

# **FISH PASSAGE AT CULVERTS**

A review, with possible solutions  
for New Zealand indigenous species

*December 1999*

NIWA

*Taihoru Nukurangi*

Department of Conservation

*Te Papa Atawhai*

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# CONTENTS

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Executive summary	v
1 INTRODUCTION	1
2 OBSTRUCTIONS TO FISH PASSAGE AT CULVERTS	2
2.1 Culvert environment	2
2.2 Culvert access and egress	2
2.3 Water depth	2
2.4 Barrel length and velocity	3
3 APPLICABILITY OF THE EXISTING INFORMATION	4
4 SWIMMING ABILITY	5
4.1 Swimming modes	5
4.2 Non-swimming modes	6
4.3 Fish length and swimming performance	6
4.4 Swimming ability of New Zealand fish	7
4.5 Water temperature and swimming performance	10
5 PRE-CULVERT CONSIDERATIONS	12
6 STREAM DISCHARGE	13
7 DESIGN CRITERIA FOR FISH PASSAGE	14
7.1 Culvert length	14
7.2 Culvert velocity	15
7.3 Assessing fish passage through culverts	16
8 CULVERT DESIGN AND INSTALLATION	18
8.1 Types of culverts	18
8.1.1 Arch culverts	18
8.1.2 Pipes	18
8.1.3 Box culverts	19
8.2 Culvert inverts	19
8.3 Inlet types	21
8.4 Gradient	24
8.5 Surface roughness	24
8.6 Alignment	25
8.7 Multiple barrels	27
8.8 Darkness	29
9 ANCILLARY STRUCTURES	31
9.1 Concrete aprons	31
9.2 Baffles	31
9.2.1 Commonly used baffle designs	33
9.2.2 Baffles and New Zealand species	39
9.3 Other barrel retrofits	41
9.3.1 Montana bedload collectors	41
9.3.2 Rebars	42
9.4 Inlet and outlet pools	44
10 ASSESSING AND INSTALLING FISH-FRIENDLY CULVERTS	49
10.1 Choice and positioning of structure	49
10.2 Fish-friendly culvert designs	49
10.3 Stream slope design option	50

10.4 Hydraulic design option	51
10.5 Stream simulation option	52
10.6 Climbing species option	53
10.7 Control of channel slope and retrofits	55
11 MONITORING	56
12 CONCLUSIONS	57
13 INTERIM RECOMMENDATIONS	58
13.1 Pre-culvert considerations	58
13.2 General culvert design	58
13.3 Further information required	59
13.4 Reporting	60
14 ACKNOWLEDGEMENTS	61
GLOSSARY	62
APPENDIX A Freshwater fisheries regulations 1983	A1
APPENDIX B Annotated bibliography, including references quoted	B1
APPENDIX C Proposed culvert evaluation form	C1
APPENDIX D Culvert characteristics checklist for sites where fish passage is required	D1
APPENDIX E Priority decisions for installation of a new in-stream structure	E1
APPENDIX F CULVERT.EXE software documentation	F1

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# Executive summary

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This joint NIWA/Department of Conservation publication reviews the literature on the effect of culverts on migrating indigenous and exotic freshwater fish. The applicability of passage solutions that have been devised elsewhere is discussed in terms of New Zealand conditions and species. Tests establishing the swimming ability of inanga and smelt, and limited trials of baffle designs potentially suitable for small New Zealand species, were undertaken. A culvert passage requirement checklist, construction checklist, evaluation procedure and computer assessment program were also developed. All users—whether they be scientists, industry, consultants, or consenting bodies—are encouraged to submit comments to the authors for incorporation into any future review and updates.

Over half of New Zealand's indigenous fish species migrate up stream at a small size. They are therefore poor swimmers in comparison to large salmonids, which most traditional culvert design criteria aim to protect. Because of their small size, New Zealand indigenous species are also more easily confused by turbulent flows, and their upstream progress can be hindered by roughness elements such as baffles that are often suggested to ease upstream passage. However, small fish need less water, so the width of the zone containing suitable velocities for fish passage can be reduced and therefore more easily achieved. Furthermore, many New Zealand indigenous species are good climbers and can negotiate very high-velocity zones by progressing along the wetted margin. For these climbing species, it may not be necessary to provide a low-velocity zone along the edge of the culvert; but ensuring the availability of a smooth, moist surface without breaks or sharp angles is essential.

When assessing whether fish passage is required at culverts, the following factors need to be considered (Section 5):

- presence of other migration barriers both up stream and down stream of the culvert;
- the composition and distribution of fish within the catchment;
- size and type of habitat available up stream;
- timing of fish migrations, duration, and flow requirements of the species concerned;
- altitude and distance from the sea.

Based on New Zealand observations and experience, the following interim recommendations are proposed:

- the culvert should be positioned so that its gradient and alignment are the same as the stream (Section 8.4 and 8.6);
- the culvert width should be equal to or greater than the average streambed width at the elevation the culvert intersects the streambed;

- the culvert invert should be set well below the current streambed (minimum of 20% of culvert diameter at downstream end) (Section 2.2);
  - weirs should be notched and impermeable so that a pathway over the weir is present at all flows (Section 9.4);
  - bed material should be assessed to determine the potential for downstream erosion. If erosion is likely, a weir, or series of weirs, should be provided down stream of the outlet. Such weirs could also provide pools that serve as resting areas, reduce culvert velocities by backwatering, and eliminate elevated outlets (Section 9.4);
  - armouring of the banks with riprap at the outlet and inlet may be required to prevent erosion (Section 8.6);
  - the average barrel velocity should ideally be below  $0.3 \text{ m s}^{-1}$ ; where this cannot be achieved, a 50–100 mm zone should be provided on either side of the culvert with velocities below  $0.3 \text{ m s}^{-1}$ ;
  - where average barrel velocities are greater than  $0.3 \text{ m s}^{-1}$ , smooth culverts provide a more suitable surface for climbing indigenous New Zealand species than ribbed ones (note, however, that ribbed culverts of the Polyflo™ type are useful for reducing barrel velocities while still providing resting areas for climbing species);
  - spoilers are useful for reducing barrel velocities as well as for providing resting areas. Such structures should only be installed where they will not cause obstruction of the culvert through accumulation of debris, and where site and engineering restrictions leave no other options (Section 9.2.1);
  - baffles are useful to ease passage of salmonids; but to ensure an uninterrupted pathway for indigenous species, they should not cut across the entire floor of the culvert (Section 9.2);
  - where low flows (and therefore shallow water depths) are a feature of the site, the apron, weir, or barrel floor (for large and box culverts) should be dished or sloped to concentrate flows (Section 9.1);
  - all junctions at the leading end of, and in between, the culvert components should be rounded to allow climbing species to pass (Section 10.6);
  - where the flow regime of the stream permits, in order to ensure the maintenance of a wetted margin the water depth should be no greater than 45% of the culvert height for the majority of the upstream migration period (Section 2.3).
-

## 1 INTRODUCTION

New Zealand possesses a relatively sparse freshwater fish fauna, with only 35 or so indigenous species, at least another 20 introduced, and half a dozen marine wanderers which periodically enter estuaries and lowland rivers. Of the 35 indigenous freshwater species currently recognised, 18 are diadromous and undergo migrations between fresh and salt water as a necessary part of their life cycle. Fish passage is therefore a significant issue in New Zealand, as natural barriers and inadequately designed in-river structures can prevent passage of migrant fish.

