depend upon their individual swimming and climbing abilities, as well as their life-stage. Baker (2003) examined the effect that the height of a weir may have upon two migrating indigenous fishes (the common bully and inanga) that migrate using the swimming mode. As height increased, the number of juvenile inanga passing the weir decreased significantly and none of these small fish passed the weir with a 10 cm fall height (Figure 3). With adult inanga, as the fall height increased from 5 – 20 cm, fewer fish were able to pass the weir, with no inanga able to pass at a fall height of 20 cm (Figure 4). For adult inanga, the size of the fish was significant in determining successful passage over the weir, with larger fish surmounting the weir with greater ease than smaller fish (Figure 4).

It is thought that the differences in fish passage ability between lifestages of inanga may be related to differences in muscle mass between juvenile fish (that had spent their lives in the sea and had relatively little muscle) and adults (who had been living in the river environment and had developed more musculature to cope with the flowing water they experience).

For common bullies, the number of bullies successfully passing the weir decreased significantly as height difference increased. Again, fish size significantly influenced successful passage over the weirs with larger fish surmounting the weirs with greater ease than smaller fish (Figure 5). No small common bullies passed the weir when the fall height was 10 cm or more. This indicates that differences in height of more than 7.5 cm between the structure water level and the water level of the downstream watercourse could restrict the passage of some sizes of common bullies.

Figure 3.

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

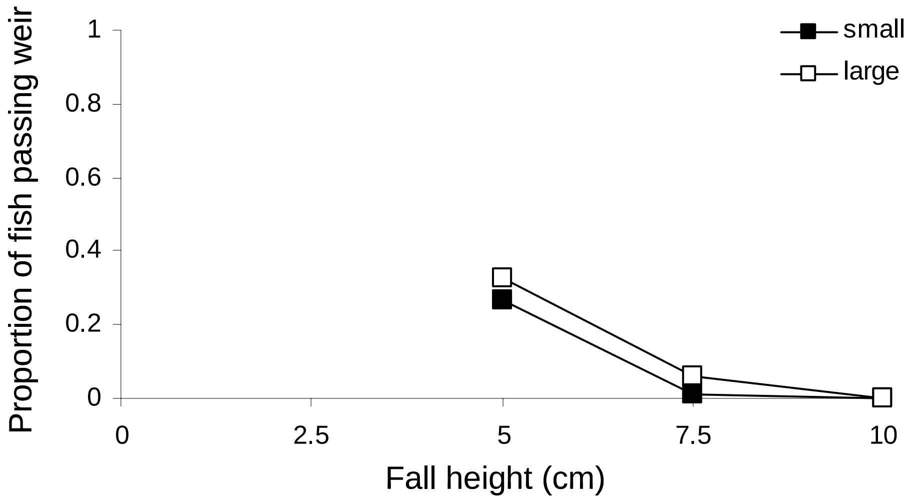


Figure 4.

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

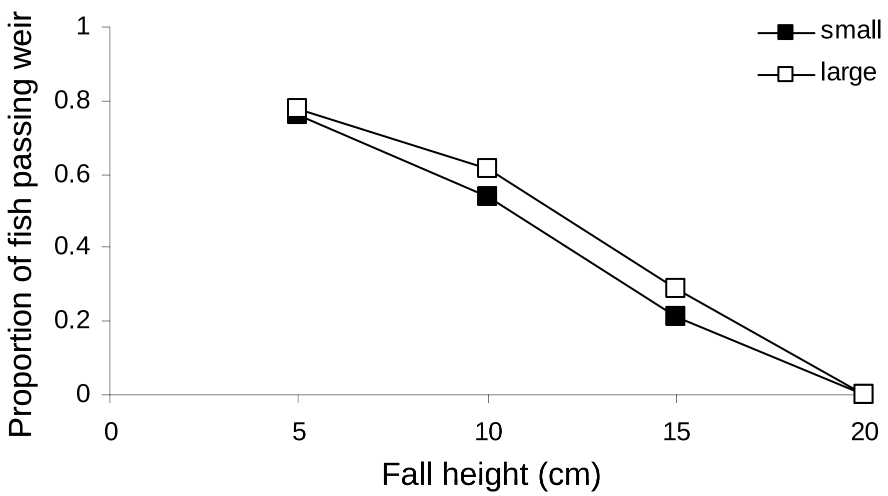
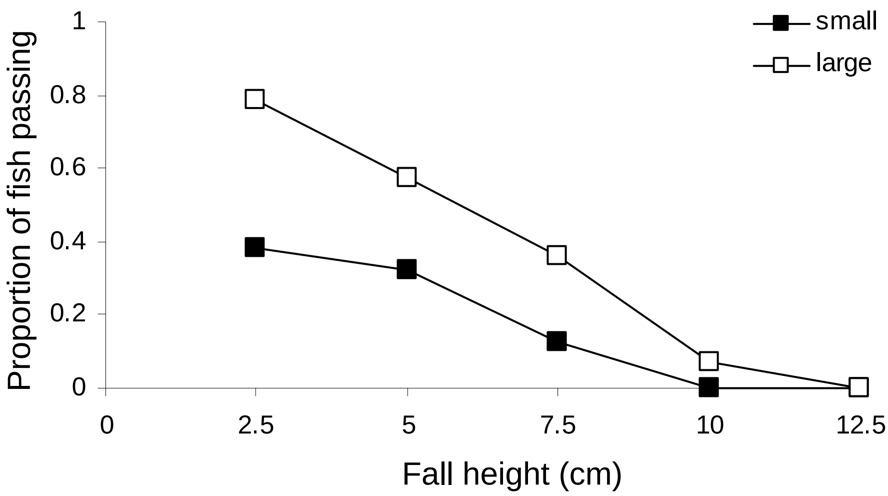


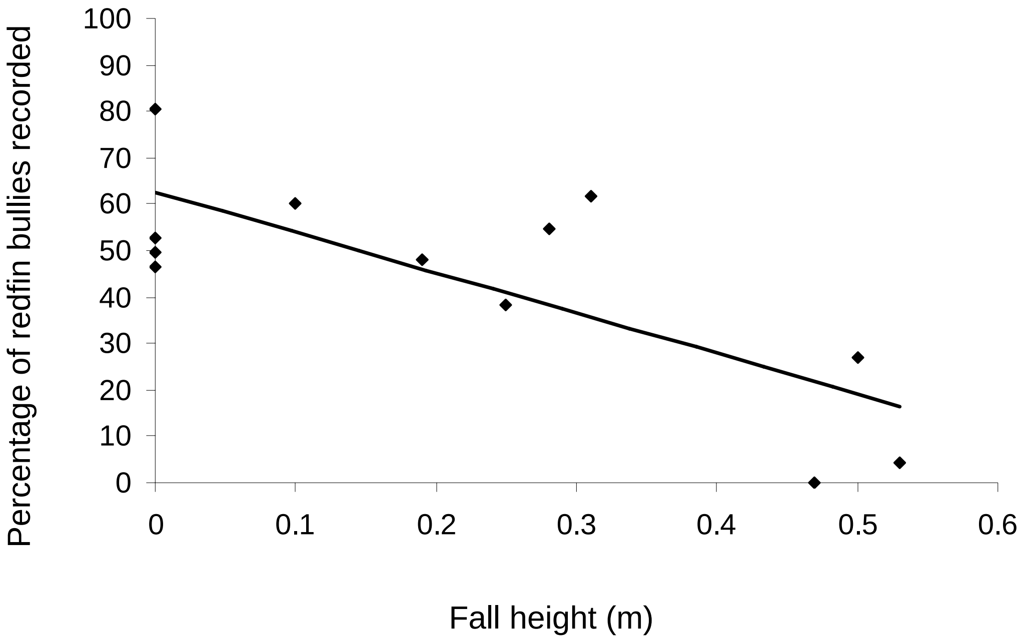
Figure 5.
Proportion of common bullies that passed a V-notch weir at different fall heights ('small' = average size of 40 mm; range 28-50mm. 'large' = average size of 57 mm; range 51-95 mm.) Reproduced from Baker (2003).



Field studies by Williams et al. (in prep.) have also indicated that fall height over in-stream obstacles such as culverts can affect the passage of indigenous freshwater fish species. In this study, the relative proportion of inanga, redfin bullies, torrentfish and smelt present above culverts and fords within the North Island was measured and related to the physical characteristics of the in-stream structures. For most species, the characteristics that had the greatest adverse effect on passage were barrel diameter or barrel water velocity. However, the study also found that the proportion of redfin bullies upstream of the structures was negatively associated with the height of the obstacle (Figure 6). Redfin bullies are considered to be capable of climbing obstacles and the results could indicate that as structures become higher, they become more difficult to negotiate, especially if wetted margins are lacking. At structures where there was no vertical drop, the relative proportion of redfins upstream varied over a range of values, indicating that there are other factors influencing the population at these sites. It is possible that the climbing medium of the structure combined with structure height may influence the upstream passage of the redfin population. The effect of the climbing surface is discussed in more detail in Section 7.1.3.

Figure 6.

Percentage of redfin bullies found upstream of twelve culverts and/or multi-barrelled fords in relation to the fall (measured from water level of structure to water level below structure). The regression equation is Y = -87.053x + 62.67 , R^2= 0.58. Redrawn from Williams et al. (in prep.).



4.3.2 Water velocity

Steepness, constricted flows and low bed roughness of in-stream structures may lead to water velocities that exceed the swimming capability of fish and so prevent upstream passage. In addition, uniform conditions of gradient, roughness and depth can lead to an absence of low velocity zones where fish can rest and recover after swimming to exhaustion.

As a guide, a zone 50-100 mm wide with a velocity of below 0.3 m/s should permit indigenous fishes to pass through a culvert using sustained swimming and fish may be able to pass at higher velocities as long as resting areas are available to allow recuperation after burst swimming. Resting areas must be of sufficient size to permit a wide range of species to use them (e.g., a resting area of 200 mm will accommodate the majority of adult indigenous (non-eel) species). Velocities greater than 1.0 m/s are likely to impede the upstream passage of indigenous fish, unless mitigation (e.g., installation of baffles, see Section 7.2) is undertaken.

4.3.2.1 Channel length

Channel length may also be a problem for fish if water velocity restricts the distance they can travel at any one time to less than the full channel length. Even if the fish can maintain a stationary position between periods of forward movement, the energetic requirements may mean that they become exhausted before they reach the end of the channel.

The addition of resting areas along the length of a channel can allow fish to recuperate after bursts of swimming. This may be undertaken using spoiler baffles, which provide resting areas at the downstream side of the baffle (Section 7.2). With appropriate positioning of baffles, resting areas may also be provided within the marginal areas of the culvert. The use of baffled substrates may also assist fish in negotiating some in-stream structures (Section 7.2.1).

4.3.3 Water depth

Insufficient water depth in channels and culverts often causes passage problems for the larger swimming species. Shallow, flat aprons at the outlets of culverts can reduce water depth and therefore become barriers during periods of low flows. In New Zealand, many upstream migrating fish species are small, can spend a considerable amount of time out of water and have good climbing ability. Therefore, shallow depth is not necessarily a problem for these fish and could even be exploited as a means of excluding the larger introduced species.

The addition of baffles to culverts increases the water depth within the culvert, as a volume of water equal to the size of the baffle is displaced. The inclusion of baffles is therefore one way of providing sufficient water depth for fish to progress through the culvert. Other advantages of baffles are discussed in Section 7.2.

4.3.4 Light

The effect of light, or the lack of it, on fish migration remains an area of debate both here in New Zealand and overseas. Darkness is not a barrier for elvers and there is evidence that banded kokopu can also migrate through long dark culverts. Information on other species is lacking, but observations indicate that many indigenous fish only require very low light levels in order to migrate.

5 When should fish passage be considered?

To determine the need to facilitate fish passage, it is essential that the following points are considered (see also Figure 7):

- Species present and distribution within the catchment.

The distribution of fish above and below a given impediment will indicate whether migrants pass through the impediment to access waters higher in the catchment. Knowing which species are present (and their swimming abilities and behaviours) enables potential passage problems to be identified, and the design to be adjusted accordingly. If the barrier has allowed a desirable native species to develop, its population could be compromised if passage for other species is eased. The need to contain a noxious species downstream may also have to be considered.

- The size and type of habitat available upstream.

If the habitat is not of the correct type, or extensive enough to support a population of a particular species, it may not be necessary to provide passage.

- The presence of other migration barriers both upstream and downstream of the structure.

This will also determine whether fish passage is an issue. It may be pointless to ensure passage at a structure if there are barriers just above or below which cannot be overcome. These barriers may be man-made (such as dams, culverts or weirs) or natural (like waterfalls and rapids).

- The timing of fish migrations, duration and their flow requirements.

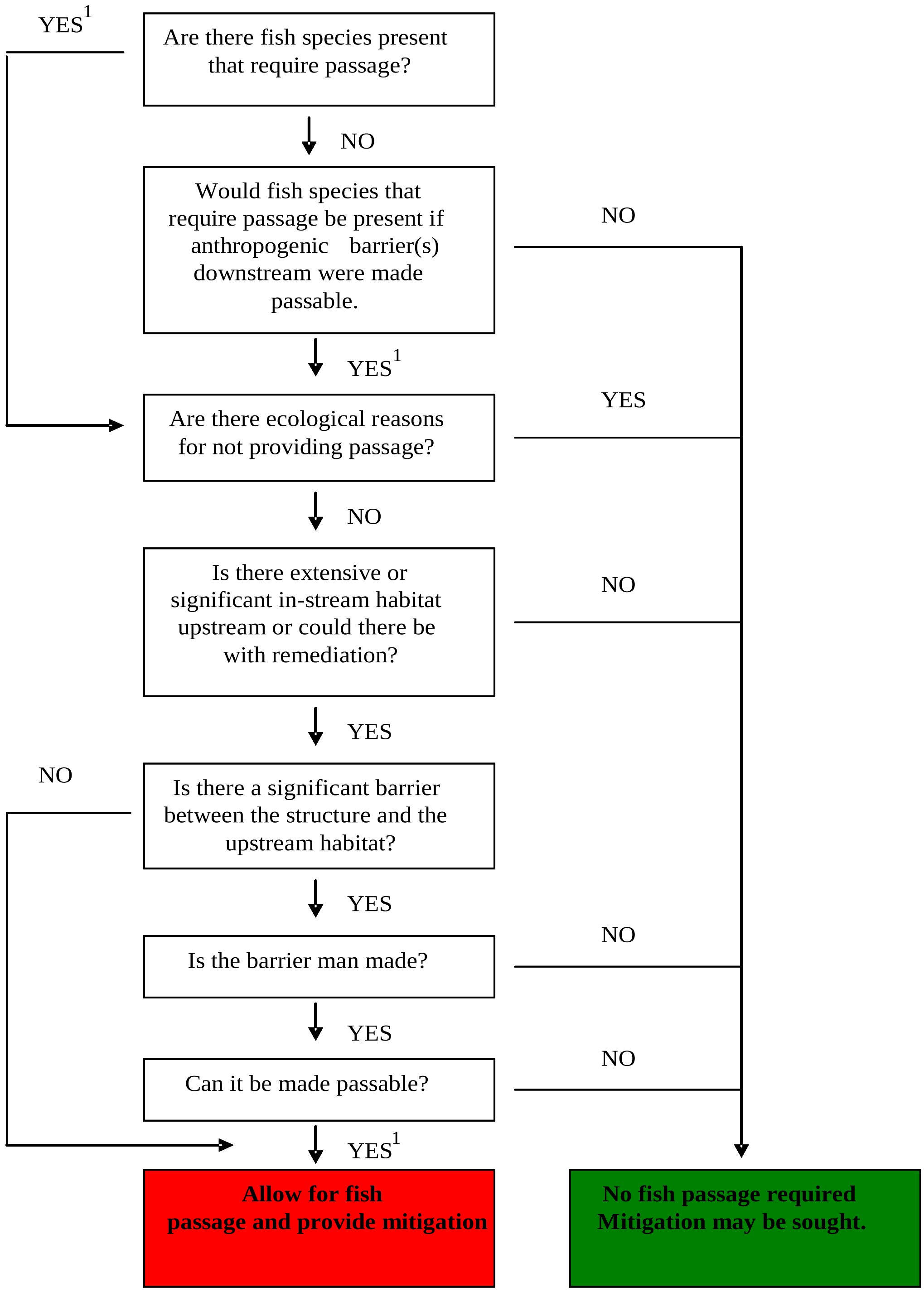
The timing of migrations can be used to set the flows at which the design will need to provide passage and help to schedule construction to minimise disruption to fish migration. The timing of migration may vary slightly between years and location. It is not expected that fish passage will be assured at all states of flow (e.g., during major floods) but, as a general rule, passage should be assured for 90% of the flows that occur between the main September to February migration period.

- Altitude and distance from the sea.

The few diadromous fish species which are found at high elevations (> 200 m) have good climbing abilities and can negotiate sections of river that are impassable to lowland species. Fish passage requirements at such sites need not be as stringent as at lower elevations. Determining which species, if any, are present and at what densities is therefore essential.

Figure 7.

Flow diagram to assist in assessing whether fish passage is required.



[1]Note: In the case of multi-barrier situations, a catch and truck system located at the lowest barrier can be used to transfer fish upstream of the uppermost barrier.

6 Existing problems

Several types of barriers are common within the Auckland Region (Evans and Glover 1999; Boubée et al. 1999). Some are natural features such as waterfalls, rapids, chutes and debris jams (Figures 8 and 9). In addition to these natural access problems, artificial barriers created by urban development have historically not provided for indigenous fish passage to and from the sea. The most common of these artificial barriers in the Auckland Region are badly positioned or undersized culverts. Other types of barriers include fords, dams and diversion structures, weirs (including flow-gauging weirs), channelisation and stormwater retention ponds (Figures 10-12). In many cases, water flowing over or through these structures was found to be too swift or too shallow for fish to pass through with ease, or drops too severe. Retrofitting options for such structures are given in Section 7.

Figure 8.
Waterfall on Okiritoto Stream. Most fish species, except for elvers and climbing galaxiids (i.e., koaro and banded kokopu), would find such natural structures impassable. Only climbing species, or species able to form landlocked populations, need to be considered above such natural structures.

Figure 9.
Turbulent chute that would prevent passage of most swimming fish.

6.1 Culverts

Many culverts are designed to minimise cost whilst optimizing flood/flow passage. Undersized culverts will have high barrel velocities during floods and this will cause scour at the culvert outlet, especially if no energy dissipation or erosion control is provided. This scouring will result in perched outlets that fish cannot surmount (Figures 10 and 11). Poor placement during construction also creates problems for fish passage from high water velocities and turbulent flows at culvert outlets, vertical drops at the end of outlet aprons, shallow water levels on culvert aprons and no wetted margins for climbing species (Figures 10-13).

