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Culvert Barrel Design to Facilitate the Upstream Passage of Small Fish

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Culvert barrel design to facilitate the upstream passage of small fish

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1 Executive Summary

Culverts are routinely used to carry stream flows through embankments. However, many are poorly designed or badly installed and can present a significant challenge to fish migrating through river systems. Perched culverts are the most common design fault encountered in New Zealand but water velocities within culverts often exceed those naturally occurring in watercourses and can also create barriers to migration. Fish access through culverts can be key in determining fish distribution in the wider system. By ensuring the upstream passage of small fish, the passage of larger fish should also be assured.

Investigations into methods of facilitating the passage of small fish in small to medium sized culverts (<0.8 m diameter) were undertaken in an experimental flume using five substrate types, two gradients and two flow rates. Tests were carried out using both 'small' and 'large' pigmented inanga (*Galaxias maculatus*). 'Small' *G. maculatus* (<60 mm total length) were found to be able to swim a distance of between 5 m and 7 m in a culvert set at 3% slope, as long as a substrate which substantially reduced water velocities along the base of the culvert was present. Three substrates – Stripdrain™, Polyflo™ and herringbone baffles – performed consistently well in facilitating fish passage. Overall, Polyflo™ was judged to be the best substrate to use in constructing small culverts as it appeared to be easier to install and maintain in comparison to the other two substrates.

To address fish passage issues in large (>0.8 m diameter) culverts, a field validated computational fluid dynamic model was used to simulate baffle installation within a culvert. The results were used to determine which designs reduced water velocities to a level that could facilitate the upstream passage of *G. maculatus*. Various baffle shapes and conformations were tested in culverts of varying diameter and at differing flows with slope ranging from 0.76% to 1.2%. Results indicated that staggered rows of rectangular shaped spoiler baffles (of dimensions 0.25 m length x 0.12 m width x 0.12 m height), were the most effective at providing a continuous low velocity pathway within culverts ranging from 1.3 m to 4 m in diameter. The spoiler baffles performed best at low flows. At higher flows, although spoiler baffles generally reduced velocities on the culvert floor, small fish would need to burst swim in order to pass through sections of the array. The availability of regularly spaced low velocity resting areas within an array of spoiler baffles was therefore an important component of the design and the resting areas provided should be large enough to accommodate the largest target fish without compromising the passage of small fish. The number of spoiler baffles that need to be installed will depend upon the diameter of the culvert but in general the baffles should cover more than one third of the base of the culvert as this will allow resting areas on the margins to be retained at most flows.

Based on the modelling work undertaken, a spacing of 0.45 m between rows of spoiler baffles (gap between rows of 0.2 m) and lateral spacing of 0.12 m between the baffles was able to provide passage for small fish such as *G. maculatus* while still providing sufficient room for large galaxiids such as adult koaro (*Galaxias brevipinnis*) and banded kokopu (*Galaxias fasciatus)*. However, using this spacing and standard baffles, increases in gradient above 2% were found to reduce the amount of low velocity water (below 0.8 m/s) that was provided by the baffles. Based on these results, we do not recommend that spoiler baffles of these dimensions be used in culverts with gradients higher than 1 – 2% .

Sheets of moulded cuboid spoiler baffles (0.24 m length x 0.24 m width x 0.18 m height) at 0.62 m longitudinal spacing (0.38 m gap between rows) and 0.24 m lateral spacing have been used in the Auckland region as a means of improving fish passage through large culverts. There are concerns over the random use of these relatively large baffles because of the reduction in culvert capacity that they cause. These concerns would be mostly alleviated by using spoiler sheets moulded with smaller baffles described in this study.

Field studies would be required to investigate how spoiler baffles perform in rivers with high bed load and to determine if the advantages seen in a clean environment are maintained over time as bed material becomes trapped within the structure. Maintenance and flow capacity issues also still need to be assessed.

2 Introduction

Culverts are routinely used to carry stream flows through embankments. They are engineered to accommodate the range of normal flows as well as flood events and are often installed in preference to bridges as they are both less expensive and less time consuming to install. Therefore, culverts are an important part of the infrastructure that supports modern society. Although culverts are useful in water flow maintenance and flood prevention they have the potential to change the ecological characteristics of a watercourse (Warren and Pardew 1998; Blakely et al. 2006). Changes in local water velocity, habitat type/quality and stream bed continuity may mean that the presence of a culvert exerts a major influence on the distribution of aquatic organisms within the system (Baker and Votapka 1990; Baker 2003).