Generally consents for the construction of dams, culverts, and other in-stream structures are part of the regional councils' functions provided for under the Resource Management Act 1991. However, where the structures create barriers to fish migration, an approval or dispensation is required from the Director-General of Conservation pursuant to the fish regulations 1983 (see Appendix A).

The size of watercourse to be crossed and the costs associated with bridging structures have meant that single or multi-barrel culverts are often the preferred means of providing passage over streams. Traditionally, culverts have been installed with consideration for their hydraulic capacity, and little thought has been given to the needs of fish passage. In order to design culverts that do not impede fish passage, or to develop retrofit or facilities that will allow passage where there is an existing problem, further information on the requirements and behaviour of the various species and life stages is required. This information is essential to allow the Department of Conservation (DOC) to adequately assess applications for fish passage not only at culverts but also at other potential barriers.

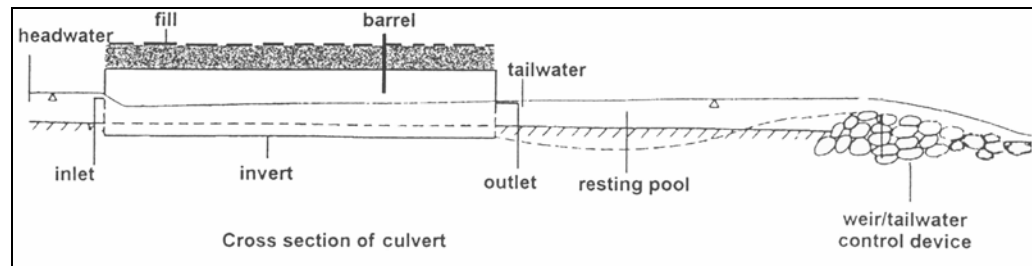
This publication collates existing information on fish passage and makes recommendations on the applicability of culvert passage solutions from outside New Zealand to local conditions and species. The report is primarily a review of the literature, but also presents the results of research undertaken to determine the swimming ability of inanga and common smelt. Limited trials using baffle designs suitable for small swimming species were made and the results, where relevant, are discussed. Guidelines for assessing fish passage at culverts, including a software programme, are provided.

All users (whether they are scientists, industry, consultants, or consenting bodies) are encouraged to submit comments to the authors for incorporation into any future review and updates.



## 2 OBSTRUCTIONS TO FISH PASSAGE AT CULVERTS

Traditionally, culverts have been installed with consideration of their hydraulic capacity, but with little thought for the needs of fish passage (e.g. WORKS 1988) (see Appendix B for annotated references). The installation of a culvert alters the hydraulic conditions of the stream at that location, and may also create upstream passage problems for fish, both within the culvert itself and at the inlet and outlet.



*Figure 1.* Culvert components. Note the outlet resting pool created by a riprap weir.

### 2.1 Culvert environment

One major fish passage problem with culverts is that their slope, construction material, and the constriction of the water flow into a smaller cross-section can increase water velocities above those occurring naturally in the stream. This increased velocity often exceeds the swimming capabilities of fish so that they are unable to move through the culvert. In addition, uniform conditions of gradient, roughness, and depth within the culvert can lead to an absence of low-velocity zones where fish can rest and recover after swimming to exhaustion.

### 2.2 Culvert access and egress

A second major problem can be the elevation of the culvert outlet. An outlet with the invert above the natural stream level, particularly if it is positioned above the water surface (Plate 1), is often an insurmountable obstacle for fish. This situation may result from either the way in which the culvert was initially installed or from subsequent erosion below it. In some circumstances, this may be a desired result to prevent the migration of certain species to upper catchment areas.

### 2.3 Water depth

Insufficient water depth in culverts has often been blamed for causing passage problems outside New Zealand. In very shallow water, depth can influence swimming

speeds because of the extra energy involved in the formation of a “bow” wave. This effect only occurs at depths less than three times a fish’s body depth, and affects burst swimming rather than sustained swimming. For example, in water that was 0.3 times the depth of a fish, swimming speeds about 30–50% lower than the maximum speeds attained in deep water have been measured (Webb et al. 1991).



**Plate 1.** *An elevated outlet created either by poor positioning at construction time, erosion from high-energy water exiting the culvert, or erosion from down stream.*

In New Zealand, many up stream migrating indigenous fish species are small, can spend a considerable amount of time out of the water, and have a good climbing ability. Therefore, shallow depths are not necessarily a problem and could even be exploited as a means of excluding the larger introduced species. However, to ensure that a climbing surface is available at the edges of culverts, water depth should not be greater than 45% of the culvert diameter for about 90% of the September–February migration period (see Section 6).

## **2.4 Barrel length and velocity**

Culvert length may be a problem for fish if the distance they can travel at any one time is restricted to less than the full length of the culvert. Even if the fish can maintain a stationary position between periods of forward movement, the high energy costs involved may mean that they become exhausted before they reach the end. In these situations, resting areas are required.

### 3 APPLICABILITY OF THE EXISTING INFORMATION

There is a large amount of international literature, predominantly from North America, on the topic of fish passage through culverts, which covers a wide range of interrelated biological, hydraulic and engineering considerations. This includes the characteristics and requirements of fish, features of the waterway and culvert site, and the design and installation of the culvert and any additional structures. The majority of the literature deals with the passage of large adult salmonids (e.g. coho, chinook, and sockeye salmon) which are strong swimmers and can jump small barriers. For relatively comprehensive references that examine culvert passage for salmonids, we recommend Dane (1978a), Baker and Votapka (1990) and Bates et al. (1999).