Figure 10.
Perched culvert.

Figure 11.
Poor culvert design at installation and/or as a result of downstream bed degradation/erosion.

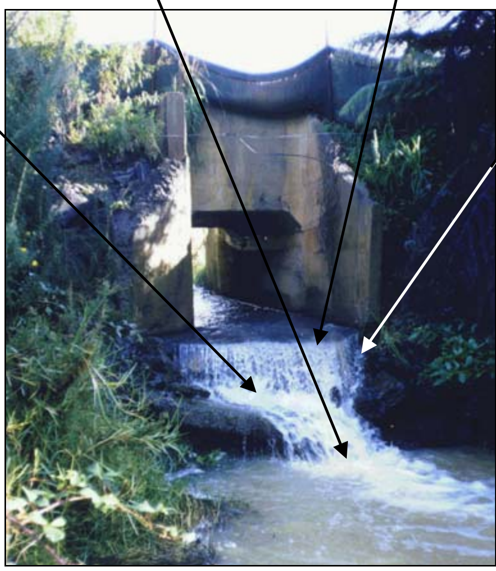


Figure 12.

Fast turbulent flows through a culvert barrel.

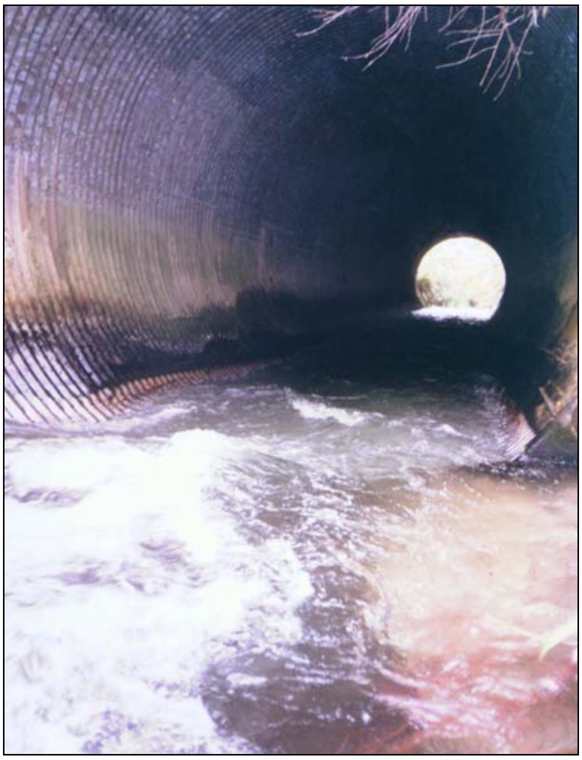
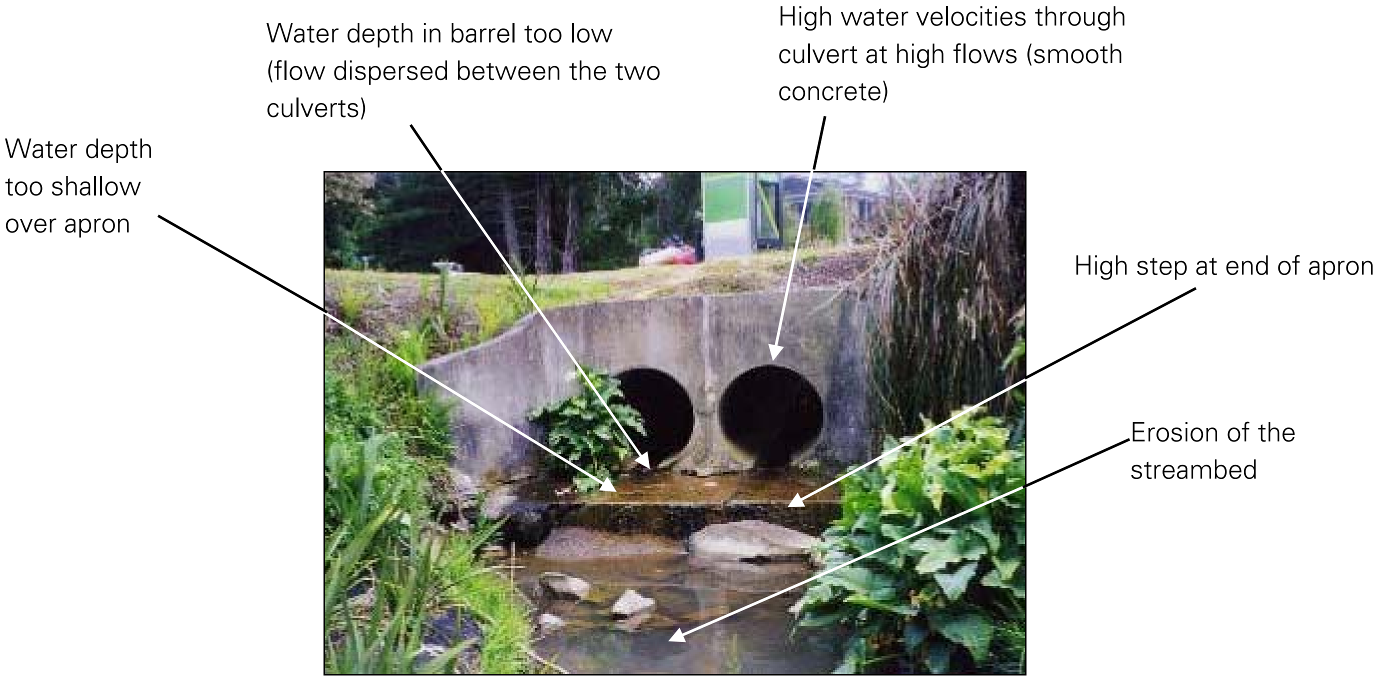


Figure 13.

Shallow water level on culvert apron during low flow periods.



6.2 Fords

Fords tend to have high barrel velocities which can restrict the passage of swimming fish species at low flows. Generally, passage for climbing species is possible at low flows but not at high flows unless the ford overtops and a climbing surface is available (Figure 14).

Figure 14.
Ford on Oratia Stream.

High water velocities

No climbing surface at high flows

6.3 Dams and diversion structures

Moderate and low head dams often limit passage to climbing fish species, however, some poor spillway designs can also prevent climbing fish passage (Figure 15).

Figure 15.
Dam crest and spillway.

Vertical drop and sharp angles

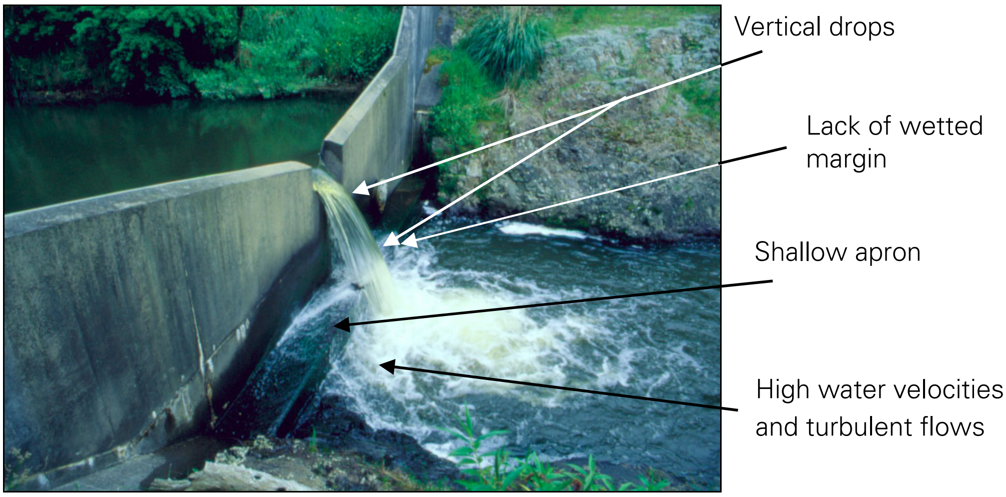
Poor position of minimum flow release (water should flow over crest of dam or over/through fishway)

6.4 Weirs

Low head dams or weirs are often used to create water features, to facilitate the abstraction of water or to measure flow. Most flow-gauging weirs have a narrow crest and sharp angles which result in high water velocities over the weir that fish cannot negotiate (Figures 16 and 17). Drops below the weir can be large, creating turbulent flows and many weirs do not maintain a wetted margin for climbing species (Figures 16 and 17).

Figure 16.
Flow-gauging weir located on the Mahurangi River.

Figure 17.
Flow-gauging weir on Mangawheau Stream.



6.5 Channelisation

Converting streams into channels is often undertaken in urban areas for flood and erosion control. Fish passage problems created by these channels include: high water velocities at medium and high flows; a lack of in-stream features where fish can rest, feed or take refuge; a lack of food (no suitable surface for aquatic invertebrates to develop and no access to land invertebrates from overhead vegetation); and a lack of shading that leads to increased water temperatures (Figure 18).

Figure 18.
Channelised section of Awaruku Stream.

6.6 Stormwater management ponds and wetlands

Stormwater management uses site design, construction, treatment and maintenance to prevent sediment and other contaminants from entering surface water, ground water and the coastal environment. Through this system, stormwater is managed in such a way that downstream flooding and erosion are reduced, watercourses are protected from the effects of pollutants/contaminants washed from impervious surfaces during rain events and the sedimentation of watercourses is controlled by allowing suspended solids to settle out in ponds/wetlands, with water mostly entering the natural stream network.

Stormwater management ponds have been used in the Auckland region for many years and are expected to remain important components of the stormwater effort to minimise the adverse impacts associated with urban land use. There are two types of stormwater management ponds currently in use within the ARC region: wet ponds and dry detention ponds. Wet ponds are the main type of pond used and consist of a permanent pond, with a standing pool of water through which water flows at a very slow rate. Wet ponds tend to be used for water quality purposes and can be 'on-line' in which the outflow enters the natural stream network or 'off-line' where the outflow enters the stormwater drainage system. Dry detention ponds are generally dry but intercept and detain stormwater during and immediately after a storm event, gradually releasing this water over time. Dry detention ponds function both in terms of improving water quality and the reduction of flooding and erosion downstream of the pond. Whilst the ARC has a preference against the use of wet 'on-line' ponds (that feed into the natural stream network), they may be the only option in situations where the catchment is already highly developed (ARC 2003). Constructed wetlands are also used to filter stormwater and are an important part of the stormwater management system.

Where suitable habitat exists upstream of wet 'on-line' ponds or constructed wetlands, fish may be unable to access the habitat if outflows, such as standpipes or weirs, restrict fish movement. Not all weirs will be a complete barrier. In Figure 19, for example, the weir may be submerged at high tides and during floods which would permit it to be negotiated by swimming species. However, any structure which restricts the passage of fish is not recommended.

Dry detention ponds do not provide suitable permanent habitat for fish, given their ephemeral nature, and therefore fish passage does not need to be considered in these situations.

Figure 19.
Outlet from constructed wetland at Longford Park Drive, Papakura.

7 Retrofitting options for fish passage barriers in the Auckland region

Structures and by-pass channels that are constructed to assist with the upstream and downstream migration of fish need to account for fish behaviour, fish swimming ability and engineering constraints. Methods of creating the appropriate hydraulic conditions for fish passage will differ between locations. Each site's suitability for fish passage should be assessed according to the characteristics of the site and the type of fish passage problem that exists (Section 4.3).

Adding features to existing in-stream structures to make them more suitable for fish passage is termed 'retrofitting'. Retrofitting can be useful in assuring fish passage as long as the hydraulic capacity of the structure is not compromised. Consideration must be given to the timing of retrofit works to ensure that works are not carried out during important migratory periods (see Table 2). Pollution control measures should be implemented whilst retrofitting is being undertaken.

The flashy nature of Auckland streams can make retrofits difficult as there are extreme variations in water levels during the season. The high flows often result in a very high incidence of bank and streambed erosion. During low flows, upstream passage of new recruits may be limited by water depth. To understand the characteristics of the site, it should be visited following a prolonged dry spell and also following heavy rain. The normal weather conditions during the September to February migratory period should be fully considered, as it is during this time (and during these weather conditions) that the retrofit will be vital in ensuring fish passage.

7.1 Ramp fishways

These fishways consist of boulder/cobble or artificial substrate ramps that either cover the whole width or a section of the barrier. They are most useful for retrofits of culvert outlets, as well as below weirs and other low head obstacles.

7.1.1 'Nature-like' rock-ramps

For obstacles where the head difference is less than 1 m (low head weirs and perched culverts), back-filling the outlet with rock can effectively promote fish passage. This type of retrofit is ideal in streams prone to floods and erosion and also looks 'natural', blending into the surrounding landscape.

Larger material such as boulders should be utilised and the smaller rocks may need to be cemented into place. This not only creates stability of the rock-ramp at high flows but also prevents water seepage, providing a continuous wetted surface at low flows.

The key features to allow passage of swimming and climbing fish are:

- The boulders should be positioned to form a pool-ramp sequence so that a pool is present at the outlet and at the base of the ramp.
- A low flow channel must be incorporated into the ramp design. This can be effectively done by creating a 'V' shape along the length of the ramp (Figure 20). This design ensures that both a wetted margin for climbing fish, and a channel for swimming fish, will be present at most flows.
- Ramp slope should be no greater than 1:5.
- Large boulders should line the stream banks and at the base of the ramp to prevent erosion of the stream bed (Figures 21 and 22).

Care must be taken when making such retrofits. For example, in the Meola Creek rock retrofit (Figure 21), the boulders were not cemented into place and subsequently erosion of the streambed and the displacement of smaller rocks occurred soon after construction, necessitating additional remedial work.

Figure 20.

Example of a boulder rock ramp designed for an obstacle such as a low head weir or perched culvert.

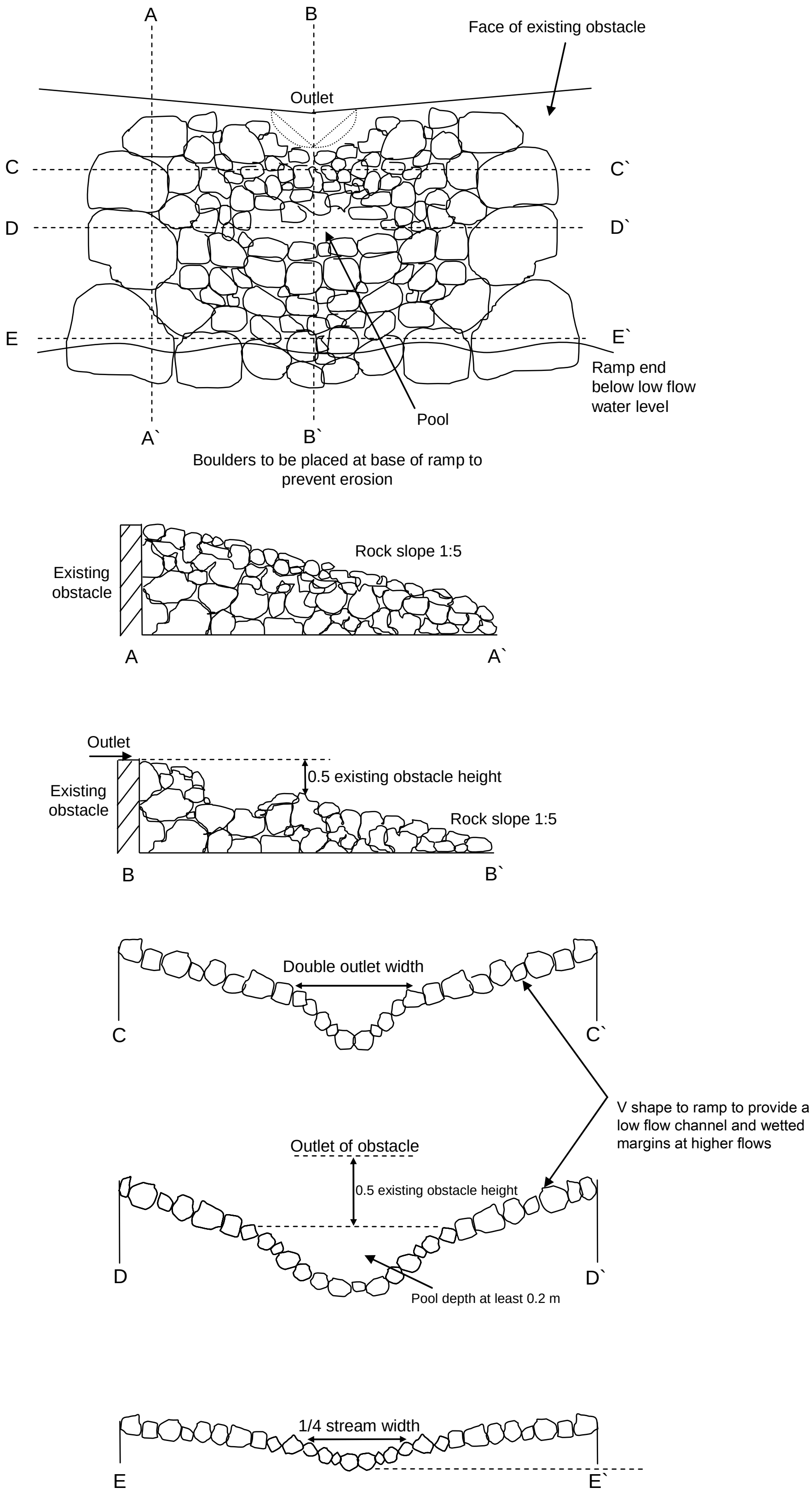


Figure 21.
Rock ramp retrofit of a gauging weir at Meola Creek.

Figure 22.
Example of a boulder rock ramp installed below a culvert.

7.1.2 Concrete ramps

In some situations (head height 1–1.5 m), a concrete ramp embedded with cobble may be more appropriate. Again, this option can be fitted below both weirs and culverts.

Ramps can be fitted directly at the culvert base, or at the base of a receiving pool. The need for a receiving pool will vary depending upon the situation; for example, if the flow downstream of the culvert is to be re-directed from its natural path (Figure 23). Utilising a receiving pool before the ramp will provide passage at all flows, as in high flow events the receiving pool can provide a spillway for excess water. This also protects the ramp from damage during flood flows. Any receiving pool should be twice the width of the outlet to provide low velocity margins to aid swimming fish passage. Pool depth will depend upon the flows experienced through the culvert, but should be at least 0.3 m. Deeper pools are desirable as they increase energy dissipation and reduce turbulence. In cases where the culvert contours into a stream/river, the ramp should be positioned along the bank and parallel to the stream channel (Figures 23 and 24).