In New Zealand, over half of indigenous freshwater fish require access to both marine and freshwater environments in order to grow and reproduce. Some land locked species also require to migrate between different habitats in order to complete their life cycle. Presently, 20 indigenous and 11 non-indigenous fish species have been recorded within the Auckland region (Appendix 1). The majority of the indigenous fish are diadromous. The requirement for migration means that fish access through culverts can be key in determining fish distribution in the wider system and that culvert access problems can have a major influence on biodiversity and may even cause local extinctions. Occasionally, there are situations where restricting fish movements could be judged beneficial (for example, in the case of preventing a non-indigenous or invasive fish from increasing its range) but in general, fish access through culverts is desirable.

Swimming ability in fish is known to increase with size (e.g. Boubée et al. 1999). Furthermore, Nikora et al. (2003) have found that a fish of length L will probably not respond to turbulent eddies much smaller than L, but will react to eddies appreciably larger than L. Many indigenous fish species tend to be small (50 – 70 mm length) when they begin their upstream migration. This means that there is potential for even slight changes in the physical environment to affect their ability to move through a watercourse. By catering for the passage of small fish through culverts, the assumption is that larger fish will also be able to migrate without difficulty provided water depth is sufficient. Fish are generally known to have two swim modes – 'burst' swimming (which can only be maintained for short periods before the fish becomes fatigued) and 'sustained' swimming (which can be maintained for longer periods). The burst swimming speed of a fish species may restrict its ability to negotiate fast water, which may limit its distribution. In New Zealand, some fish can surmount obstacles by climbing (Appendix 2) and the differing needs of swimming and climbing fish should be recognised whenever fish passage is assessed.

This report provides guidance for the design of culverts so that passage of fish can be maximised. The report considers the engineering criteria for constructing 'fish friendly culverts' and improvements that could be made retrospectively in existing culverts of small (<0.8 m) and large diameter (>0.8 m) where the passage of small fish[1] in the 'swimming' mode is known to be restricted.

[1] For the purpose of this study, a small fish refers to species such as inanga (*Galaxias maculatus*). Results are expected to be valid for other small fish species that predominantly use the "swimming" mode to progress upstream (e.g. common smelt *Retropinnna retropinna*).

3 Facilitating fish passage

In a culvert, the primary aim is to maintain water flow. Culvert walls tend to be smooth without any roughness as this could potentially impede the passage of water or act as a surface for the attachment of debris, both of which could reduce the culvert's efficiency. Water moving through the smooth walled culvert environment is often characterised by areas of high water velocity, which may be uniform in nature. The lack of resting areas afforded by this uniform environment can be problematic for small fish attempting to ascend through the culvert. Uniform velocities are not usually found in a natural riverine environment, as the natural substrate on the river bed breaks up the flow of water resulting in areas of both low and higher velocities. Small fish tend to choose to follow a low velocity path through a natural river system and limit their exposure to higher velocity areas where burst swimming is likely to be necessary. Short periods of burst swimming may be acceptable during migrations as long as low velocity resting areas are available at appropriate distances.

Flow conditions will vary within a culvert dependent upon rainfall in the upstream catchment and the characteristics of that catchment (such as gradient, geology and land use). Some systems will naturally have sporadic flood events of short duration whilst others will have more regular high flow events, which may extend over a longer period. Culverts vary in terms of their diameter dependent upon the types of water flows that they are expected to accommodate. When flow/flood passage optimisation is the main objective, large diameter culverts are used.

To construct a 'fish friendly' culvert, it is best to consider fish passage requirements from the planning stage. Whilst it is possible to engineer a 'fish friendly' culvert at a later stage by the addition of ancilliary structures to the culvert, retrofits are expensive and often have limited success. The 'stream slope design' option, in which the culvert and watercourse have the same gradient and the culvert arches across the entire watercourse (Boubée et al*.* 1999) is an ideal design. This design avoids interference with natural river processes, such as water flow, substrate movements and the movement of flora and fauna. It is, however, recognised that existing culverts may have been constructed without consideration of fish passage requirements and that remedial work may be necessary. Full reviews of the designs that could be used to improve fish passage at culverts can be found in Baker and Votapka 1990, Boubée et al*.* 1999, ARC 2000 , Bates et al*.* 2003 and CALTRANS 2007. Most of these designs have been used in Europe and North America to ease the passage of salmonids through culverts but few cater for the small migratory fishes that are common in Australasia. In large culverts, the addition of ancilliary structures (to reduce barrel velocities) may not significantly reduce the hydraulic efficiency of the culvert (Baker and Votapka 1990). However, smaller culverts are more vulnerable to blockage with debris and the addition of baffles may increase this risk as well as restricting water flow and reducing hydraulic efficiency.