In contrast, New Zealand's diadromous indigenous fish species mostly migrate up stream as juveniles—some only 20 mm long (bullies). Some also have a good climbing ability (e.g. elvers, koaro, and banded kokopu) or make use of the boundary layer and interstices between substrate particles to progress up stream (Table 1). Due to these special characteristics, New Zealand's indigenous fish species have different requirements, making some commonly used criteria irrelevant. Nevertheless, information available for weak swimmers, such as Arctic grayling and salmonid fry, is applicable to non-climbing indigenous New Zealand fish species. There are also many general features of culvert design which are relevant to the passage of all fish species.

## 4 SWIMMING ABILITY

Swimming ability, water temperature, and especially behaviour influence the ability of fish to migrate up stream. For example, MacPhee and Watts (1976) have noted that breeding status may give fish greater motivation to surmount barriers, and found that ripe females were more successful at ascending culverts later in the spawning run. The swimming abilities of some New Zealand freshwater fish species are described in Table 1.

**Table 1.** *Swimming ability classification of some New Zealand freshwater fish species (modified from Mitchell & Boubée 1989).*

Swimming ability classification	Species
<b>Anguilliforms:</b> These fish are able to worm their way through interstices in stones or vegetation either in or out of water. They can respire atmospheric oxygen if their skin remains damp.	Shortfinned and longfinned eels, and to some extent juvenile kokopu and koaro. Torrentfish may also fit into this category, but they need to remain submerged at all times.
<b>Climbers:</b> 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). The freshwater shrimp, a diadromous native crustacean, is an excellent climber.	Lamprey, elvers, juvenile kokopu, koaro and shrimp. To a limited extent juvenile common and redfinned bullies.
<b>Jumpers:</b> 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, salmon, and possibly (on a scale of 20–50 mm) smelt and inanga.
<b>Swimmers:</b> Fish 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, and grey mullet.

### 4.1 Swimming modes

In order to design culverts that maximise fish passage, the swimming and climbing abilities of the fish moving through the culvert must be known. At least two arbitrary categories of swimming ability have been described:

- **sustained speed**—we have used the term sustained speed to describe the velocities that fish can maintain for long periods without fatigue (Hunter and Mayor 1986, Mitchell 1989). Also referred to in the literature as cruising and prolonged (Powers and Orsborn 1985, Bell 1986). Sustained speed has also been defined as the speed that can be maintained for periods of minutes without fatigue (Bell 1986).

- **burst speed**—can only be maintained for a matter of seconds and is used to escape predation and/or for feeding (Powers and Orsborn 1985, Mitchell 1989). Also known as darting speed (Bell 1986).

## 4.2 Non-swimming modes

In addition to swimming, several New Zealand indigenous species (such as eels and some galaxiids) have the ability to climb moist surfaces. This climbing behaviour gives the fish the ability to migrate over considerable barriers and penetrate far inland. It may be advantageous to capitalise on this feature to allow passage of fish at culverts, as some fish pass designs do (Mitchell 1993, Boubée 1995), but it may subject fish to increased predation and desiccation as they are exposed on a bare surface without easily accessible cover. Some fish species may also be classified as anguilliforms or jumpers, and may possess abilities that permit passage without having to consider water velocity and/or swimming ability.

## 4.3 Fish length and swimming performance

Fish use two sets of muscle for swimming: white muscles for darting (burst swimming), and red muscles for sustained (prolonged) swimming. A fish contains high volumes of white muscle tissue and relatively low volumes of red muscle tissue. White muscle has low rates of blood flow, and provides high power for a short time, but energy is quickly depleted or too much lactic acid is accumulated. By contrast, the supply of blood to red muscle is high, so that a fish can use these “low-power” muscles almost continuously, without oxygen deficit or lactic acid build up. The physiological differences between the muscle structures and functions suggest that there are two swimming modes, rather than the three categories into which swimming ability is normally divided. This discussion of swimming speeds therefore uses the term **sustained** to refer to the swimming mode where fish use their red muscles and **burst** to the mode where they use their white muscles.

Because New Zealand indigenous fish species migrate up stream at a small size, they have an even lower swimming ability than larger-sized species considered weak swimmers elsewhere (Table 2). Therefore, in absolute terms they cannot negotiate velocities as high as those species can, nor travel as great a distance between resting areas.

In a comprehensive review of fish swimming performance, Hunter and Mayor (1986) fitted logarithmic curves to swimming speed data from a number of authors to give two formulae that modelled the red muscle (sustained) swimming ability of fish and the white muscle (burst) swimming ability. The general relationship was of the form:

$$V_{fw} = aL^b t^c \dots\dots\dots(1)$$

where  $V_{fw}$  (the velocity of the fish in relation to the water) was the maximum velocity ( $\text{m s}^{-1}$ ) that could be sustained for  $t$  seconds by a fish of  $L$  length (in metres), and  $a$ ,  $b$ , and  $c$  were coefficients that depended on the fish species.

Typical sustained swimming speed relationships for some North American species are (Hunter and Mayor 1986):

$$\text{Sockeye salmon } V_{fw} = 4.46L^{0.63} t^{-0.1}$$

$$\text{Rainbow trout } V_{fw} = 3.28L^{0.37} t^{-0.1}$$

$$\text{Brook trout } V_{fw} = 2.71L^{0.52} t^{-0.1}$$

and for burst swimming:

$$\text{Coho salmon } V_{fw} = 13.30L^{0.52} t^{-0.65}$$

$$\text{Rainbow trout } V_{fw} = 12.3L^{0.52} t^{-0.51}$$

$$\text{Chinook salmon } V_{fw} = 11.49L^{0.32} t^{-0.5}$$

#### 4.4 Swimming ability of New Zealand fish

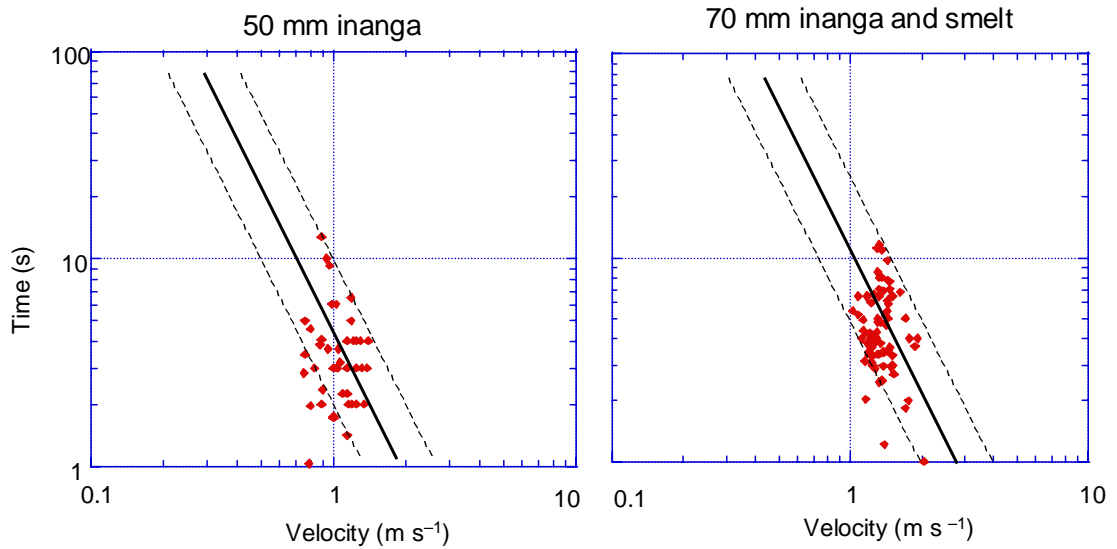
In order to establish similar relationships for inanga and smelt their burst swimming ability was tested in a 5-metre long culvert with a slope that could be altered. Fish were released at the bottom end of the culvert and their passage up the culvert timed until they either reached the top or were swept downstream. Initial tests with low gradients and velocities between  $0.3$  and  $0.7 \text{ m s}^{-1}$  indicated that the fish would stay in the culvert for 5–12 seconds and then swim downstream. Increasing the gradient and water velocity caused a change in behaviour so that, when released, most fish attempted to swim up stream at a fast rate, probably in the burst swimming mode. The performance of individual fish varied. Some fish did not try to swim up stream, whereas others only appeared to make a token effort. Smelt swam up stream, gradually slowed down until they were stationary, and then moved towards the sides into lower-velocity water before being washed downstream. Inanga swam quickly up stream and held position for a short time, before turning around and swimming downstream with the flow.

**Table 2.** *Swimming speeds, migration rates and velocity preferences of indigenous New Zealand freshwater fish species, and comparison with some North American data for weak swimmers.*

	Species	Speed (m s <sup>-1</sup> )	Comments	Source
<b>A</b>	New Zealand data			
	inanga (whitebait)	0.007–0.18	upstream migration gain in the Waikato River	Stancliff et al. 1988
	inanga (whitebait)	0.07–0.39	migration speed based on release and capture times of marked fish in estuary	Boubée et al. 1992
	inanga (adult)	≈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
		<0.15	water velocity which fish select and can easily negotiate	Mitchell and Boubée 1995
	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 steady speed (>30 s)	Mitchell 1989
	mullet (85–96 mm LCF)	0.12 0.20	sustained speed steady speed (>30 s)	Mitchell 1989
	mean NZ species <sup>1</sup> (excluding mullet)	0.20 0.32	sustained speed steady speed (>30 s)	Mitchell 1989
	-----			
<b>B</b>	North American data (Bell 1986)			
	elvers (100 mm)	0.0–0.15	sustained speed	
	mullet (13–69 mm)	0.14–0.46	burst speed	
	Arctic grayling (50–100 mm)	0.46–0.76	steady speed (minutes)	
	Arctic grayling (adult)	0.81–2.1	steady speed (minutes)	

<sup>1</sup> from observations obtained with juvenile shortfinned eel, common bully, common smelt, inanga, and banded kokopu

Tests were carried out with large inanga (average size, 72 mm), smelt (average size, 70 mm), and small inanga (average size, 50 mm). On average, the swimming velocity of large inanga was 27 % higher than small inanga, with small fish swimming at an average velocity of 1.07 m s<sup>-1</sup> and 72 mm fish at 1.35 m s<sup>-1</sup> (Figure 2). This suggests that the swimming ability of inanga is proportional to their length to the power of 0.63.



**Figure 2.** Relationship between maximum swimming velocity and time for inanga and smelt. The solid lines show the derived relationships according to the methods of Hunter and Mayor (1986) (95% confidence limits indicated by the dashed lines).

Relationships between time and velocity for both large and small inanga and smelt gave the following relationship for burst swimming speed:

$$V_{fw} = 14.4L^{0.63} t^{-0.43} \dots\dots\dots (2)$$

To establish the relationship that best represented the swimming ability of smelt and inanga in the sustained swimming mode, a power curve of velocity versus time was fitted to Mitchell’s (1989) experimental results for swimming durations longer than 2 minutes (Figure 3). In this analysis, it was assumed that the average fish size was 60 mm and that the swimming ability increased with the length of fish to the power of 0.63 (as found in the burst swimming mode). The relationship was:

$$V_{fw} = 5.29L^{0.63} t^{-0.16} \dots\dots\dots (3)$$

As very little difference has been found between the swimming ability of bullies, smelt and inanga (Figure 3), we believe that the above relationship can also be used to describe the performance of bullies swimming in the sustained swimming mode. However, the swimming ability of eels is lower than that of most other freshwater fish species because of their sinuous swimming motion. Mitchell (1989) found that shortfinned eels could swim at 0.2 m s<sup>-1</sup> for longer than 20 minutes and at more than 0.5 m s<sup>-1</sup> for a short period. Studies with the American eel (McCleave 1980) have shown that they swim at similar velocities. The linear relationship derived for burst swimming of eels is:



$$V_{fw} = 5.6L^{0.5} t^{-0.33} \dots\dots\dots (4)$$

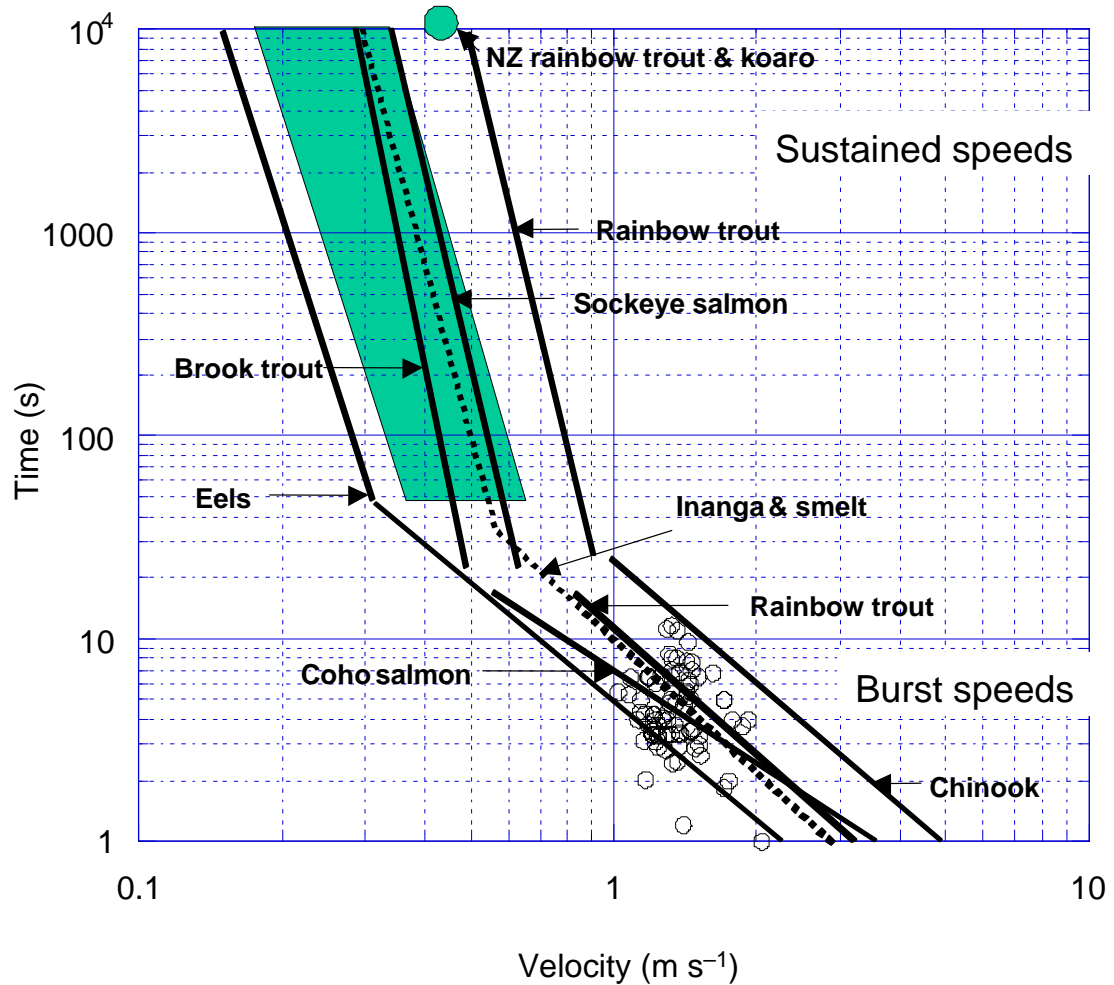
and for sustained swimming:

$$V_{fw} = 1.87L^{0.5} t^{-0.13} \dots\dots\dots (5)$$

#### **4.5 Water temperature and swimming performance**

MacPhee and Watts (1976) found that Arctic grayling were successful at ascending higher velocity culverts with increasing temperatures, and that swimming speeds also increased with temperature. An increase of 4–5°C resulted in increases in swimming ability of 12.2–17.8%. Furthermore, Brett and Glass (1973) showed that an increase of 5°C in water temperature increased the maximum sustained swimming speed of sockeye salmon by about 20%.

Watts (1974) suggested maximum allowable velocities be decreased by 35% or more at extremely high or low temperatures. It may therefore be important to match any tests of swimming speeds to predominant temperatures during the time of migration. However, no studies on the change in swimming performance of indigenous species with temperature have been undertaken; hence the importance of temperature on the ability of indigenous freshwater fishes to negotiate culverts remains speculative.



**Figure 3.** *Swimming speeds of New Zealand fish compared to swimming speeds calculated for North American fish species 70 mm in length. The New Zealand rainbow trout and koaro swimming speeds were measured by Moffat (1986). The shaded area represents common bully, shortfinned eel, smelt, banded kokopu and inanga swimming speeds for fish with sizes between 40 and 70 mm (Mitchell 1989). The circles show smelt and inanga (average size, 70 mm) burst speeds measured in this study, and the dotted lines are the derived swimming speed relationships for 70 mm smelt and inanga.*

## 5 PRE-CULVERT CONSIDERATIONS

From a review of the literature, the following points emerged as essential when considering fish passage requirements (also see Appendix E to assist with the decision process):

- **Presence of other migration barriers both up stream and down stream of the culvert.** This will determine whether fish passage is an issue—it may be pointless to ensure passage at a culvert if there are barriers just above or below it which cannot be overcome. These barriers may be anthropogenic in origin (such as dams and other culverts) or natural (like waterfalls and rapids).
- **Species and distribution of fish within the catchment.** The distribution of fish will indicate whether migrants pass through a reach to access waters higher in the catchment. Knowing which species are present (and thus their swimming abilities and behaviours) enables potential passage problems to be identified, and culvert location and design to be adjusted accordingly. There may also be good reasons for not allowing passage. For example, the presence of a rare or endangered species which may be compromised by allowing passage of a potential competitor, the risk of spreading a pest species, or the presence of toxic compounds that could bio-accumulate.
- **Size and type of habitat available up stream.** 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.
- **Timing of fish migrations, duration, and their flow requirements.** The timing of migrations can be used to determine the passage flow for target species, and to schedule culvert construction to minimise disruption to fish migration.
- **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 what species, if any, are present and at what densities is therefore essential.

## 6 STREAM DISCHARGE

North American studies have found that it is not necessary to provide passage during floods because fish do not move during these times<sup>1</sup>, instead taking shelter until waters recede. In some countries/states, the maximum discharge at which fish passage is required has been set as the level which is equalled or exceeded 10% of the time in the main six-month migration period, or 5% of the time in 12 months (Kay and Lewis 1970; Evans and Johnston 1974).

In New Zealand, the main upstream migration period for species with access to the sea is from about September to February, and it would be appropriate to design new culverts to allow passage over 90% of that time period. However, regardless of fish passage requirements, all culverts should be designed to accommodate the appropriate design flood events (e.g. Ministry of Works and Development 1975; Dane 1978a and 1978b; WORKS 1988). They should also be cost-effective, easily installed and maintained.

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<sup>1</sup> Note that this may not be the case with New Zealand indigenous species, but providing passage during flood events is unrealistic. We do not believe that the delay incurred during such flood flows will be significant, given the relatively long period over which migration occurs.