Ideally, ramps should be angled horizontally to provide a range of water depths that taper to a wetted margin (Figure 25). This will provide low water velocities for swimming fish and a wetted margin for climbing species. It is essential that the width of the ramp provides a wetted margin at both high and low flows (Figure 26).

Ramp fishways are designed to make the velocity of water exiting the culvert negotiable by the target fish species. To ensure that target fish are also able to pass successfully through the culvert, adding baffles within the culvert barrel may be necessary (Section 7.2).

A weir could also be retrofitted with a concrete ramp, embedding cobble (150 – 200 mm) to the front face of the weir (Figure 27). The cobble should be haphazardly placed as opposed to uniform lines. To maximise the height of the cobble above the concrete ramp, each stone should be embedded longitudinally with the widest part of the stone upright (Figure 28). The spacing between each cobble should be between 50 – 80 mm. The cobble will not only lower water velocities down the front face of the weir, but also provide small pockets of water on the wetted margins that can act as resting areas for fish such as inanga that must swim over the weir (Figure 29).

The key features to remember when retrofitting concrete ramps to weirs are:

- ❑ Ensure rocks are cemented into place to prevent water seepage.
- ❑ Armour banks downstream to prevent erosion.
- ❑ Tilt the ramp horizontally to provide a range of water depths tapering to a wetted margin (see Figure 25).
- ❑ Ensure structure has rounded edges with no sharp margins that may be impassable to climbing fish.
- ❑ Ensure width of ramp will provide a wetted margin for climbing fish at all flows.

Figure 23.

Example of a concrete ramp below a culvert that is perpendicular to the downstream water body. Here a receiving pool has been added at the base of the culvert to direct the ramp downstream along the river margin. This provides the foundations for a low sloping ramp.

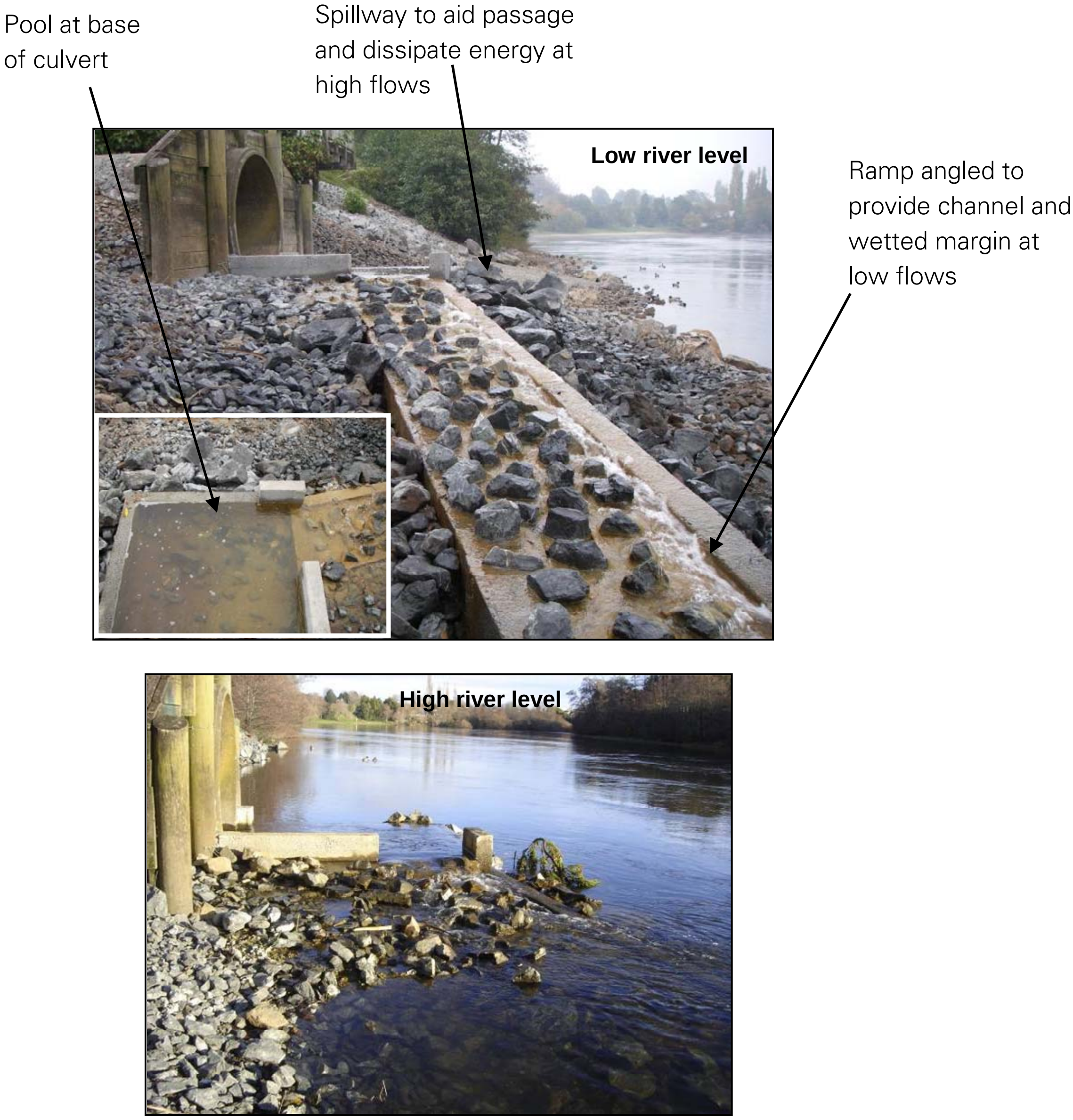


Figure 24.
Plan view of ramp fishway from culvert contouring into stream /river.

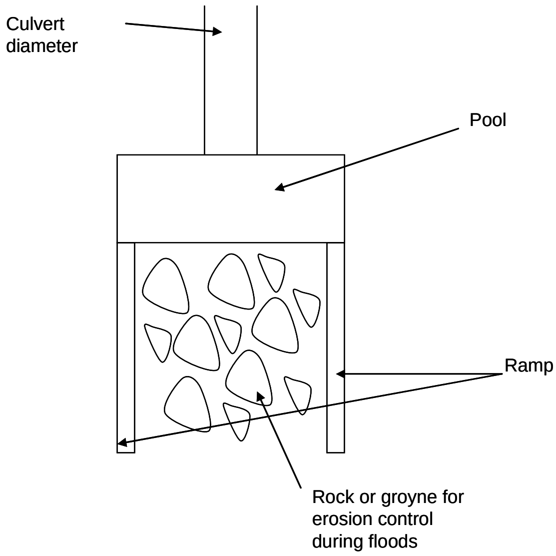


Figure 25.
Transverse cross-section of a ramp showing a horizontal tilt which provides a range of water depths tapering to a wetted margin.

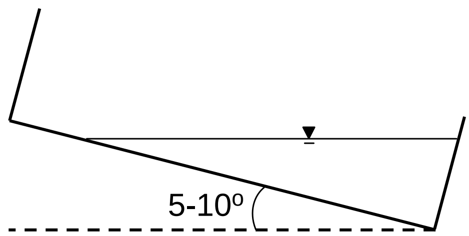


Figure 26.
A concrete ramp below a culvert on West Hoe Stream, Orewa.

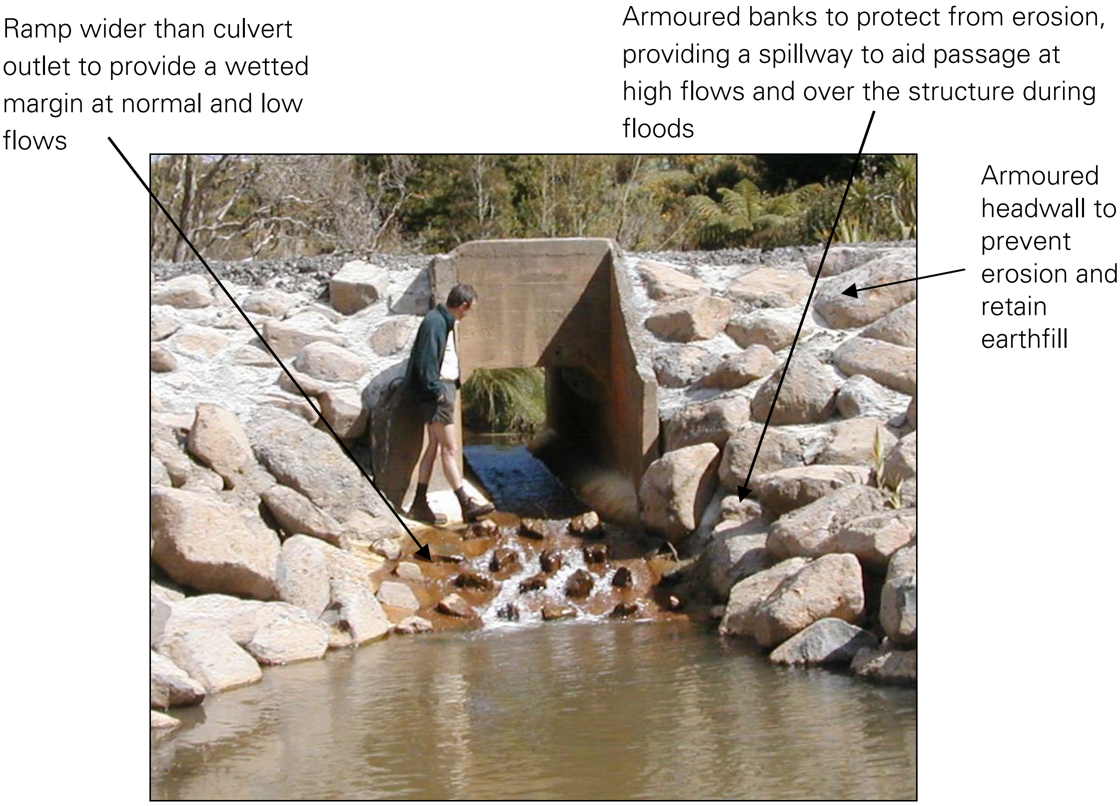


Figure 27.
An example of cobble embedded into concrete to increase the roughness of the ramp surface and lower water velocities.

Figure 28.
Cobble should be embedded into the concrete along the longitudinal axis with the widest part of the stone upright.

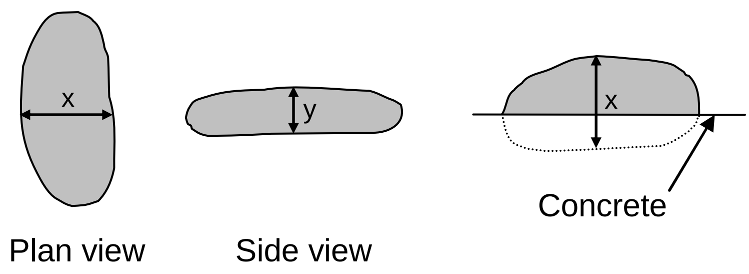
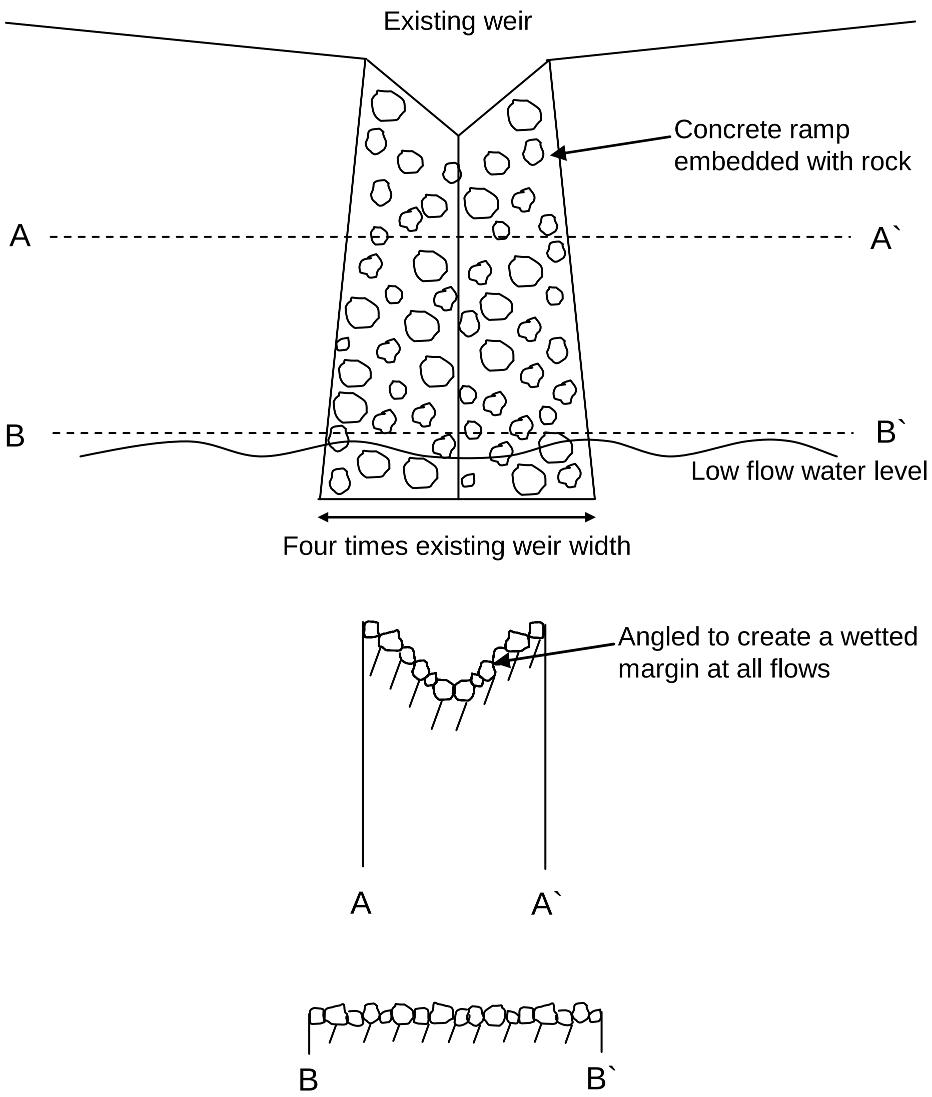


Figure 29.
Weir with concrete ramp embedded with cobble.



7.1.3 Artificial substrates

Smooth substrates are not as effective as rougher substrates for fish passage so the roughness of smooth surfaces should be increased with natural (e.g., rock or wood) or artificial substrates (e.g., constructed from concrete or plastic). Substrate roughness and spacing should cater for the target specie(s). The cross sectional size of roughness elements should be at least 1.5 times larger than the cross sectional area of the target fish and the spacing of roughness elements should not be smaller than the length of the fish. For example, a roughness element with a height of at least 60 mm and a spacing of 200 mm would be required to permit most adult galaxids to use the ramp.

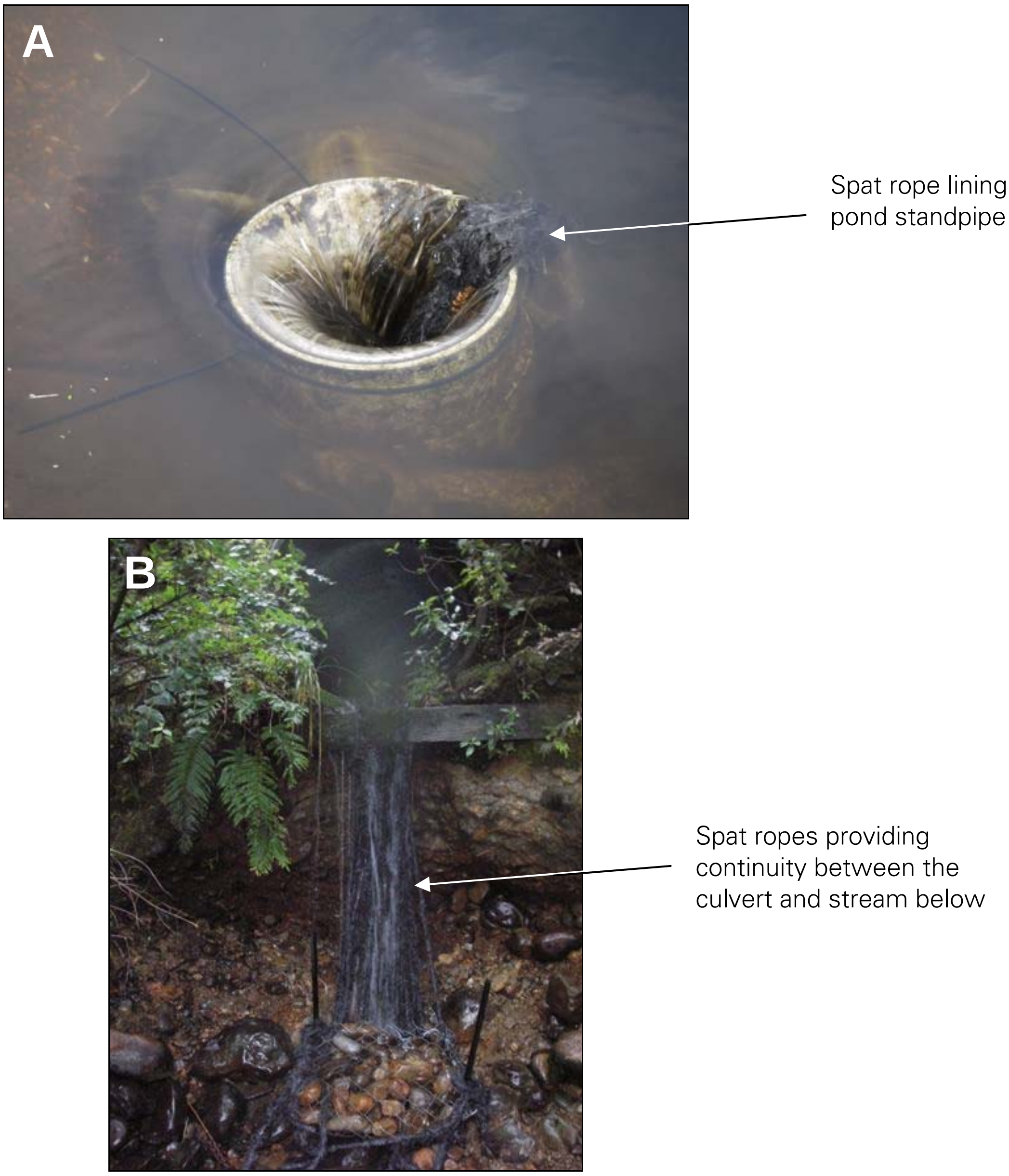
Baker and Boubée (2006) evaluated the effects of a range of artificial ramp substrates on the passage of inanga and redfin bullies. Smooth surfaces performed poorest and were insurmountable by either fish species when vertical slopes greater than 15º were used. Gravel, nylon brush and the plastic cores of two drainage products (Miradrain™ and Cordrain™) resulted in high passage rates for inanga at vertical slopes of 15 and 30º. At a vertical slope of 45º, Miradrain™ was the only surface that permitted adult inanga passage although no juveniles successfully negotiated the ramp using this surface. As redfin bullies used the wetted margin for climbing, the surface of the ramp did not generally affect their passage success with the exception of the smooth surface which was insurmountable. Overall, the Miradrain™ (Figure 30) surface provided the highest passage success for inanga and redfin bullies at a slope of 15º.