During flood conditions whose magnitude and duration may vary, it is accepted that it is unrealistic to expect fish passage through culverts to be ensured. In New Zealand as long as a culvert can be considered to be passable by small fish for 80 - 90% of the September to February migratory period, it can be classified as being 'fish friendly'.

3.1 Small culverts

Small diameter culverts (<0.8m diameter) tend to be installed on small streams, where they are traditionally judged to be of sufficient size to carry the existing flow. Regularly these small culverts are installed without consideration for flood flows, let alone fish passage. Small culverts are also difficult to access for retrofitting, modification and maintenance and therefore need special consideration.

Small diameter culverts are more vulnerable to blockage by debris than larger culverts due to their smaller cross sectional area. The addition of components within the culvert barrel with the intention of facilitating fish passage increases this risk, as it invariably reduces flow capacity, whilst the added component can act as an area for the attachment of debris.

Fish passage through small diameter culverts is however extremely important, as first order streams are often the only habitat within catchments that can still support the original fish fauna.

One possible means of ensuring fish passage at small culverts is to install a culvert that minimises barrel water velocity while minimising the risk of blockage. Boubée et al. (1999) reported that culverts constructed with corrugations reduced barrel velocities sufficiently enough to allow small fish (*Galaxias maculatus*) to travel up to four times further than was recorded in smooth culverts.

3.1.1 Experimental test of substrates

In order to investigate the types of substrate that may be most effective in facilitating small fish passage through small culverts, studies were undertaken using an experimental flume consisting of a 7.8 m pipe of 0.65 m diameter that could be tilted to alter the slope. Two slopes (3% and 5%) and five substrate types were tested: smooth, corrugated, herring-bone baffle, Polyflo™ and Stripdrain™ (Table 1, Figure 1). Flows of 0.004 m^3/s and 0.006 m^3/s were used, with these flows providing sufficient depth for the fish to swim in while still maintaining a wetted margin for resting.

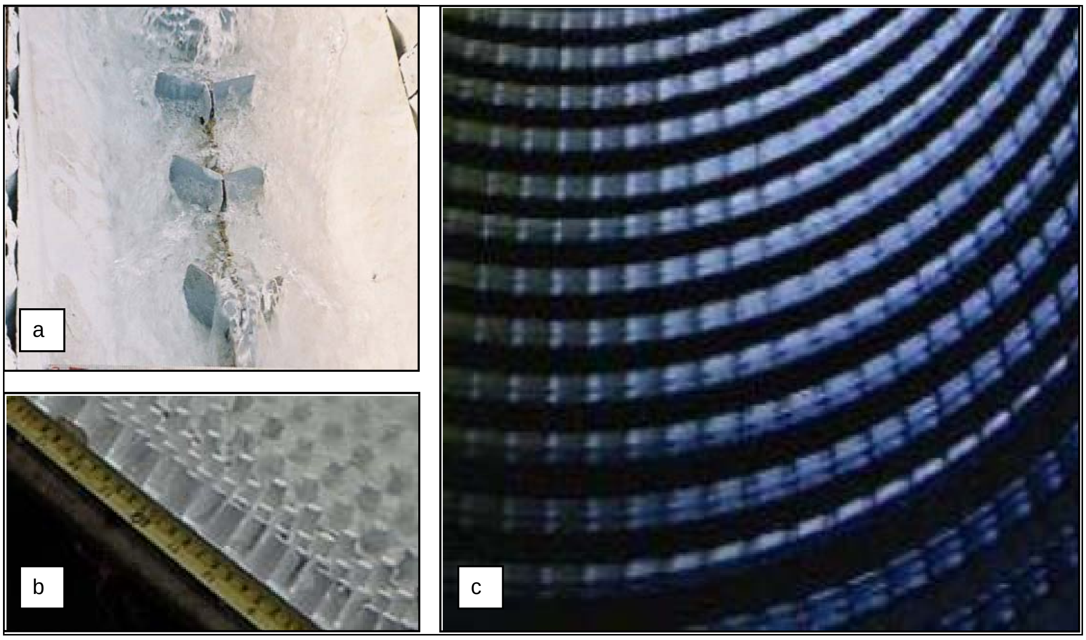
The test fish were pigmented *G. maculatus* ranging from 40 – 120 mm total length. These small indigenous fish are common in both New Zealand and Australia and use the swimming mode to progress upstream. The maximum water velocity that pigmented *G. maculatus* can negotiate without fatigue (sustained speed) has been reported as being between 0.30 and 0.34 m/s (Mitchell and Boubée 1995, cited in Boubée et al. 1999). Their burst swimming velocity ranges from 0.47 to 1.35 m/s (Mitchell 1989; Boubée et al. 1999). Given a choice, pigmented *G. maculatus* will choose to swim at velocities of about 0.07 m/s (Mitchell and Boubée 1995, cited in Boubée et al. 1999). The small size of the fish means that only a narrow low velocity zone (50 to 100 mm wide) needs to be present for fish to progress upstream with ease (Boubée et al. 1999).