## 7 DESIGN CRITERIA FOR FISH PASSAGE

### 7.1 Culvert length

It is possible to calculate the maximum distance over which a fish in the swimming mode will be able to travel from the following formula:

$$D = V_f t = (V_{fw} - V_w) t \dots\dots\dots (6)$$

where:

$D$  = distance (metres);

$V_{fw}$  = the velocity of the fish relative to the water ( $\text{m s}^{-1}$ );

$V_w$  = the velocity of the water ( $\text{m s}^{-1}$ );

$V_f$  = the velocity of the fish relative to the ground ( $\text{m s}^{-1}$ );

$t$  = the time for which the fish is able to swim at  $V_{fw}$  before becoming fatigued (seconds).

For a fish to be able to progress up stream, the velocity of the fish relative to the ground must be greater than the velocity of the water.

Substituting equations 2 or 3 for  $V_{fw}$  in equation 6, then differentiating with respect to  $t$ , finds the value of  $t$  that gives the maximum distance a fish can swim. For example, for inanga and smelt of length ( $L$ ), swimming in the sustained swimming mode (equation 3):

$$D = (5.29L^{0.63} t^{-0.16} - V_w) t$$

$$t_{max} = \left( \frac{4.44L^{0.63}}{V_w} \right)^{6.25} \quad \text{and}$$

$$D_{max} = \frac{2130L^{3.94}}{V_w^{5.25}} \dots\dots\dots (7)$$

For white muscle burst swimming (equation 2):

$$D = (14.4L^{0.63}t^{-0.43} - V_w)t$$

$$t_{max} = \left( \frac{8.208L^{0.63}}{V_w} \right)^{2.32} \quad \text{and}$$

$$D_{max} = \frac{100L^{1.46}}{V_w^{1.32}} \dots\dots\dots (8)$$

Thus, for a given water velocity, the maximum distance that a fish can swim can be predicted (e.g. Figure 4). Furthermore, maintaining a zone with water velocities below  $0.3 \text{ m s}^{-1}$  would allow fish to travel through a culvert without needing to rest.

## 7.2 Culvert velocity

The average water velocity in a culvert can be calculated using Manning's equation (Henderson 1966):

$$V = \frac{R^{0.67} S^{0.5}}{N} \dots\dots\dots (9)$$

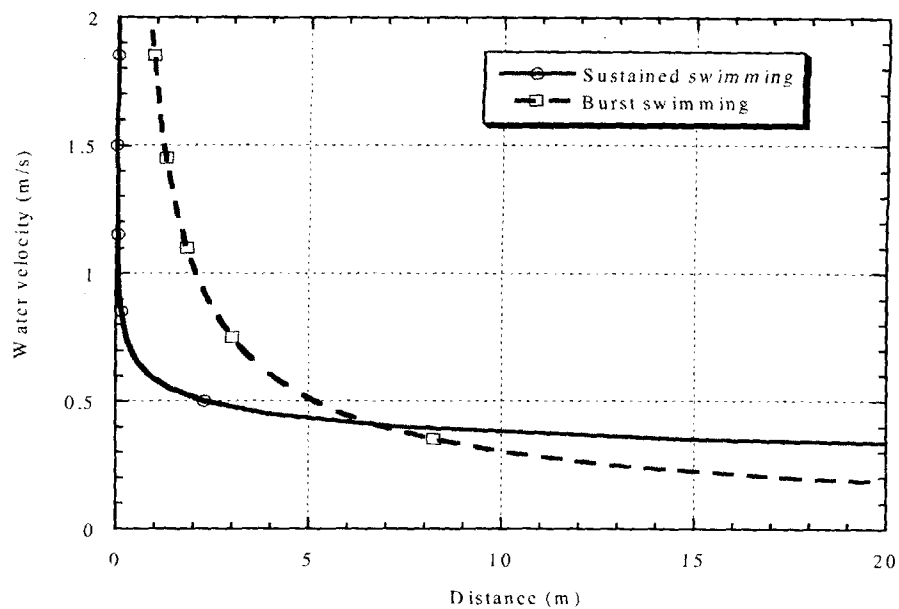
where:

V = mean water velocity ( $\text{m s}^{-1}$ );

R = mean hydraulic radius (metres). (Area of the cross-section of water ( $\text{m}^2$ ) divided by the wetted perimeter (m); the wetted perimeter is the part of the culvert perimeter in contact with the water);

S = slope or gradient (m/m);

N = Manning's roughness coefficient (See Appendix, F17).



**Figure 4.** Comparison of maximum swimming distances for large (70 mm) smelt and inanga, for sustained and burst swimming.

### 7.3 Assessing fish passage through culverts

To account for fish swimming ability, the diameter, slope and roughness of the culvert can be adjusted (equation 9) until the desired water velocity can be obtained for the average stream flow during the migration period. Where the mean water velocity cannot be matched to the target fish swimming ability, a zone should be provided along the full length of the culvert to allow fish passage.

The width and depth of the fish passage zone will depend on the species and size of fish concerned. Water velocities at the sides of culverts are always lower than those in the centre, and Behlke et al. (1991) have observed that swimming species make use of these zones to progress up stream. Ensuring that the velocity of these edge areas does not exceed the velocity of the fish through the water should therefore safeguard fish passage.

Behlke et al. (1991) estimated that for Arctic grayling, the velocity in the area where fish swim ( $V_{occ}$ ) is about 0.4 times the mean cross-sectional velocity ( $V_{mean}$ ) in the culvert, i.e.:

$$V_{occ} = 0.4 V_{mean} \dots\dots\dots (10)$$

We have observed that this criterion can be relaxed for New Zealand's smaller, juvenile upstream migrants and propose that a 50–100 mm zone with velocities below  $0.3 \text{ m s}^{-1}$  would ensure free passage of swimming fish species.

Based on our results, we developed a computer program to assess the ability of trout, inanga, smelt, bullies and elvers to negotiate culverts. A copy of the program and manual is given in Appendix F. Table 3 summarises the formulae that have been used in the program. As discussed in Section 4.4, the swimming performance of bullies has been assumed to be the same as that of inanga and smelt. Mitchell's (1989) data suggest this is a conservative assumption for sustained swimming speeds.

Where basic design modifications cannot be made to permit the target fish to traverse the culvert without swimming to exhaustion, resting areas will be needed (see Section 9.2.2). Alternatively, designs may exploit the climbing and anguilliform abilities of some New Zealand indigenous species.