Figure 30.
Redfin bully climbing a ramp utilising Miradrain™ substrate. Note: ramp is tilted to provide a wetted margin on the left hand side to facilitate climbing passage.

Standpipes used in stormwater retention ponds may be made passable with the use of artificial substrates. In most situations, it would be difficult to retrofit the structure to allow the passage of swimming fish. However, it may be possible to permit passage for climbing species through standpipes using substrates such as spat ropes (ropes used for the collection of mussel spat for aquaculture), fixed within the internal diameter of the standpipe (Figure 31A). Work by Dr Bruno David (Environment Waikato (EW)) has indicated that these spat ropes can slow velocities by braiding the water flowing over and through the substrate, resulting in improved passage conditions for climbing fish. An alternative to using spat ropes could be angling the standpipe to 45° and lining it with baffled media, but this has not yet been tested in the field.

Spat ropes may also be useful for providing passage of fish past perched culverts (Figure 31B). This type of retrofit will facilitate climbing fish passage but it is unlikely to provide swimming fish passage. Field trials of perched culverts are currently being undertaken to determine the efficacy of these ropes (B. David, EW, pers. comm.).

Figure 31.
Use of spat ropes for climbing fish passage. A, Pond standpipe with spat rope providing linkage between bottom of pipe and the waterbody. B, Spat ropes lining a perched culvert and joining the stream bed below (photo courtesy of B. David, Environment Waikato).

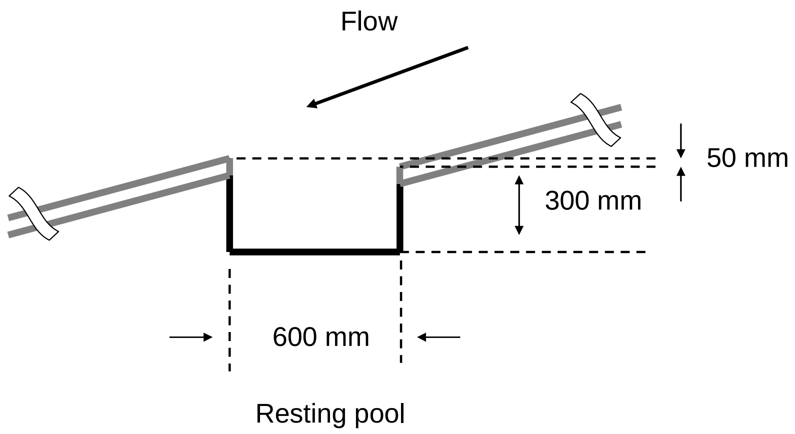


7.1.4 Ramp slope and length

Even at low slopes, the length of ramp can affect fish passage. There is limited information available of the effect of ramp length on fish passage but for ramps with slopes of 15° and fitted with Miradrain™, resting pools should be at 1.5 m spacing (Figure 32). Spacing between pools can be increased by reducing the ramp slope. As many species, notably the juveniles of climbing galaxiids and eels, are able to use the wetted margins to recover, resting pools are not always essential if only climbing species are targeted. In all circumstances, protection from predation by birds, rats and other predators is essential.

Figure 32.

Resting pools within a ramp. Pools should be deep enough to provide fish with resting areas below the turbulence created by the overflowing water and should be spaced appropriately for the slope of the ramp and its length.



7.2 Culvert baffling

The suitability of a culvert for baffling depends upon its diameter and length. Baffles are not considered suitable for use in culverts smaller than 0.8 m diameter due to blockage concerns and installation problems.

7.2.1 Small culverts (< 0.8 m diameter)

Low profile, artificially roughened substrates may be used on the floor of a small culvert to improve fish passage. Spoiler baffle installation is not generally desired in small culverts as the baffles can markedly reduce the cross sectional area resulting in a loss of hydraulic capacity and also act as areas for the attachment of debris. It is vital to ensure that the addition of roughened substrates onto the base of a small culvert does not impede the flow to the extent that its capacity is compromised.

A recent study investigated the effects of different culvert substrate types (Table 5 and Figure 33) on the upstream passage of inanga (ARC 2008). It found that baffled substrates allowed inanga to travel up to five times the distance compared to a smooth culvert floor (Figures 34 and 35). Both large and small inanga were generally more successful on the Miradrain™ and Polyflo™ substrates than on the other substrates tested (Figures 34 and 35). Observations also indicated that the Polyflo™ pipe was the best solution to ease fish passage in small diameter culverts as it provided larger resting areas for fish compared to Miradrain™, and was also less likely to trap debris. Polyflo™ culverts should not exceed 5.5 m in length when installed at a slope of 3% if weak swimming fish passage is to be assured. Longer culverts may be installed if the slope is reduced.

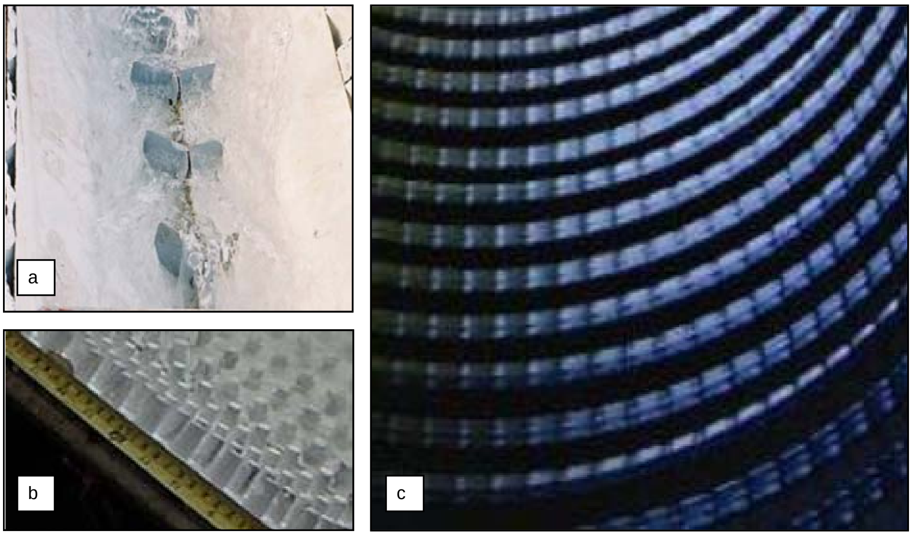
Table 5.

Details of substrate types used in experimental work.

Substrate type	Description
Smooth metal	Flat metal sheets
Corrugated	A plastic pipe with 70 mm wide and 15 mm high regular transverse corrugation
Herring-bone baffle	Opposing 60 mm long 60 mm high steel baffles attached to a central rib every 200 mm and angled about 120 degree upstream. Structures positioned mid - channel over a smooth substrate.
Polyflo™	A plastic pipe with transverse trapezoidal corrugations 30 mm wide at ridge, 60 mm wide at base 20 mm deep and spaced at 160 mm
Miradrain™	A pipe lined with a thin plastic sheet with rows of 24 mm high cones at 30 mm centres and 15 mm spacing at the base

Figure 33.

Substrate types tested: a) herring-bone baffle, b) Miradrain™ and c) Polyflo™.



Substrates such as Polyflo™ may be suitable for use in newly constructed culverts but can be difficult to retrofit in a confined area. There have been some recent developments involving the use of a bracket system which works in a similar way to the herringbone baffle, but this has not yet undergone field testing (Kelly Hughes, Advanced Traffic Supplies, Whakatane, pers. comm.). The use of spat ropes (Section 7.1.3) fitted within culverts may also provide a way of reducing velocities to an acceptable level. Trials are currently being carried out by Environment Waikato to examine this potential.

Figure 34.

The mean distance travelled by 'small' inanga (<60 mm total length) in a 7.8 m pipe of 0.65 m diameter, fitted with differing substrates. The number of fish tested for each experiment was 40, except for 3% slope and smooth substrate where over 60 fish were tested. Error bars show one standard deviation. Means with the same letter are not significantly different from each other (ANOVA, P<0.001).

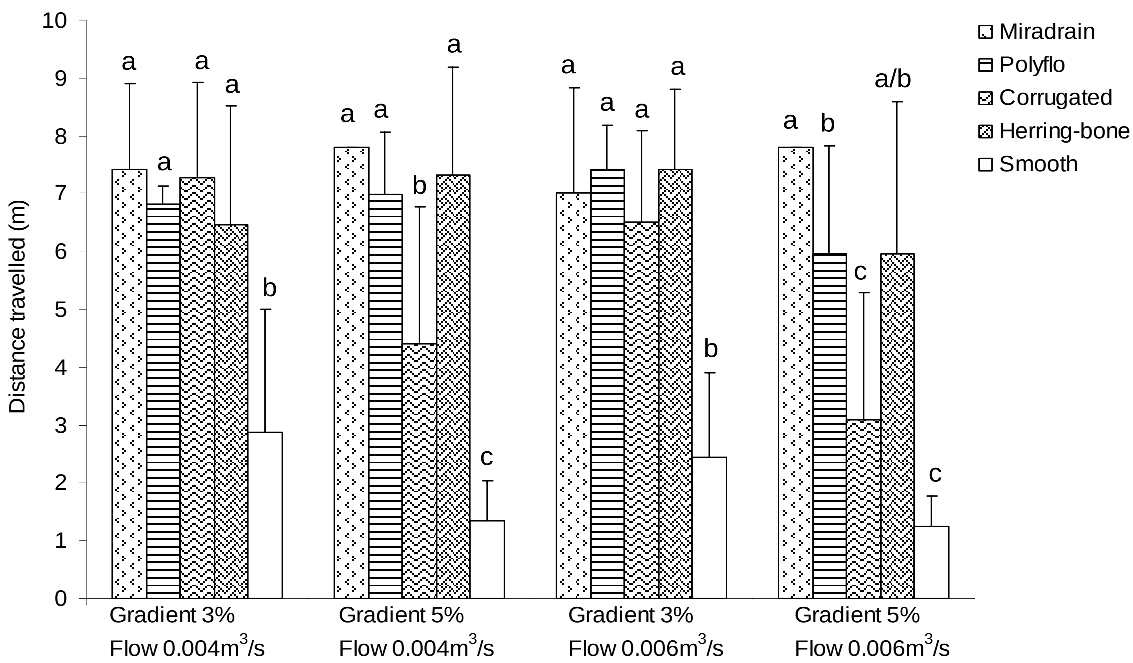
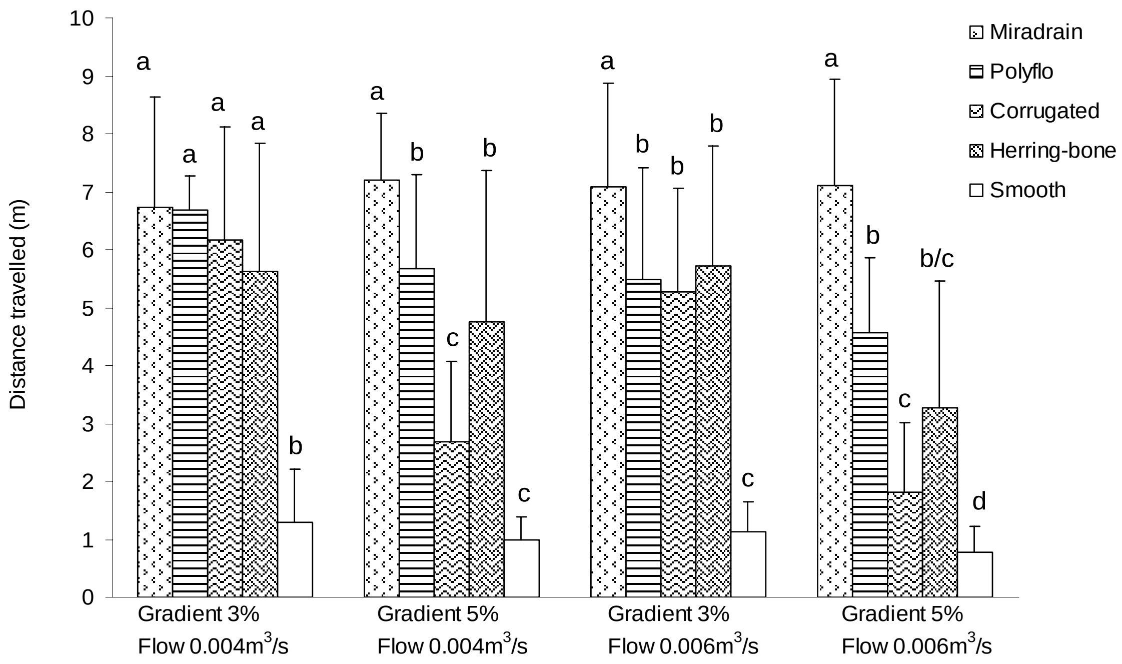


Figure 35.

The mean distance travelled by 'large' inanga (>60 mm total length) in a 7.8 m pipe of 0.65 m diameter, fitted with differing substrates. The number of fish tested for each experiment was 40, except for 3% slope and smooth substrate where over 60 fish were tested. Error bars show one standard deviation. Means with the same letter are not significantly different from each other (ANOVA, P<0.001).



7.2.2 Large culverts (> 0.8 m diameter)

Where high barrel velocities, shallow water and a lack of wetted margins are restricting passage, the use of spoiler baffles may be appropriate. Spoiler baffles installed in a suitable conformation can reduce velocities within the culvert barrel and create low velocity resting areas, which are regularly spaced within the burst swimming distance of most small indigenous fishes. The aim of fitting spoiler baffles is to reduce the average barrel velocity to 0.3 m s–1 or less, this velocity being the maximum sustained swimming speed of the inanga. However where this cannot be achieved, it is acceptable to fit spoiler baffles to provide a 50–100 mm zone along the base and sides of the culvert with velocities below 0.3 m s–1.

ARC (2008) used a computational fluid dynamic model to investigate the effect of adding rectangular spoiler baffles (0.25 m length, 0.12 m width and 0.12 m height) to culverts. In this study, simulations were undertaken for 'large' pipe culverts ranging from 1.3 m to 4 m in diameter. The simulations permitted velocity profiles to be generated for a range of different flows. The velocities recorded within the culverts could then be compared to the known velocity requirements of indigenous species.

The results indicated that the spoiler baffles can create a continuous low velocity zone along the base of 'large' diameter culverts (Table 6 and Figure 36). Lower velocity areas were created by the comparatively close spacing of the spoilers, where the bottom layer of water passed through the spoilers in a sinuous manner and therefore velocities were reduced. Whilst the velocities between spoilers were lowered, they still ranged from 0.38 to 0.95 m/s. A typical indigenous fish, such as the inanga, using the swimming mode could therefore be expected to use sustained swimming to achieve upstream progress for the lower part of this velocity range but for the upper part of the range, the fish would be required to burst swim. However, low velocity resting zones are provided on the downstream end of the baffles (Figure 36) and also at the culvert margins to allow fish to recuperate after bouts of burst swimming.

The simulation work also permitted the velocity and turbulence profiles of other shapes of spoiler baffle to be investigated. Cuboid baffles (0.12 m length, 0.12 m width and 0.12 m height) were shown to reduce velocities at gradients up to 3%; however, no field testing has been undertaken. In the absence of field data, the current recommendations are restricted to rectangular spoiler baffles. Baffle wedges, with a sloped upstream face, produced a turbulent flow behind them and were not recommended. Rectangular baffles longer than 0.25 m in length were found to channel the water and create areas of increased velocities and were not considered suitable.

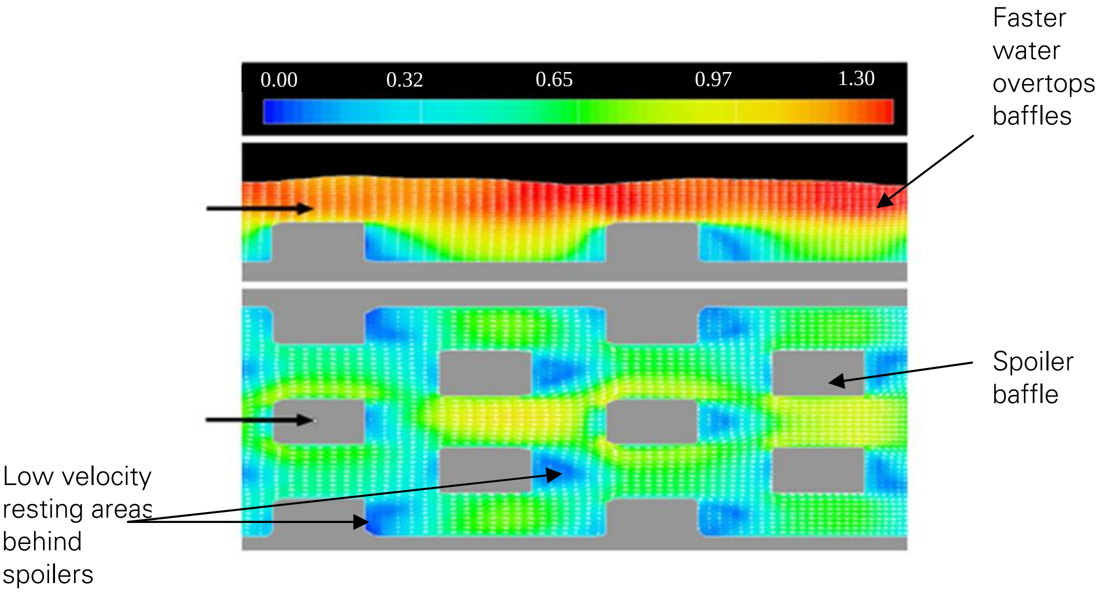
Table 6.

Simulated velocities at different flows on the base of culverts of varying diameter fitted with spoiler baffles. Water velocities tabulated are the maximum velocity in gaps between spoilers (lateral and longitudinal). The gradient of the culvert is 1.2%.