Table 1:

Substrate types tested by Roper and Ito, (University of Waikato unpublished records) in a 650 mm wide circular experimental flume.

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
Stripdrain™	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 1:
Substrate type tested: a) herring-bone baffle, b) Stripdrain™ and c) Polyflo™.



Fish were assigned to a group based upon their size – 'small' (<60mm length) or 'large' (≥ 60mm length). Fish used in the experiment were collected from the Waikato River and tributaries of Raglan Harbour during the usual migration period (August to November).

Larger *G. maculatus* were generally found to swim further than smaller *G. maculatus* and all of the substrates tested facilitated passage compared to the smooth pipe (Figures 2 and 3). During their ascent, the fish were observed to swim back and forth until they found a path within their swimming ability. With the Stripdrain™, once fish had found a lane with manageable velocities and appropriate water depth, they continued to swim up the flume without needing to move laterally, thus maximising the distance they could travel before tiring.

Based on the characteristics of the substrate it was expected that velocities would decrease, water depth increase, and hence passage improve in the following order: smooth, herring-bone, corrugated, Polyflo™ and Stripdrain™. Certainly, of the five substrate types tested, Stripdrain™ was found to be the most effective for 'small' *G. maculatus* in terms of greatest mean distances travelled (Figure 2). The Stripdrain™ structure is therefore the best at easing *G. maculatus* passage, but the improvement compared to the other roughed surfaces was small at a slope of 3% or less.

Figure 2:

Mean distance travelled by 'small' *G. maculatus* (<60 mm total length) in a 7.8 m pipe of 0.65 m diameter fitted with differing substrate. The number of fish tested for each experiment was 40, apart from 3% slope and smooth substrate where over 60 fish were tested. Error bars show one standard deviation. Means with same letter are not significantly different from each other (ANOVA, $P < 0.001$) (Roper and Ito, University of Waikato, unpublished records).

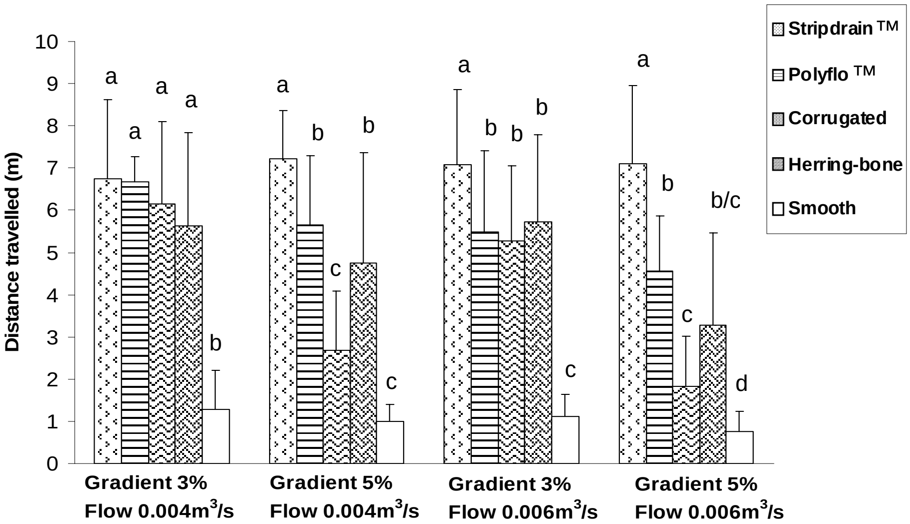
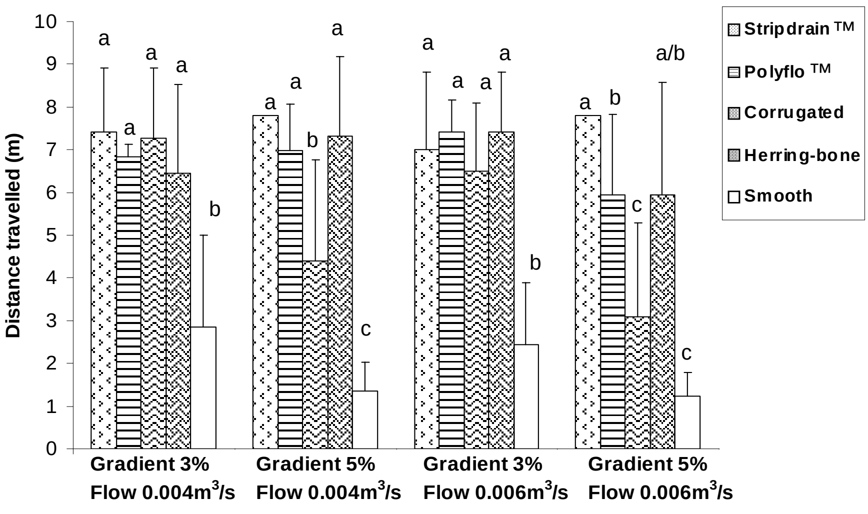