**Table 3.** *Summary of swimming speed formulae for New Zealand fish, examples of swimming speeds that can be sustained for several hours by 70 mm fish, and burst speeds that can be maintained for 10 seconds by 70 mm fish. L is the fish length in metres, V is the water velocity in metres per second, and t is time in seconds. (Refer to Section 4 for source of material).*

	Trout	Eels	Inanga/smelt
• Sustained swimming speed ( $\text{m s}^{-1}$ )	$3.28L^{0.37}t^{-0.1}$	$1.87L^{0.5}t^{-0.13}$	$5.29L^{0.63}t^{-0.16}$
• Sustained swimming speed for 70 mm fish for 2.8 hours ( $\text{m s}^{-1}$ )	0.49	0.15	0.23
• Maximum sustained distance (m)	$5580 L^{3.7} V^{-9}$	$6.31 L^{3.9} V^{-6.69}$	$2130 L^{3.94} V^{-5.25}$
• Burst speed ( $\text{m s}^{-1}$ )	$12.3 L^{0.52} t^{-0.51}$	$5.6 L^{0.5} t^{-0.33}$	$14.4 L^{0.63} t^{-0.43}$
• Burst speed of 70 mm fish for 10 seconds ( $\text{m s}^{-1}$ )	0.95	0.69	1.00
• Maximum burst distance (m)	$28.2 L^{1.02} V^{-0.96}$	$27.07 L^{1.5} V^{-2.03}$	$100 L^{1.46} V^{-1.32}$



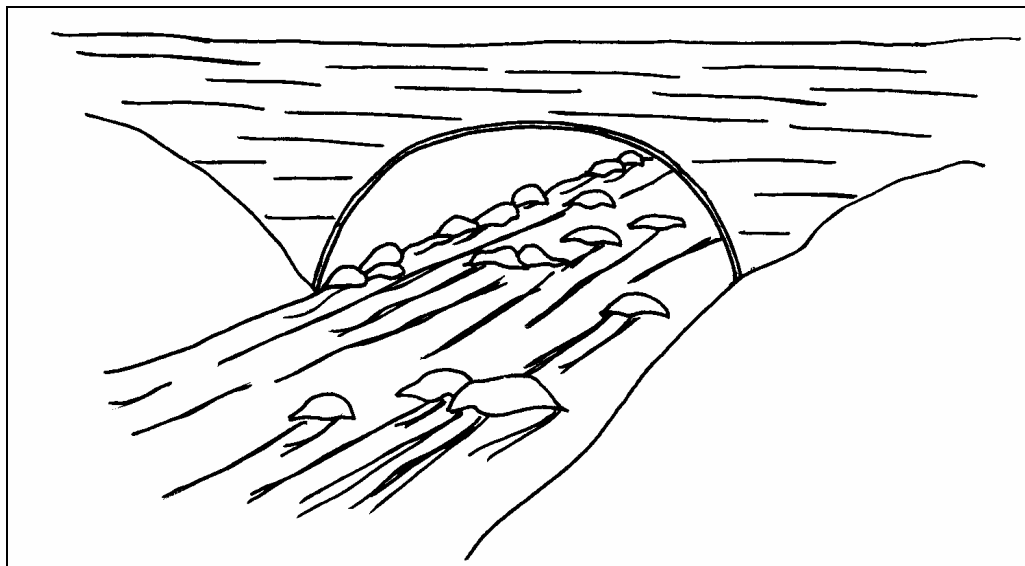
## 8 CULVERT DESIGN AND INSTALLATION

Fish passage is determined by the design and installation of the culvert. Wherever possible the design should replicate or simulate the bed and bank characteristics of the natural stream. Features to be considered include the bed material used and its configuration, gradient, cover, and distance between resting areas.

### 8.1 Types of culverts

#### 8.1.1 Arch culverts

Arch culverts (Figure 5) have the advantage of leaving the natural stream bottom in place, and the design is suitable for low cover depths. Care should be taken to avoid selecting a barrel that is too small, as this can lead to erosion. To prevent this potential problem armouring is sometimes included at installation, however care is needed so as not to remove the desired natural stream bottom particularly when paving or concrete is used (Dane 1978a and 1978b).



*Figure 5.* Arch culvert leaves the natural stream bottom and gradient in place.

#### 8.1.2 Pipes

If a pipe is used, then it should preferably have transverse corrugations to increase bed roughness and decrease water velocities. For small, New Zealand indigenous fish, however, observations have indicated that the waves generated by corrugations can confuse fish and can seriously hinder upstream passage. Bates (1992) also suggests that increasing roughness in culverts creates turbulence barriers to juvenile coho

salmon, and refers to a study in which such individuals were found to only utilise low-velocity boundary layers during low turbulence. Increased turbulence from increasing roughness was also found to decrease the velocity allowed in the occupied zone ( $V_{occ}$ ).

Mitchell and Boubée (1995) found that rolled sheet metal with corrugations at spacings commonly used in New Zealand culverts did not change bankside velocities significantly. However, they found that square projection profiles could be used effectively to provide resting areas between ridges. A commercially available product that appears to have similar characteristics to the square profile tested by Mitchell and Boubée (1995), is the ribbed Polyflo™ polyethylene culvert<sup>2</sup>. Preliminary tests with this product (see Section 8.5) have indicated considerably improved passage over smooth culverts.

### 8.1.3 Box culverts

Concrete box culverts can be placed next to each other, giving a large end area in low fills. This does not restrict the natural stream channel and is similar to a bridge in hydraulic characteristics (Dane 1978a). Generally, however, they are undesirable because of the higher velocities and the spreading of flows to shallow depths across their wide, flat cross-sections (Plate 2), though the latter may not be a problem for our indigenous fish given their small size, as well as climbing and anguilliform abilities. In streams with periodic low flows the culvert floor must be dished or made to slope to one side to maximise water depth.