Culvert diameter (m)	Baffle configuration	Flow (m^3/s)	Maximum velocity between rows of spoilers (m/s)	Max velocity between spoilers within a row (m/s)
1.3	Alternating rows of 3 and 4 baffles	0.119	0.38	0.8
		0.22	0.48	0.9
		0.275	0.51	0.9
		0.33	0.54	0.94
2.0	Alternating rows of 6 and 7 baffles	0.30	0.47	0.8
		0.55	0.50	0.9
		1.10	0.60	1.0
		1.65	0.62	1.4
3.0	Alternating rows of 10 and 11 baffles	0.75	0.53	0.9
		1.50	0.52	1.0
		3.00	0.61	1.17
		4.50	0.59	1.20
4.0	Alternating rows of 13 and 14 baffles	2.00	0.61	1.0
		4.00	0.73	1.27
		7.50	0.88	1.5
		11.00	0.95	1.65

Figure 36.

Longitudinal view (top section of diagram) and 0.075 m depth plan view (bottom section of diagram) of modelled water velocity in a culvert fitted with spoiler baffle design, with alternating rows of rectangular spoiler blocks (0.25 m length, 0.12 m width and 0.12 m height), spaced 0.20 m apart at a flow of 0.11 m/s. Arrows indicate the direction of flow. Culvert diameter = 1.35. The coloured band at the top of the figure gives the flow velocity range (red = 1.30 m/s, blue = 0 m/s).



The addition of baffles to a culvert will change the hydraulic efficiency of the culvert but using spoiler baffles of an appropriate size and arrangement for a given culvert size will ensure that efficiency losses are minimized.

Rectangular spoiler baffles have not yet been trialed in catchments which have a high level of waterborne debris or watercourses which have large bedload movements. Both debris and sediment could reduce spoiler baffle efficacy by becoming trapped between baffles and preventing velocities from being reduced, as well as reducing the physical resting area available for fish. The current recommendations are therefore restricted to catchments which do not carry large amounts of debris or sediment.

The number of spoiler baffles fitted to a culvert will vary dependent upon the culvert size (Table 7) but as a general rule, baffles should aim to cover approximately one third of the culvert's internal circumference. This should benefit fish passage without unduly affecting flood capacity. Research has found that the addition of alternating rows of three and four spoilers to a 1.3 m culvert in the arrangement shown in Figure 37, resulted in a uniform 8% increase in culvert fullness as discharge increased from 0.11m3/s to 0.33 m3/s (ARC 2008).

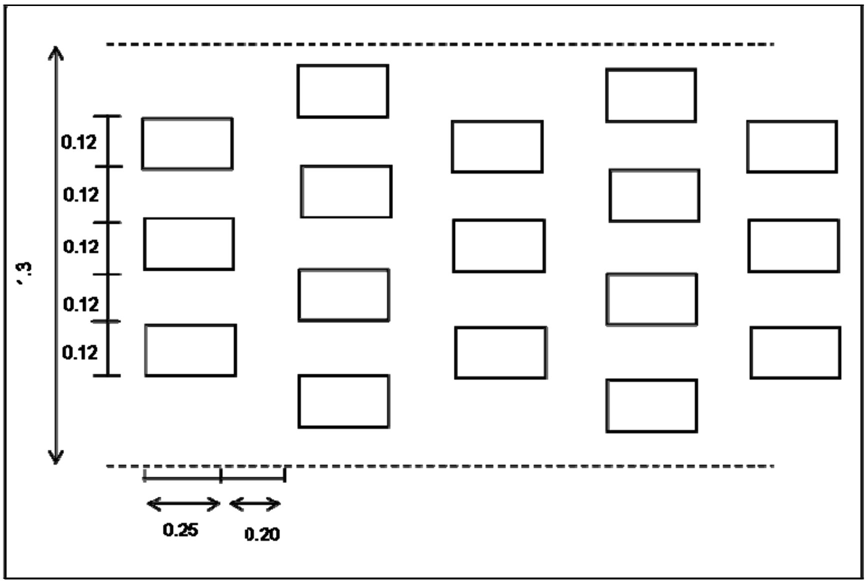
Not having all the baffles submerged during base/low flows is advantageous as the partially submerged baffles on the culvert margins can provide important resting areas for migrating fish.

Table 7.

Number of baffles to be installed in culverts in relation to culvert diameter.

Culvert diameter (m)	No. of baffles in alternating rows
1	3 and 4
2	6 and 7
3	10 and 11

Figure 37.
Plan view of spoiler baffle arrangement within a 1.3 m culvert. Rectangles represent wooden baffles (0.25 m length, 0.12 m width and 0.12 m height). Dotted lines signify culvert edges, at one third diameter. Rows of baffles are staggered and alternate in rows of three and four baffles. All dimensions are in metres.

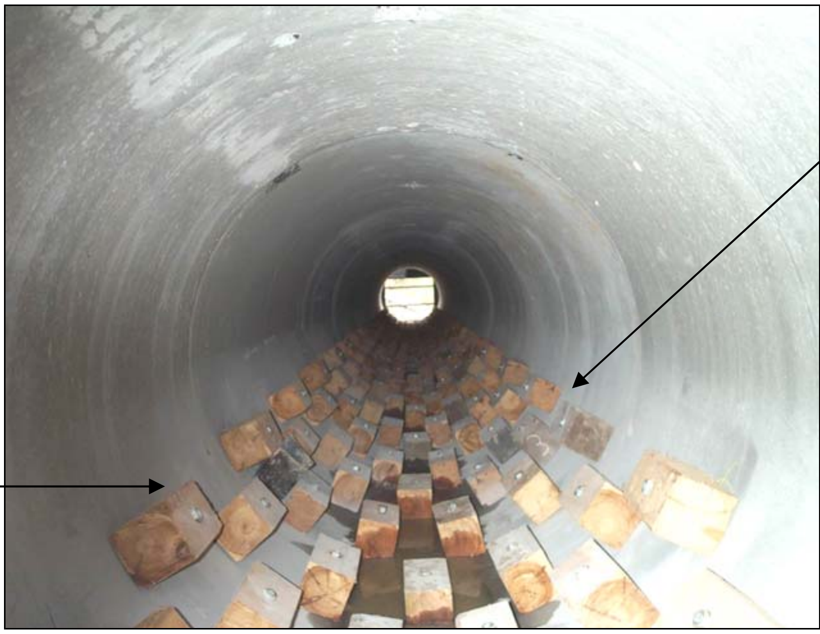


Baffles should be fitted in a complex arrangement (Figures 37 and 38) with staggered rows to force the flow on the culvert floor to meander through the culvert, as this is one of the ways in which velocity is reduced. The fact that baffles are not placed in a continuous line across the culvert floor allows fish to progress upstream between low velocity areas without having to negotiate the higher velocity flow above the baffles. It is, however, critical that baffle rows are placed throughout the entire length of the culvert as it is their combined effect within the culvert that reduces barrel velocities.

The spacing of the baffles is important as this will ensure that fish are able to use the resting areas created between rows of baffles. A spacing of 0.20 m between baffles will ensure that migratory fish up to 200 mm in size (which will include most indigenous adult fish) are able to fit between rows. It is recommended that rectangular baffles are only installed in culverts with slopes of 2% or less, as they may not be effective at reducing water velocities at higher slopes.

Figure 38.

Wooden spoiler baffles in culvert, during construction phase of a 1.3 m diameter culvert. Note alternating rows of five and six baffles. Spoiler baffles are rectangular (0.25 m length, 0.12 m width and 0.12 m height) and are attached to the culvert with stainless steel bolts.



Baffles placed in repeating sequence to provide resting areas at regularly spaced intervals

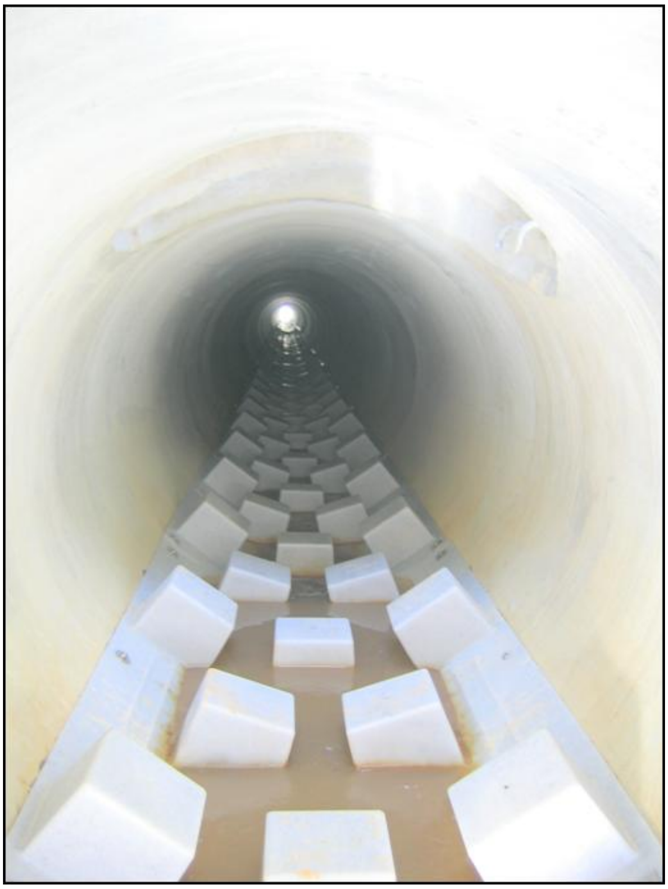
Baffles placed on base of culvert, over approximately one third of culvert internal circumference (during average flows, baffle bases will be submerged)

Wooden baffles should be attached to the culvert base with stainless steel bolts. Because wooden baffles will deteriorate over time, it will probably be necessary to regularly check and replace some of the baffles. If a more durable and time-effective installation is desired, moulded plastic spoiler sheets could be considered (Figure 39). These flexible sheets (available from Rotational Plastics – see Appendix 5 for details) are manufactured with multiple baffles that can be installed using anchor bolts. Sheets of spoilers may not be appropriate for use in all culvert situations as they can double the roughness in comparison to a plain barrel (Leong 2007).

The Rotational Plastics spoiler sheets have been installed in a culvert on Bankwood Stream in Hamilton. Baffling of the culvert has provided passage for inanga and smelt which were previously prevented from accessing the stream by the high water velocities within the culvert. Field testing of these sheets has shown that secure fastening to the culvert base is essential to withstand damage during flood flow events. Regular maintenance to remove accumulation of large debris after high flows is also recommended.

In all culverts that are fitted with baffles, the first row of baffles should be attached flush to the end of the pipe at the culvert inlet, in order to ensure that the flow at the inlet is even. The first row of baffles should have the lesser number of baffles for a conformation (e.g., in a three and four baffle conformation, the first row should only have three baffles not four). This is to prevent excessive water backing up behind the baffles at the inlet.

Figure 39.
Spoiler sheets installed in a culvert at Otanerua, Auckland. The baffles shown are larger in size than the standard baffles (0.12 m x 0.12 m x 0.25 m) recommended for use in culverts.



7.3 Nature-like channels

Artificial channels can be an effective means of ensuring passage of swimming fish past obstacles such as moderate head dams. In general, the channel needs to be well armoured and as diverse as possible and should include pools, riffles, runs and backwaters (Figure 40). By including channel diversity, a range of velocities will be provided within the channel but it is essential that these velocities are within the sustained swimming speed of weak swimming fish with only a few areas where burst swimming would be required. It is also important to maintain a low gradient and shape the channel so that at both low and high flows, low velocity wetted margins remain available for fish passage. In catchments prone to extreme water fluctuations, the channel should be able to cater for the range of flows that exist (Figure 41). Wherever possible, different sized material (including woody debris) should be used in the construction. Pool and riffle spacing of six times the channel width and a meander of 12 times the channel width have been recommended (Newbury 1996). The banks should be planted to provide shade as well as maximise flood protection and in-stream cover. A range of plants should be included to encourage the development of a balanced canopy (see ARC Technical Publication 148 ‘Riparian Zone Management’ for guidelines on appropriate flora). Until overhead vegetation is dense enough to reduce plant growth immediately adjacent to the water, the in-stream vegetation may need to be controlled to ensure that the channel does not become overshaded.

Figure 40.
Example of a bypass channel that could be constructed to allow fish passage upstream of a moderate head obstacle. The channel has natural characteristics, such as resting pools and run/riffles.

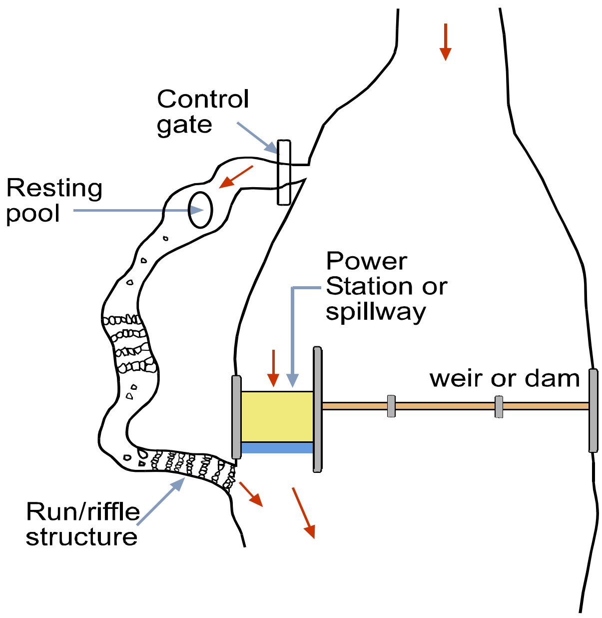


Figure 41.
Nature-like channel at Lake Waikare. Channel allows fish to by-pass the floodgate.

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

Above all, it is important to ensure that the nature-like pass is functioning correctly and to initiate a regular monitoring programme. This could include visually inspecting the channel, to ensure that the original channel design has not been moved during floods. This may also include undertaking velocity measurements at points throughout the channel to ensure that low velocity zones (below 0.3 m/s) are maintained.

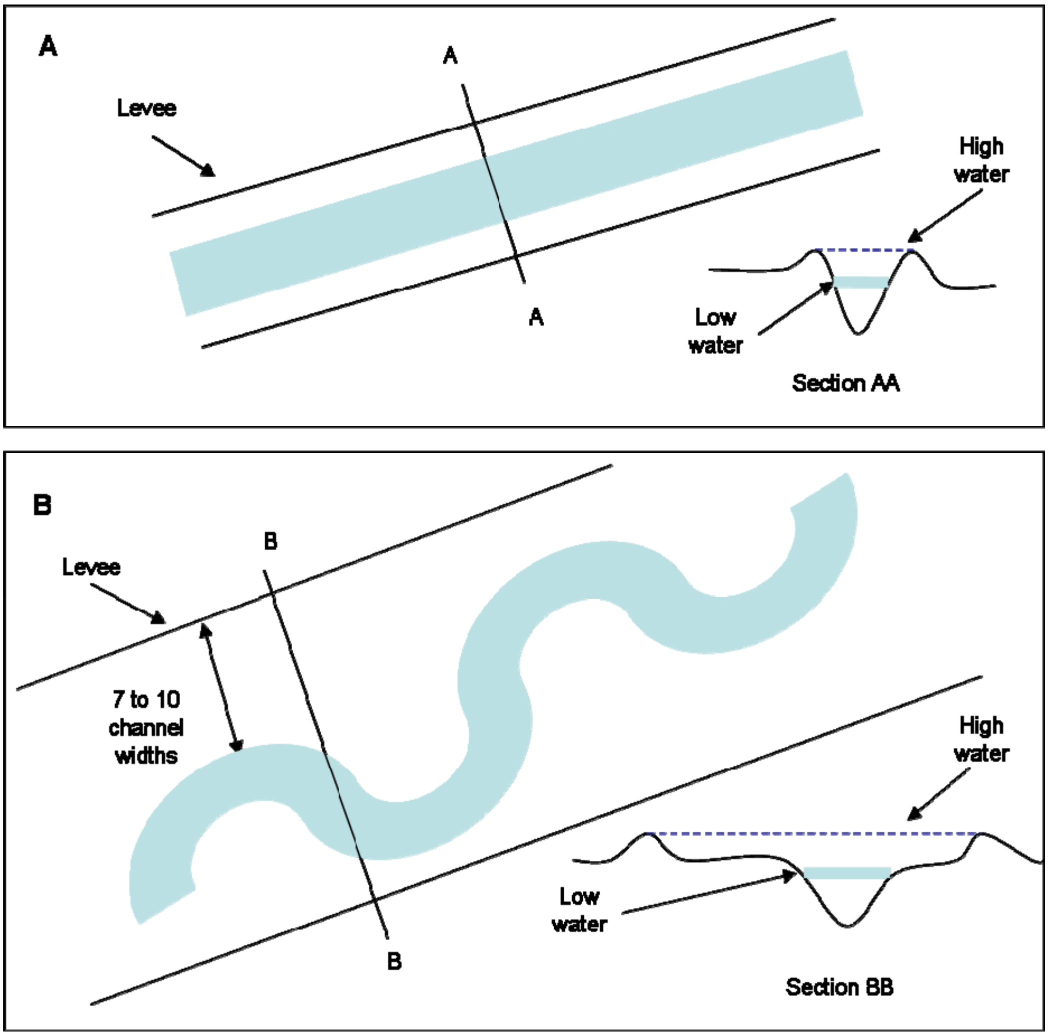
7.3.1 Restoring channelised streams

Channelised streams have generally been designed to have high hydraulic efficiency. To this end, streams may have been straightened, dredged and paved to ensure the rapid transport of water but these characteristics may also result in creating a relatively uniform high velocity environment. Remediating channelised streams involves recreating the characteristics of a 'natural' stream environment and may also include reconnecting stream environments to wetlands and ponds that may have been part of the original habitat mosaic.

In streams that have been straightened, an ideal would be to reintroduce meanders in an imitation of the original stream route and to reinstate the flood plain. It may be possible to use old maps to determine where the stream was routed prior to channelisation. As with creating bypass channels, pool and riffle spacing of six times the channel width and a meander of 12 times the channel width are recommended (Newbury 1996). Levees can be created 7 to 10 channel widths from the stream, which will allow the establishment of a new flood plain and natural meanders whilst ensuring that flooding does not occur (Figure 42). In low gradient systems, new meanders may have to be constructed as there may not be enough energy to allow meanders to create naturally. Root wads (the root mass of a tree which includes a portion of the trunk), wood and rock deflectors can be added to the channel to assist in the reestablishment of meanders. In highly developed catchments, there may be insufficient space to allow reinstatement of floodplains and the high economic cost may also reduce the will to undertake such a project. However, there are many benefits to undertaking such works such as an increased capacity to cope with flood conditions and a more aesthetically pleasing environment, as well as improved fish passage opportunities.

Figure 42.

Reinstatement of floodplains. A, Channel prior to reinstatement of flood plain, with levees immediately adjacent to watercourse to prevent flooding. B, Rehabilitated situation with levees set back from the channel and the watercourse meandering through floodable land. In low gradient systems, it may be necessary to construct meanders rather than leaving them to form naturally (redrawn from FAO, 1998).



To restore the in-stream habitat and return it to a more 'natural' state where fish passage is ensured, the roughness of the channelised stream will need to be increased. This may be achieved by removing paving or concrete and returning the channel to its natural soil type. Dependent upon the soil type, bank armouring may be necessary to protect against erosion in areas where the watercourse changes direction or on the outside edge of corners. The planting of native flora will stabilise banks and provide fish with cover and shade the watercourse, as well as adding food to the stream, both through leaf litter and terrestrial invertebrate input. In order to ensure that flora is planted appropriately, the ARC Technical Publication 148 'Riparian Zone Management' should be consulted prior to undertaking planting. Relying upon natural revegetation for reinstated banks is not recommended as it is likely that weeds will become dominant in the bankside vegetation.

To increase habitat complexity in a previously channelised section, large substrates and woody debris should be added to the channel. The addition of these substrates will increase roughness and reduce velocities. In order to gauge what sizes of substrates and amount of woody debris may be appropriate, it may be possible to visit a similar part of the stream system that has not been affected by channelisation and use this as a 'template' for remedial works. All introduced substrates should be well washed to avoid introducing excess sand or silt (or pest species) to the channel. Depending upon the gradient of the channelised stream and the material it is constructed from, it may be necessary to attach some form of bed stabilisation to prevent substrates being removed during high flows (Section 8.3.1), particularly if the channel remains in its straightened form. It is only appropriate to undertake works such as this when there is an assurance that doing so will not affect the channel's capacity to remove the design flow to an unacceptable extent. This is especially important in areas where there is housing or important social infrastructure.

7.4 Monitoring and Maintenance

All retrofits will require a maintenance schedule to ensure the structure or channel is operating as designed. During maintenance, the current condition of the retrofit should be compared to the original work plan to ensure that the structure is operating in the way in which it was intended. The retrofit should be examined at the very least on an annual basis and any maintenance required undertaken.

When debris or sediment maintenance is required, only enough debris and/or sediment should be removed as is necessary to ensure that design flows are conveyed. Small amounts of woody debris and moderate amounts of bed material can provide important habitat for fish and invertebrates and woody debris should therefore be retained.

8 Guidelines for the construction of in-stream structures

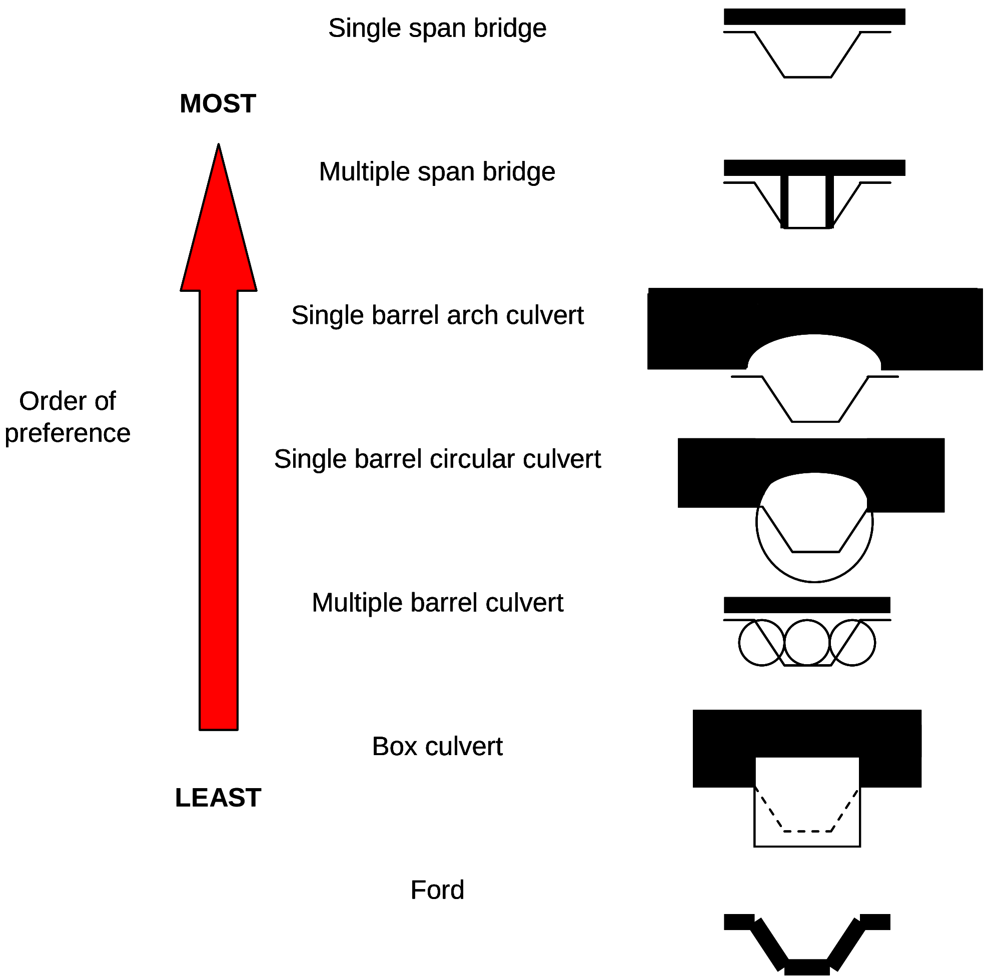
All stream crossings have the potential to adversely affect the aquatic habitat and its biota. It is therefore essential that the number of in-stream crossings be minimised through proper planning. When a stream crossing is shown to be essential, bridges are the best means of ensuring fish passage. Where these are not practicable, the correct choice of appropriate in-stream structures and correct installation will reduce the impact on the habitat and ensure fish passage.

The timing of works during installation of any in-stream structure should be considered in relation to the lifecycles of the fish that inhabit the watercourse and the flow conditions that could be experienced during installation. From Table 2, it is clear that freshwater fish migration occurs throughout the year in the Auckland region but it is unlikely that all of these species or life-stages will occur in the same area. Therefore, it is important to know which species are present at a proposed site in order to avoid undertaking works during migration periods. As a general rule, avoiding the September to February migration period is advisable when planning installation works.

Installation works should not be undertaken during high flows and during installation, water should be diverted around, or through, the construction site but always ensuring that works do not contaminate water downstream (see ARC Technical Publication 90 'Erosion and Sediment Control Guideline for Land Disturbing Activities in the Auckland Region' for details of watercourse protection). Any temporary structure used to maintain water quality during installation should not itself be a barrier to fish movement.

There is a hierarchy of preference for in-stream structures in terms of fish passage (Figure 43). Bridges are the preferred way of installing stream crossings where no part of the bridge structure enters the water. It is beyond the scope of this document to provide details of bridge construction but useful information on consents may be found in ARC Fact Sheet 9 'Construction of a bridge: Consent requirements'. It is important to note that, despite the hierarchy of preference, any of the structures in Figure 43 have the potential to impede passage if they are not installed or maintained correctly. Regular monitoring and maintenance of newly constructed works is an important part of post-construction review.

Figure 43.
Order of preference for stream crossings.



8.1 Culverts

Most of the culverts installed in the Auckland Region have been designed to optimise flow/flood passage; they generally do not have the roughness and variability of a natural stream channel and therefore do not dissipate energy as readily.

The two most common faults found in Auckland culverts in a previous survey (Evans and Glover 1999) were:

1) Vertical drops at the end of outlet aprons that several fish species would not have been able to overcome during low flows and large concrete aprons that dissipated flow so that water levels were too low for fish to swim through.

2) High culvert barrel velocities and downstream channel scour that created perched outlets that fish could not surmount at low and medium flows.

The installation of new culverts should aim to avoid repeating these faults.

8.1.1 General culvert design

Across the Auckland region, there is wide variation in rainfall. The size of a culvert installed at a site will depend upon the flows that it is expected to accommodate and the features of the watercourse that the culvert is being installed in. Calculations can be made to determine which size and slope of culvert is appropriate to provide water velocities within the abilities of target fish species (Appendices 1 - 4). It is critical to ensure that culverts are not undersized, as this causes the majority of fish passage problems. However, there are also some general guidelines that should be applied when new culverts are being installed:

- culvert width should be greater than the average streambed width during average flow, at the point where the culvert intersects the streambed. A rule of thumb for this is 1.2 x channel width + 0.5 m. Arch culverts and the use of large culverts that exceed the minimum hydraulic requirements of a site can achieve this objective. By ensuring that flow is not restricted by the culvert, this should ensure that velocities remain at the levels expected within a natural stream, which should include a route through the culvert with velocities below 0.3 m s^{-1};
- the culvert should be positioned so that both its gradient and alignment are the same as that of the existing stream. This should ensure that no increases in velocity occur at the culvert inlet or outlet;
- the culvert floor should be set well below the current streambed (minimum of 20% of culvert diameter/rise at downstream end and maximum of 40% of the culvert diameter/rise at the upstream end). The inlet should not project out of the headwall and the outlet should remain flooded at all flows;
- ideally the natural streambed will be retained within the culvert by using an arch culvert but where this is not possible (e.g., in the case of installing a single barrel culvert), rocks should be placed within the culvert to provide cover and introduce resting areas whilst the streambed builds;
- headwalls should be provided at both the culvert inlet and outlet to retain earthfill and improve hydraulic efficiency, as well as providing protection against erosion (Figure 25). Headwalls should ideally be sloped rather than vertical. Headwalls and aprons should be protected from scour by using riprap. On the inlet headwall, riprap must only be placed on the headwall where the full force of the flow is received and not on the side walls of the inlet. On the outlet, measures should be taken to reduce soil erosion during energy dissipation. Here, the use of riprap on an apron can also benefit climbing fishes during low flows (Section 7.1.2);
- bed material downstream of the culvert should be assessed to determine the potential for erosion. If erosion is likely, a rock-ramp could be provided downstream of the outlet (Section 7.1.1) to stabilise this area. This will have additional benefits such as creating pool resting areas, reducing culvert velocities by backwatering and eliminating elevated outlets. It is essential to have a low flow channel incorporated into the design;
- where low flows (and therefore shallow water depths) are a feature of the site, the apron, weir, or barrel floor should be dished or sloped to concentrate flows;

- all the ends and junctions of the culvert should be rounded to allow climbing species to pass;
- the outlet pool should be twice as wide as the original stream and generally deeper pools are considered to be the best option;
- trash racks should not be positioned immediately upstream of a culvert as they may block the culvert and prevent fish passage;
- where the flow regime of the stream permits, to ensure the maintenance of a wetted margin, water depth should be no greater than 45% of the culvert height for the majority of the September to February main upstream migration period (Table 2);
- although not applicable to all sites, choice of a site for a culvert where there is capacity to build a lowered spillway immediately adjacent to the culvert will allow controlled overtopping. This may be of benefit during low frequency high flow events. In this case, the spillway outlet should be armoured to counter erosion;
- as low light levels may affect the migration of certain fish species, it is recommended that any culvert fitted has no bends;
- all culverts should be checked regularly for the build up of debris or excessive sediment and maintained as appropriate.

8.2 Fish-friendly culvert designs

The process of installing culverts requires the consideration of several important issues, including fish passage requirements and the hydrological and physical characteristics of the site.

The various fish species present in the Auckland Region all have different swimming and climbing abilities. It is therefore possible to "custom build" in-stream structures to cater for the fish species present in a particular catchment, although it is important to ensure that there is suitable habitat for the species upstream of the culvert. Four basic designs are proposed (Figure 44):

- no-slope (stream slope);
- stream simulation;
- hydraulic design;
- climber design.

The no-slope (stream slope) design option (Figure 45 and Figure 46) requires few, if any calculations. It is the preferred option when both swimming and climbing fish require passage. The broad range of fish passage opportunities and the fact that the within-culvert environment is very similar to the natural stream environment have led some authorities to label it as being conservative. However, the larger size of culverts that are constructed using this design effectively avoid many of the problems caused by undersized culverts. In practice, this option will be limited to relatively short culverts in low gradient streams. The stream simulation design option (Figure 47) creates flow conditions inside the culvert that are similar to that of the natural stream channel found upstream and downstream of the structure. The slope cannot vary much from that of the natural channel. The hydraulic option (Figure 48) is designed using the velocity and depth requirements of target fish species and requires more complex calculations. It may not always be possible to manipulate the characteristics of a culvert to permit a hydraulic design at a site, especially at sites which have a sloping gradient. Finally the climber design option (Figure 49) makes use of the ability of many indigenous freshwater species (e.g., elvers and climbing galaxiids) to use the wetted margin to progress upstream. In terms of design, the climbing species option is the least restrictive but is only useful in high gradient streams where fish diversity is already limited.

Figure 44.
Fish friendly culvert design options.

Species that require passage	Culvert design (in order of preference)	Culvert specifications	Special requirements of design	Additional structures that may be required
ALL species (swimmers, anguilliforms, jumpers and climbers)	**NO-SLOPE**	**Length:** *short (<20 m?)* **Width:** *> average channel width* **Water depth:** *specific to largest fish needing passage* **Slope:** *same as stream (normally flat)* **Alignment:** *same as stream* **Water velocity:** *mean* $\leq$ *0.3 m/s* **Culvert invert:** *below stream bed*	None	None
Species known to be **PRESENT** only	**STREAM SIMULATION**	**Length:** *moderate to long* **Width:** *> average channel width* **Water depth:** *specific to largest fish needing passage* **Slope:** *low to moderate (similar to stream)* **Alignment:** *same as stream* **Water velocity:** *same as stream* **Culvert invert:** *below stream bed*	**Rocks** arranged and held on culvert floor to simulate the natural streambed	**Bed retention** devices (inside culvert) and **water/bed level control devices** (inlet and outlet)
TARGETTED species only	**HYDRAULIC** Miradrain™	**Length and width:** *length and distance between resting areas calculated to achieve passage* **Water depth:** *specific to largest fish needing passage* **Slope:** *calculated to achieve passage* **Alignment:** *straight* **Water velocity:** $\leq$ *0.3 m/s (50-100mm on sides)* **Culvert invert:** *at or below stream bed*	Culvert may require to be constructed from **corrugated materials. Spoilers or rocks** may be required on culvert floor to provide resting areas and reduce water velocities	**Low flow channel** and **water/bed level control devices** (inlet and outlet)
CLIMBING species known to be present only	**CLIMBER**	**Length:** *moderate* **Width:** *any, as long as wetted margin provided* **Water depth:** *wetted margin required* **Slope:** *<40°* **Alignment:** *straight* **Water velocity:** *low velocity, moist margin* **Culvert invert:** *at or below stream bed*	Ensure that the **entry and exit** of the culvert are **smooth. No breaks** along culvert. **Climbing media** may need to be installed within culvert	**Water/bed level control devices** (at inlet and outlet)

Figure 45.

Fish friendly culvert at Oteha Stream, with annotation to show the desirable features. Note that gradient is the same as the natural stream bed and support structure of arch avoids interference with natural river processes, such as flow, substrate movements and the movement of flora and fauna.

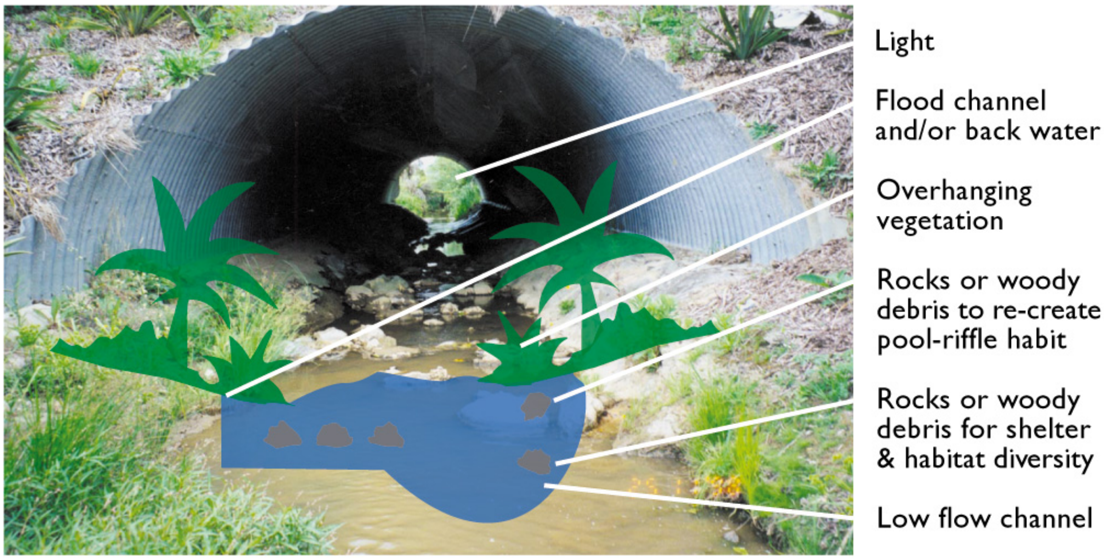


Figure 46.

No-slope design assessment diagram for culverts. All conditions need to be met before the design can be considered acceptable.

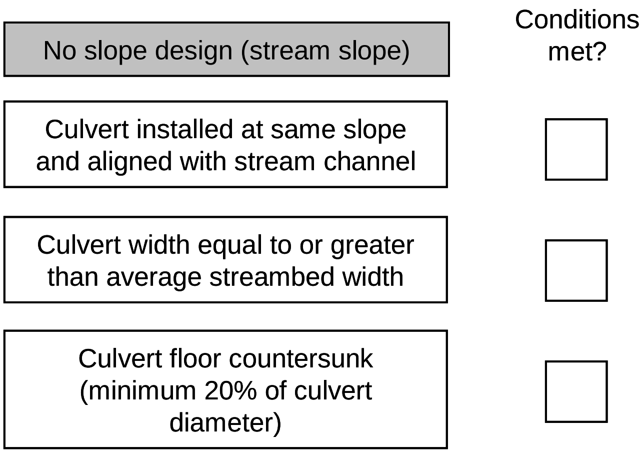


Figure 47.
Stream simulation design assessment diagram for culverts. All conditions need to be met before the design can be considered acceptable.