## 8.2 Culvert inverts

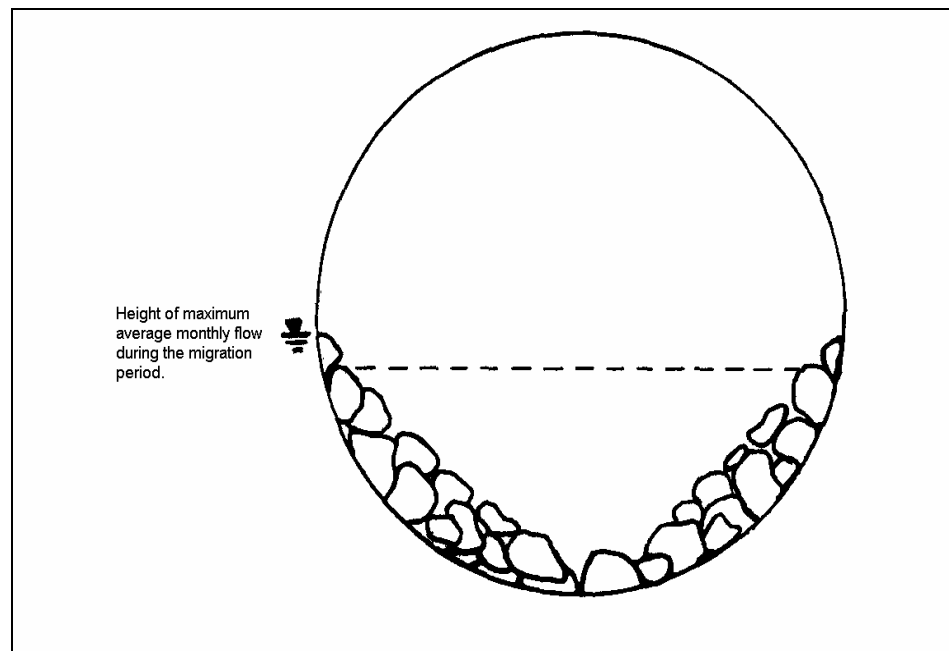
The level of the culvert invert relative to the streambed is the most important design criterion for fish passage. The culvert should be buried so that the bottom is filled with streambed material, which not only increases bed roughness but also imitates a natural stream bottom. Pipes under 3 m in diameter should be buried to a depth of 0.3–0.6 m, and those greater than 3 m to a depth of one-fifth of their diameter (Clay 1995). Filling the invert in a V-shaped profile will accommodate flows during low discharges (Figure 6).

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<sup>2</sup> Polyflo™ is the trademark of Promax Plastics, Maruata Rd, R.D.3, Glenbervie, Whangarei, New Zealand. Phone (09) 437 6864.



**Plate 2.** *Concrete box culvert. Note the wide cross-section resulting in a thin stream of water over the bottom, and the drop at the end of the concrete pad that is a barrier to swimming species.*



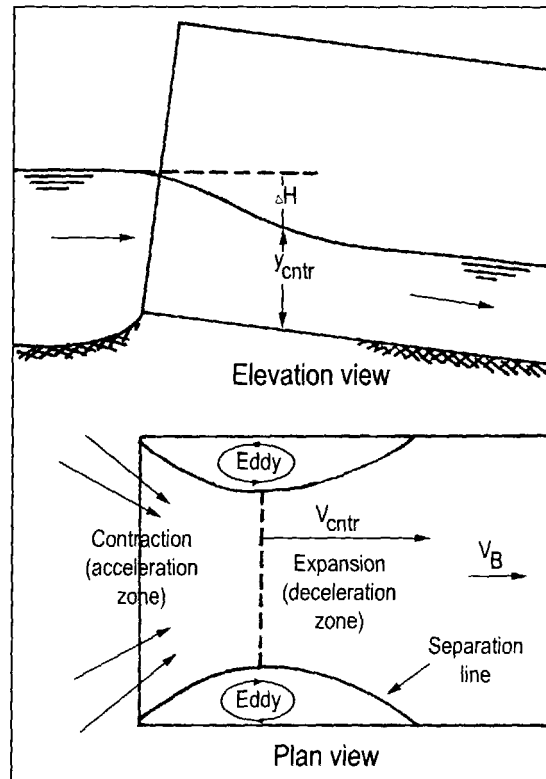
**Figure 6.** *V-shaped infill increases bed roughness and provides for periods of low flow.*

### 8.3 Inlet types

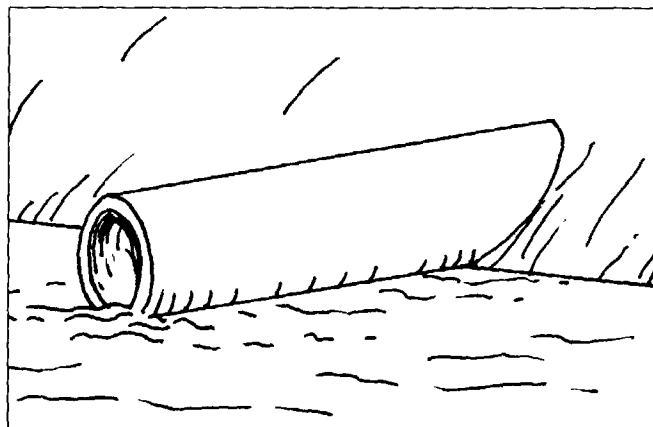
The traditional “non-fish friendly” culvert design typically has a cross-sectional flow area that is smaller than that of the stream approaching it. As a result, the velocity of the water entering the culvert is greater than that of the stream. The size of this velocity increase is influenced not only by the change in cross-sectional flow area, but also by the way in which the water approaches the culvert invert (Behlke et al. 1991).

The behaviour and speed of the water entering a culvert can vary depending on the type of inlet headwall in place. If streamlines of the water flow entering the culvert are bent, a horizontal contraction may occur just inside the entrance of the culvert, thus increasing the speed of the flow at the entrance. As the water continues down the barrel of the culvert, it loses kinetic energy and decelerates as the streamlines start to spread out and use the full width of the culvert (Behlke et al. 1991) (Figure 7).

Three main inlet types exist; the **projecting inlet** (Figure 8), the **vertical headwall inlet** (Plate 3), and the **bevelled inlet** (Plate 4). Each has different hydrological qualities, which can influence fish passage. The projecting inlet is generally considered to be the least hydrologically efficient of the three culvert entrance types. If the culvert is projecting into an inlet pool that is at least twice as wide as the culvert width, the flow area at the contracted section in the culvert is approximately three-quarters of the flow cross section down stream in the barrel (Behlke et al. 1991). This type of culvert inlet should never be employed or, if existing, needs to be modified. This can be done by either removing the overhang, rebuilding the banks to create a headwall type inlet, or (preferably) a bevelled inlet, which in turn will minimise the entrance contraction. To further reduce eddying and velocity jumps at the culvert entrance, it is possible to round the headwall using rocks and/or mortar (see Odeh et al. 1997).



**Figure 7.** *Water flow in culvert inlet zone.  $\Delta H$ , drop in water surface from inlet pool to contracted inlet section;  $y_{cntr}$ , depth of flow at centreline of culvert at inlet contraction;  $V_{cntr}$ , water velocity at centreline of culvert at inlet contraction;  $V_B$ , average water velocity in the culvert barrel down stream from inlet zone (redrawn with permission from Behlke et al. 1991).*



**Figure 8.** *Projecting culvert inlets create high entrance contraction problems and should not be used.*

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