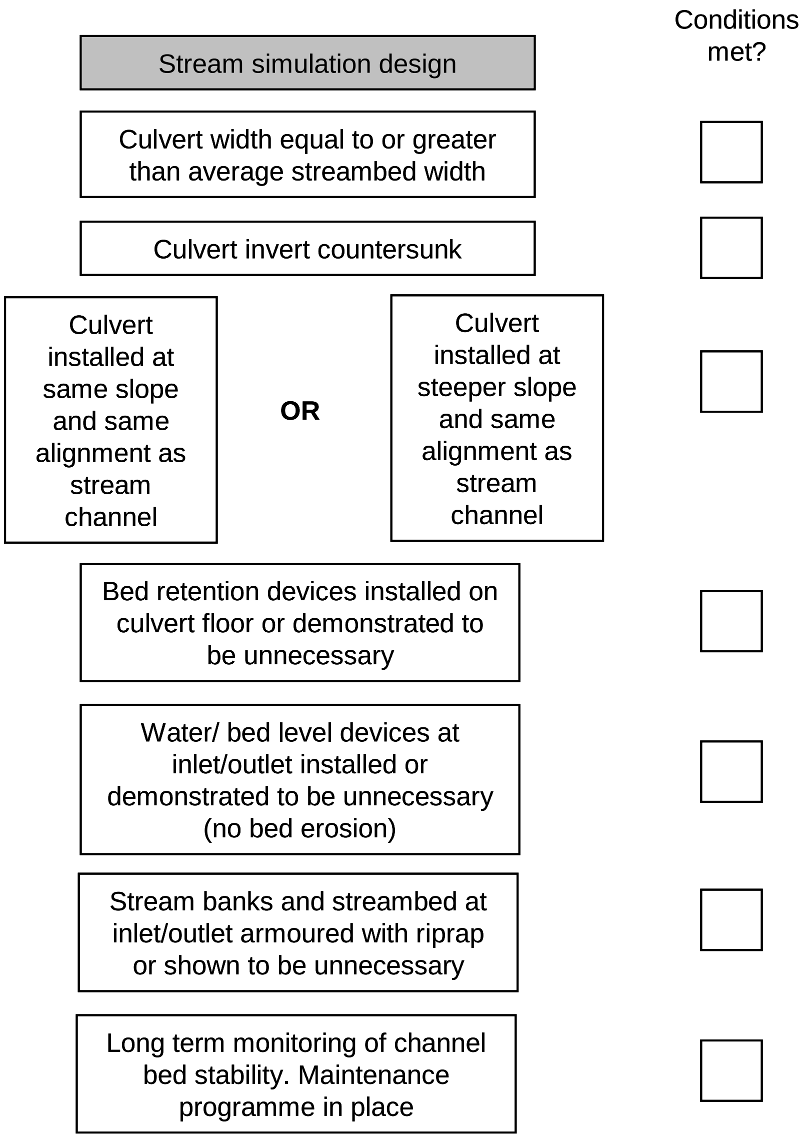


Figure 48.

Hydraulic design assessment diagram. All conditions need to be met before the design can be considered acceptable.

Hydraulic design	Conditions met?
Information on diameter, slope and length required	☐
Information on minimum and maximum flows, barrel velocities, fish species present and swimming capabilities of fish present provided	☐
Velocity and water depth estimate made and culvert shown to be negotiable by target species. Include design of any spoilers, baffles or rocks to be inserted to increase roughness	☐
Low flow channel in culvert floor provided or shown to be unnecessary	☐
Water/bed level control devices at inlet/outlet included	☐
Armouring of stream banks and streambed at inlet/outlet	☐
Short term monitoring plan devised, to determine if culvert is providing passage as predicted	☐
Long term monitoring and maintenance plan designed to ensure integrity of structure and to ensure passage retained over time	☐

Figure 49.

Climber design assessment diagram. All conditions need to be met before the design can be considered acceptable.

Climber design	Conditions met?
Entry and exit of culvert smooth (no breaks)	
Smooth, even surface within culvert with no breaks	
Climbing media within culvert barrel installed or demonstrated to be unnecessary	
Water level/ bed control devices at inlet/outlet installed	
Armoured stream banks and streambed at inlet/ outlet	
Short term monitoring plan devised to ensure that the culvert is providing passage as predicted	
Long term monitoring and maintenance plans devised to ensure integrity of structure (including erosion control measures at inlet/ outlet) to ensure passage measures over time	

8.3 Weirs

The construction of weirs and water bed/level control devices can be used to promote good fish passage conditions in a variety of situations. Low control notches should be included in all weir and water/bed control structures. Ideally ‘V’ shaped notches should be used as these provide both a wetted margin for climbing fish and a wetted channel for swimming fish that is present at all flows.

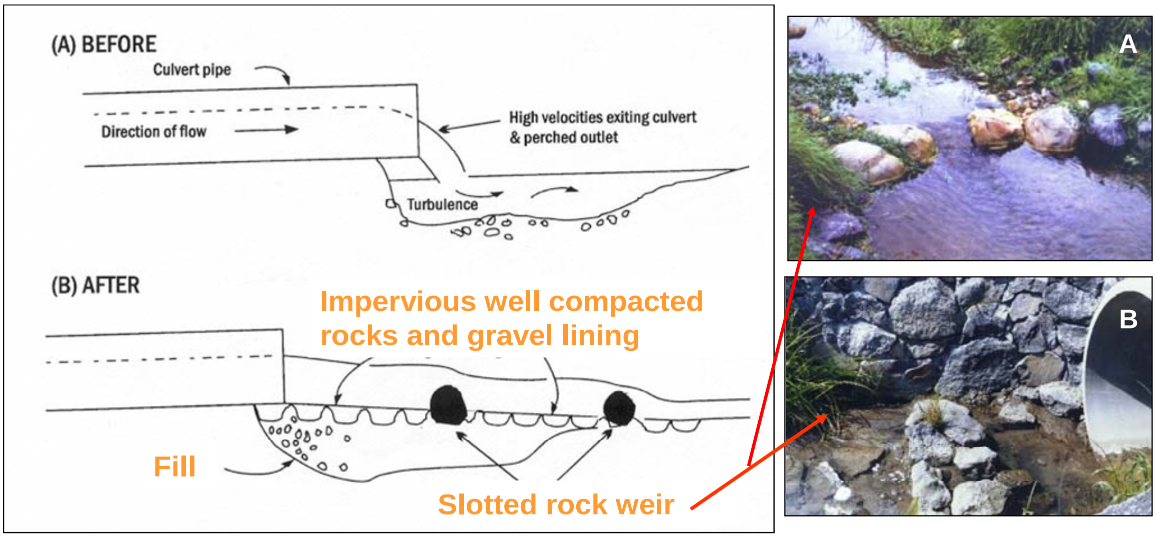
Rock revetments should always be constructed to prevent the banks alongside weirs or control structures from becoming washed out during high flows. These revetments should be designed to a height greater than the water level of the design flood.

8.3.1 Low weirs and water/bed level control devices

Even where best practice guidelines are followed (Section 8.1.1), engineering constraints at the site may result in a structure whose slope is greater than the stream slope and whose velocities are above acceptable levels. Water and bed level control devices may need to be used to enhance passage conditions both upstream and downstream of an in-stream structure. Hydraulic control devices can be used to anticipate and effectively prevent perching in culverts. For example, low weirs can be constructed to ensure backwatering of a culvert and also to mitigate against the effects of gradients that are too high (Figure 50). The presence of the weir will raise water levels at the outlet and create a pool which, if the pool is sufficiently deep, will encourage energy dissipation. The width of the basin should be around twice the diameter of the culvert to allow for energy dissipation without erosion downstream and to provide low velocity margins for swimming species. Depths greater than 0.3 m are recommended. The weir should provide passage for fish at low flows.

In addition to backwatering in-stream structures, low weirs can also be used to create low head dams, such as on farms, whilst still allowing fish passage. Weirs can be used individually or in series. Two types of weirs are most commonly used: rock weirs or concrete weirs. For rock weirs, the durability and effectiveness depends greatly upon the skill with which the weir is constructed. Large rocks should be used. Rocks with a rectangular profile will create a more stable structure than round rocks. Careful attention should be paid to how the boulders key together. To reduce permeability, rocks should also be concreted in position and rocks at the base of the structure should be buried across the streambed and river bank. In high energy watercourses where scouring may be a problem, it may be worthwhile burying further bed control structures within the stream bed so that control is maintained even as the scouring occurs. Ensuring that there is adequate spacing between weirs and other in-stream features (e.g., bedrock strata) is one way of reducing the probability of erosion occurring. Rock weirs can be constructed straight across the stream or can be curved (Figures 51 and 52) and constructed to point upstream producing a vortex weir, which will encourage scour below the apex of the weir whilst maintaining bed stability elsewhere. This may be beneficial in creating depth variation within the in-stream environment.

Figure 50.
Slotted rock weirs used to create resting pools (A) and flood the toe of a culvert (B).



Climbing species will follow wetted routes at the margins of the flow and it is important to ensure that there are appropriate continuous wetted areas available on the rock weir, at low and high flows. This could involve concreting some parts of the weir to make it impermeable. Low velocity marginal areas 50-100mm wide should also be provided for swimming species. Having areas within the weir where the water pools is also advantageous as it provides swimming species with additional resting areas.

Figure 51.
Plan view of a rock weir. Arrow shows direction of flow.

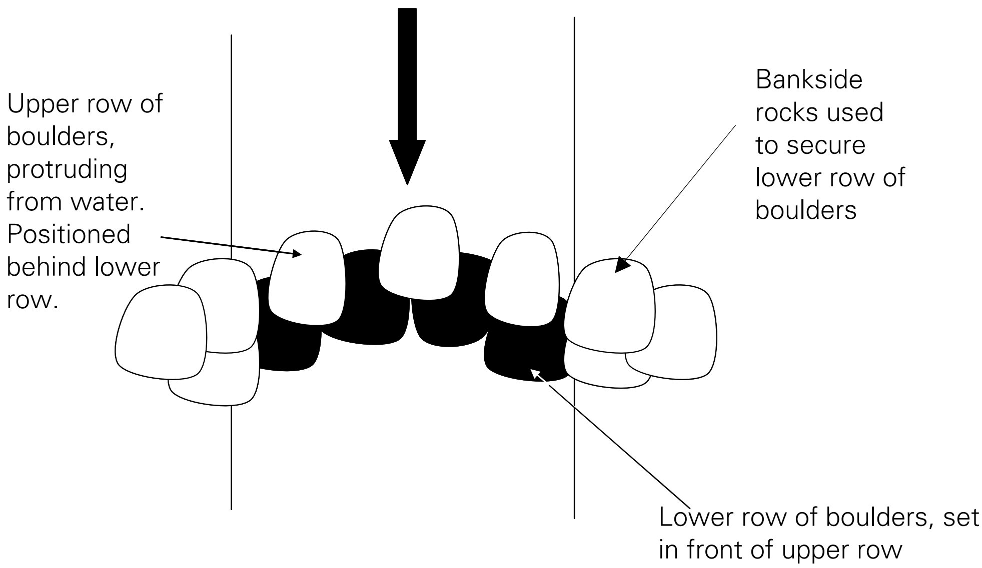
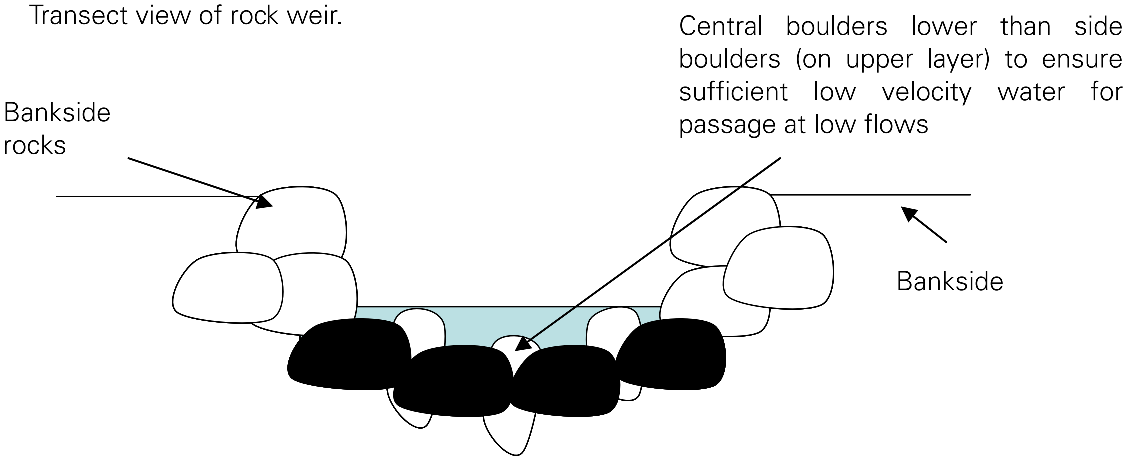


Figure 52.
Transect view of rock weir.



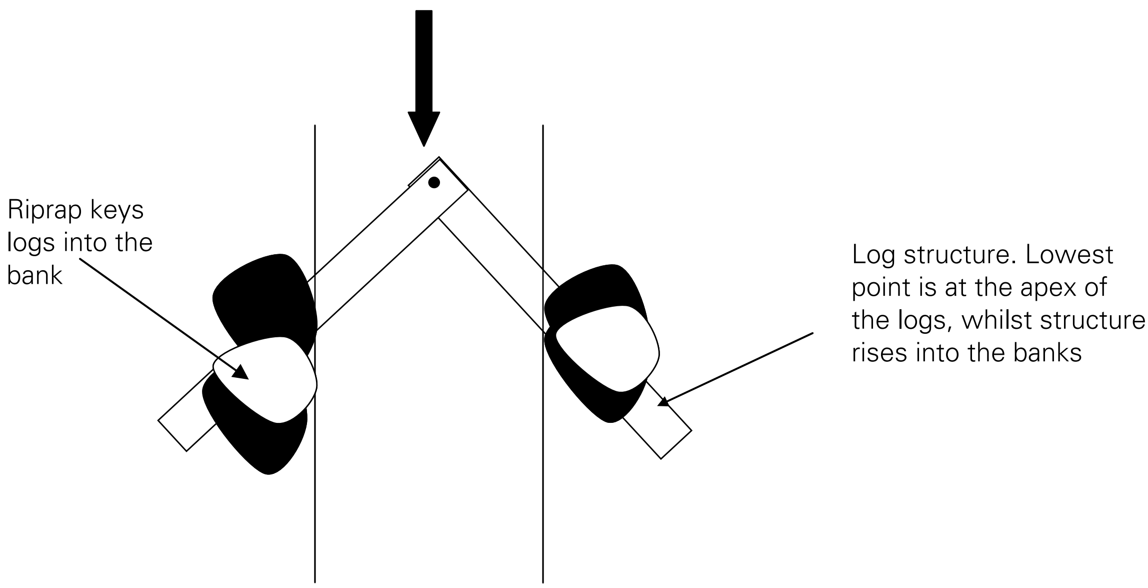
Concrete sill weirs (Figure 17) can be built at a steeper slope than rock weirs, however, concrete weirs do not offer the same diversity in terms of opportunities for fish passage as rock weirs, due to their structural simplicity. Therefore, these weirs are not recommended unless the design incorporates features to facilitate fish passage (see Section 8.3.2).

In situations where culvert replacement is being undertaken and a small diameter culvert is being replaced with a larger culvert, sediment may have accumulated upstream of the culvert site. The switch to a larger culvert could mobilize this material, resulting in downstream sedimentation, unless bed control devices are installed during culvert replacement to promote stabilisation. Bed control devices could include boulder weirs placed upstream of the culvert, which allow the channel to re-grade slowly. Two rows of boulders are generally advocated for grade control, with the lower row of boulders positioned slightly in front of the upper row (Figure 51). The upper row creates the crest over which the flow drops and the second prevents scour beneath the top row of rock (Figure 52). The upper row of rocks do not touch each other, with a space of one half to one third stone width between rocks. The upper row of rocks should protrude no more than 10-15% of the bankfull channel depth (SMRC 2008). In small, low gradient streams boulders should be sized greater than 0.5 m mean dimension and in large high energy streams, boulders could be as large as 1 m mean dimension. The rocks that are used to key the structure into the bankside should ideally slope up the bankside, to provide a wetted margin for climbing fish.

An alternative to using rock or concrete weirs for bed stabilisation in larger catchments could be the construction of log sills, with or without log abutments to key the logs into the bank. These multi-log sills (comprising a stack of 6 logs or more) span the entire channel and are fixed with piles into the stream bed, although the sides of the log also extend into the bank to provide additional stability. The stack of logs is buried in a trench beneath the stream bed with the uppermost log on the same level as the bed of the stream. The use of log abutments within the bank appears to reduce the opportunity for scour to undercut the structure. A variation on this weir is to construct a V-log structure. This structure is buried to stream bed level or below at the apex of the logs but rises into the streambanks, where it is secured with riprap (Figure 53). The velocity is concentrated in the centre of the stream by the shape of the structure and lower velocity marginal areas are provided at the stream edges. The gradual rise of the logs into the streambank may also provide a wetted margin that is suitable for climbing species.

Logs should only be placed on straight sections of the channel, should be notched to provide fish passage at low flows and must be anchored properly into stream banks (Figure 53). This may require boulders to be anchored to fixed features. Logs should be permanently submerged to resist decay. Double logs can be used to reduce the opportunity for scouring beneath the logs. In larger watercourses where multiple logs are placed in series, logs should not be placed closer than three times the channel width, as then the scour pool will extend to the next log which prevents bed material from accumulating and protecting that log. The design life of wooden structures is generally less than that of rock and concrete structures but logs are relatively low cost to install in comparison to the other structures.

Figure 53.
V-log structure used to stabilise the stream bed. Arrow indicates direction of flow.



Bed control measures should not be installed too close to the culvert inlet as energy dissipation from the control structure could remove the stream bed material that has accumulated within the culvert, resulting in an overall increase in mean barrel velocity. Grade control structures should be spaced no closer to the inlet than three times the channel width (Caltrans 2007).

Gabion baskets have been used in the construction of weirs but during low flows, the watercourse can effectively disappear into the rocks within the baskets, preventing fish from accessing the water. Therefore, gabion weirs are the least preferable material for constructing low weirs.

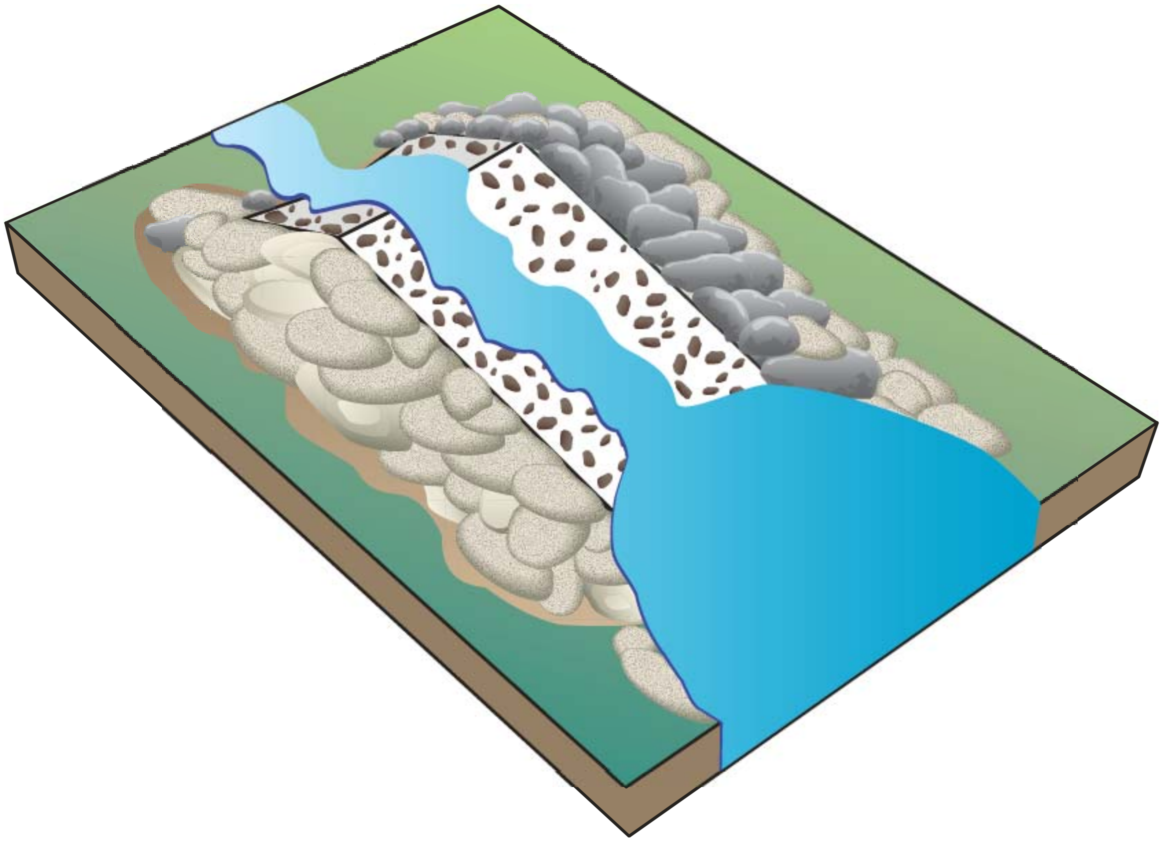
All weirs should aim to ensure that the difference in water levels between the weir and the watercourse downstream of the weir is no more than 7.5 cm (Section 4.3.1) as water level differences greater than this may restrict the passage of some swimming species.

8.3.2 'Crump-style' weirs

Gauging weirs can be a major obstacle to the migration of indigenous fishes. Stringent conditions are placed upon these weirs during construction, as they are required to meet very precise hydraulic requirements. These conditions may conflict with fish passage requirements. Crump weirs are one type of gauging station that is in common usage overseas. A Crump weir has a triangular profile in the direction of flow, with 1:2 upstream and 1:5 downstream slopes and provides stable hydraulic conditions for precise flow measurement.

There are indications that it may be possible to modify the traditional design of Crump weirs to accommodate New Zealand's weaker swimming indigenous fish species. In this 'Crump-style' modification, the slope of the weir remains the same, but the weir design is modified to provide a 'V' shape which extends along the full length of the downstream and upstream sloping weir faces (Figure 54). Following the principles outlined in Section 7, cobbles should be added to the downstream face of the structure to provide substrate roughness, which will reduce water velocities and provide resting areas for fish. The wing walls of the structure must be angled to provide low velocity wetted margins for climbing fishes at all flows. Maximum water velocities over the weir should be below 1.5 m/s which is within the burst swimming distance of most swimming indigenous fish.

Figure 54.
'Crump style' weir.



9 Acknowledgements

We would like to thank Takeshi Ito and Mark Roper, past students of the University of Waikato, for making the results of the flume study available.

10 References

ARC (2003). Design guideline manual for stormwater treatment devices. Auckland Regional Council, Technical Publication No. 10, July 2003.

ARC (2008). Culvert barrel design to facilitate the upstream passage of small fish. Auckland Regional Council, Technical Publication No. 366 , May 2008.

Baker, C. (2003). Effect of fall height and notch shape on the passage of inanga (*Galaxias maculatus*) and common bullies (*Gobiomorphus cotidianus*) over an experimental weir. *New Zealand Journal of Marine and Freshwater Research 37*, 283 – 290.

Baker, C.F. & Boubée, J.A.T. (2006). Upstream passage of inanga *Galaxias maculatus* and redfin bullies *Gobiomorphus huttoni* over artificial ramps. *Journal of Fish Biology 69*: 668 – 681.

Bannon, H.J. (2006). Effects of water quality parameters on prolonged swimming ability of freshwater fishes. Unpublished PhD Thesis, University of Waikato.

Beamish, F.W.H. (1978). Swimming capacity, in W.S. Hoar and D.J. Randall (Eds) Fish Physiology, Academic Press, New York pp. 101 - 187

Behlke, C.E.; Kane, D.E.; McLean, R.F. & Travis, M.D. (1991). Fundamentals of culvert design for passage of weak-swimming fish. State of Alaske, Department of Transportation and Public Facilities for the Federal Highway Administration. Report No. FHWA-AK-RD-90-10.

Bell, M.C. (1986). *Fisheries Handbook of Engineering Requirements and Biological Criteria*. United States Army Corps of Engineers, Fish Passage Development and Evaluation Program, Portland. 290 p.

Boubée, J.; Williams, E. & Richardson, J. (2000). Fish passage guidelines for the Auckland region. Auckland Regional Council, Technical Publication No. 131, June 2000.

Boubée, J.; Jowett, I.; Nichols, S. & Williams, E. (1999). Fish passage at culverts: A review, with possible solutions for New Zealand indigenous species. Department of Conservation, Wellington, New Zealand.

Caltrans (2007). Fish Passage Design Guide. Published by the Californian Department of Transportation.

Clay, C.H. (1995). Design of fishways and other fish facilities, Second edition. Florida, Unites States, CRC Press Inc, 248p.

Evans, B. & Glover, D. (1999). Barriers to fish passage in the Auckland Region: Identification of barriers and monitoring the effect on native fish migration. Internal Report, Auckland Regional Council.

FAO (1998). *Rehabilitation of rivers for fish*. Edited by Cowx, I.G. & Welcomme, R.L. Published by Fishing News Books, Oxford.

Hammer, C. (1995). Fatigue and exercise tests with fish. *Comparative Biochemistry and Physiology: Part A Physiology 112*: 1-20

Leong, D. (2007). Creating fish habitat: Mitigating the impact of long culverts. Presentation at the International Symposium of Ecohydraulics, Christchurch, New Zealand, February 2007.

Mitchell, C.P. (1989). Swimming performances of some native freshwater fishes. *New Zealand Journal of Marine and Freshwater Research 23*: 181-187

Mitchell, C.P. & Boubée, J.A.T. (1989). *Investigations into Fish Pass Design. Stage 1.* New Zealand Freshwater Fisheries Miscellaneous Report No. 50. MAF Fisheries, Rotorua

Mitchell, C.P. & Boubée, J.A.T. (1995). Evaluation of materials to allow fish passage past Huntly Power Station. Report to ECNZ by Mitchell and Associates. 10p.

Newbury, R.W. (1996). Dynamics of flow. In F.R. Hauer and G.A. Lamberti (eds.) *Methods in Stream Ecology*, Academic Press, San Diego, California pp. 75 - 92

Nikora, V.I.; Aberle, J.; Biggs, B.J.F.; Jowett, I.G. & Sykes, J.R.E. (2003). Effects of fish size, time-to-fatigue and turbulence on swimming performance: a case study of *Galaxias maculatus*. *Journal of Fish Biology* 63: 1365-1382.

SMRC (2008). Stormwater Manager's Resource Centre, Centre for Watershed Protection. http://www.stormwatercenter.net/ . Accessed 12/11/08.

Stancliff, A.G.; Boubee, J.A.T.; Palmer, D. & Mitchell, C.P. (1988). The upstream migration of whitebait species in the lower Waikato River. New Zealand Freshwater Fisheries Report 96. 44pp.

Williams, E.; Boubée, J. & Smith, J.P. (in prep.) Characteristics of in-stream structures obstructing the passage of indigenous freshwater fish species in New Zealand.

11 Appendix 1 – Calculate your culvert size

- ✓ **Determine the catchment area above the crossing.** This can be calculated using a NZMS: 1:50,000 topographic map, where one square on the map equals 100 ha. To calculate watercourse catchment area, identify the watercourse you are interested in and mark out all of the main stem and tributaries that enter the watercourse above the point at which you will install your culvert. Now find the most elevated contour that surrounds the main stem and tributaries of the catchment and mark this in on the map. If this is difficult to visualize, imagine standing by the proposed culvert site and looking upstream – you are drawing in the line used to describe the highest point at which water would run off the surrounding land and enter your watercourse.
- ✓ **Determine the rainfall for your catchment area.** This can be undertaken by comparing the catchment area of your watercourse to the maps provided by High Intensity Rainfall Data System (HIRDS) or by site specific rainfall data that you may have. Further details on rainfall and culvert information are also available from the Ministry for the Environment website at http://www.mfe.govt.nz/publications/land/culvert-bridge-oct04/culvert-bridge-oct04.pdf Where your catchment falls into more than one band, you should use the band with the higher rainfall.
- ✓ **Determine your culvert size.** Select the table for your catchment's rainfall band on the following pages (provided by the Ministry for the Environment). Then look for your appropriate catchment size within the table. The shaded column will tell you what culvert size you require.

Rainfall bands

VERY LOW RAINFALL	
Catchment size	Culvert size
5 ha	300 mm
10 ha	375 mm
15 ha	450 mm
20 ha	525 mm
30 ha	600 mm
40 ha	675 mm
50 ha	825 mm
100 ha	975 mm
150 ha	1200 mm
200 ha	1350 mm
250 ha	1600 mm
300 ha	1600 mm
350 ha	1600 mm
400 ha	1800 mm
450 ha	1800 mm
500 ha	1950 mm

LOW RAINFALL	
Catchment size	Culvert size
5 ha	300 mm
10 ha	450 mm
15 ha	525 mm
20 ha	600 mm
30 ha	675 mm
40 ha	825 mm
50 ha	900 mm
100 ha	1200 mm
150 ha	1350 mm
200 ha	1600 mm
250 ha	1800 mm
300 ha	1800 mm
350 ha	1800 mm
400 ha	1950 mm
450 ha	2100 mm
500 ha	2100 mm

Rainfall bands (continued)

LOW-MEDIUM RAINFALL	
Catchment size	Culvert size
5 ha	375 mm
10 ha	450 mm
15 ha	600 mm
20 ha	675 mm
30 ha	825 mm
40 ha	900 mm
50 ha	975 mm
100 ha	1350 mm
150 ha	1600 mm
200 ha	1800 mm
250 ha	1950 mm
300 ha	1950 mm
350 ha	2100 mm
400 ha	2100 mm
450 ha	2550 mm
500 ha	2550 mm

MEDIUM RAINFALL	
Catchment size	Culvert size
5 ha	375 mm
10 ha	525 mm
15 ha	600 mm
20 ha	675 mm
30 ha	825 mm
40 ha	975 mm
50 ha	1050 mm
100 ha	1350 mm
150 ha	1600 mm
200 ha	1950 mm
250 ha	2100 mm
300 ha	2100 mm
350 ha	2550 mm
400 ha	2550 mm
450 ha	2550 mm
500 ha	n/a

Rainfall bands (continued)

HIGH RAINFALL	
Catchment size	Culvert size
5 ha	450 mm
10 ha	600 mm
15 ha	675 mm
20 ha	750 mm
30 ha	900 mm
40 ha	1050 mm
50 ha	1200 mm
100 ha	1600 mm
150 ha	1800 mm
200 ha	2100 mm
250 ha	2550 mm
300 ha	2550 mm
350 ha	2550 mm
400 ha	2550 mm
450 ha	n/a
500 ha	n/a

VERY HIGH RAINFALL	
Catchment size	Culvert size
5 ha	450 mm
10 ha	600 mm
15 ha	675 mm
20 ha	825 mm
30 ha	975 mm
40 ha	1200 mm
50 ha	1200 mm
100 ha	1600 mm
150 ha	1950 mm
200 ha	2550 mm
250 ha	2500 mm
300 ha	2500 mm
350 ha	2550 mm
400 ha	n/a
450 ha	n/a
500 ha	n/a

Rainfall bands (continued)

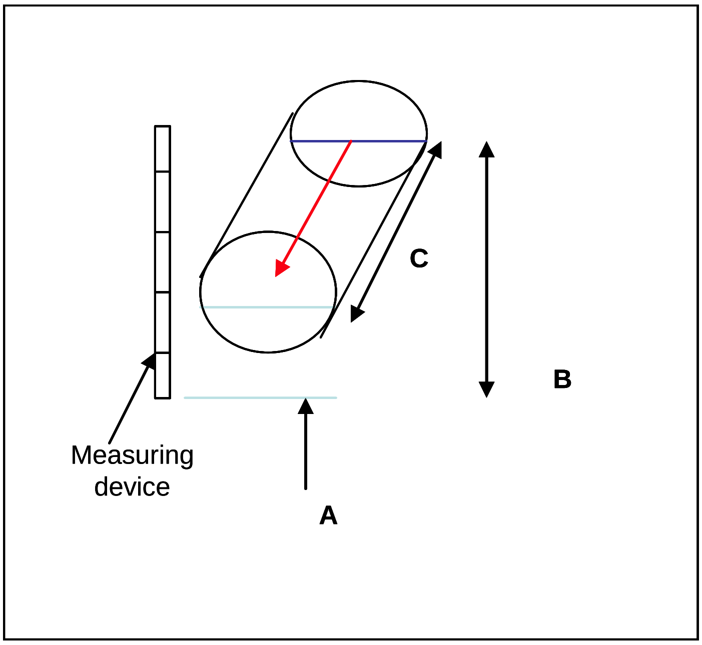
EXTREME RAINFALL	
Catchment size	Culvert size
5 ha	525 mm
10 ha	675 mm
15 ha	825 mm
20 ha	975 mm
30 ha	1200 mm
40 ha	1350 mm
50 ha	1600 mm
100 ha	1800 mm
150 ha	2550 mm
200 ha	2550 mm
250 ha	n/a
300 ha	n/a
350 ha	n/a
400 ha	n/a
450 ha	n/a
500 ha	n/a

12 Appendix 2 - Calculate your slope

To calculate the average slope, calculate the difference in height between the water level upstream of the culvert and the water level downstream of the culvert then divide this difference by the culvert length.

In practical terms, this can be done by positioning a measuring device (e.g., metre stick or tape measure) downstream of the culvert, measuring the downstream height and then reading the height of the water level upstream of the culvert from this device without moving position (Figure i).

Figure i.
Calculating the slope of a culvert. Measurement A demonstrates the downstream water level, Measurement B provides the upstream water level and the difference between these should be divided by length C and multiplied by 100 to give the slope of the culvert.



So, for a culvert that is 5 m in length and has a downstream water level of 0 m on the measuring device with an upstream water level of 0.4 m, the slope is:

$$\frac{0.4-0 \times 100}{5}$$

$$= 0.8 \quad \%$$

13 Appendix 3 - Calculate flow

A quick estimate of river flow for selected sites is available from http://edenz.niwa.co.nz/map/riverflow. Further information on flow is also available from the New Zealand Freshwater Fish Database (NZFFD) which can be accessed for free at http://www.niwa.cri.nz/services/free/nzffd .

To access flow information on the NZFFD, register as a user and run the set-up file (FISHDB.exe). Click on 'View' and choose 'Expanded stream network'. Now click on 'Map' and choose 'North Island/South Island' as appropriate from the drop down menu on the right hand size. Names of stream catchments and other features can be added to the map by selecting 'place names' from the view menu. Hold down the left mouse button and drag the mouse to select your catchment of interest, using the magnifying glass symbols to zoom in/out. When you have your catchment in clear view, click on the 'pointing finger' icon on the toolbar and then click on your catchment. The name and mean flow for your catchment will be displayed.

Please note that it is imperative that flow records are re-measured on site to ensure their accuracy and applicability prior to use.

14 Appendix 4 - Calculate your average culvert velocity

Once you have data on the size of culvert, the slope of the culvert and the expected flow, the average culvert velocity can now be calculated using the Culvert programme (included on an accompanying CD). To use this programme, you also need to know the length of the culvert, the diameter of the culvert and the Manning's Number of the material that the structure is constructed from (Table i). This data is entered into the first screen of the programme (accessed using the Properties tab). The Manning's Number of the material that the culvert is made from should be entered for bed as well as side walls. This will ensure that any design using that material is acceptable in terms of fish passage, even if no streambed forms within the culvert.

The target species should now be selected from the list on the right hand side of the page. If a range of species is expected to use the culvert, select the fish that migrates at the smallest size (and is therefore potentially the weakest swimmer) which will generally be common bullies or inanga.

Once this data has been entered, you must change the flow of the culvert. To do this, click on the set button in the 'Inlet and Outlet conditions' section of the first screen. This will bring up a second screen, which allows you to enter the flow through the culvert.

Once you have entered all this information, click on 'Model flow' on the toolbar and then scroll down through the output to the bottom where the output table will provide you with the fish passage parameters of the culvert and suggest ways in which the velocity may be reduced, if it is at an unacceptable level for your chosen species. If it is not within the range of your target species, you should alter your construction materials or develop a new design.

Table i.

Manning's roughness coefficient for channels and pipes with varying construction and bed materials.

Type of pipe/ channel	Manning's N
Concrete	0.012
Plastic	0.012
Clay	0.012
Ductile iron/ Cast iron	Min. 0.013
Corrugated metal 68 mm x 13 mm 76 mm x 25 mm 152 mm x 51 mm 229 mm x 64 mm	 0.029 0.032 0.04 0.044
Rubble set in cement	0.017
Earth, smooth no weeds	0.02
Earth, some stones and weeds	0.025
Clean, straight natural river channel	0.025-0.030
Weedy and winding natural river channel	0.075-0.150
Shallow gravel channels	0.025

15 Appendix 5 – List of suppliers

For spoiler sheets,www.rotationalplastics.co.nz

For information on bracket fish pass system, www.advancedtrafficsupplies.com

For Miradrain™ contact Geotech Systems Ltd, geotech@xtra.co.nz