Figure 3:

Mean distance travelled by 'large' *G. maculatus* (≥ 60 mm total length) in a 7.8 m pipe of 0.65 m diameter fitted with differing substrate. The number of fish tested for each experiment was 40, apart from 3% slope and smooth substrate where over 60 fish were tested. Error bars show one standard deviation. Means with same letter are not significantly different from each other (ANOVA, $P < 0.001$) (Roper and Ito, University of Waikato, unpublished records).



Overall results indicated that passage success for 'small' and 'large' *G. maculatus* was very similar with Polyflo™, Stripdrain™ and even herring-bone baffles. The corrugated substrate also facilitated passage but was distinctly less successful at the higher gradient (possibly because the roughness element in the product tested was relatively small). Therefore, all of the substrates are suitable for facilitating fish passage in small culverts. However, the production, installation and maintenance issues for the substrates are very different. Culverts which contain either herring-bone or Stripdrain™ structures are more complicated to construct and install than Polyflo™ and their profiles more prone to debris trapping. Conversely, both can be retrofitted to an existing culvert thus saving on the cost and inconvenience of replacement. Stripdrain™ has a further disadvantage over the other substrates tested, in that larger fish such as adults of the other galaxiid species, as well as lamprey, are unable to fit in the spaces between the cones of the existing product. To be effective, therefore, this type of substrate would need to have the cones at spacings of 40 – 50 mm. Upon consideration of all of these factors, the Polyflo™ pipe (or equivalent) appears to be the best solution to ease fish passage in small diameter culverts. It is important to note, however, that to maximise fish passage, either water velocities 50 – 100 mm from the culvert walls need to be below 0.3 m/s, or the culvert at base flow needs to have an effective wetted margin to provide fish with resting areas (essentially base flows should fill no more than one third of the culvert circumference).

In the experiment carried out at 3% slope, 'small' *G. maculatus* were on average able to traverse close to 5 m of culvert before swimming to exhaustion and falling back. To maximise passage of *G. maculatus* over a longer distance, either the slope must be reduced or resting pools have to be provided. Based on the experiment undertaken at 3% slope, it would be advisable to have pools at 4 to 5 m intervals. If such resting pools cannot be created, slope needs to be reduced. This is discussed in more detail in Section 3.2.3.2.

3.2 Large culverts

Large diameter culverts (>0.8 m) are not as restrictive to work in as smaller culverts and due to their larger cross sectional area, can be fitted (or retrofitted) with a greater variety of ancilliary structures to facilitate fish passage. Examples of structures which could be added to improve fish passage include offset baffles, spoiler baffles, side baffles, fish weirs and weir-baffle systems (Boubée et al. 1999).

3.2.1 Pilot modelling study

3.2.1.1 Baffle design

To investigate the effects of introducing structures such as spoiler baffles, weirs and rings into culverts, FLOW-3D (Flow Science Inc. Version 8.2), a computational fluid dynamic simulation model available at the University of Innsbruck, Austria, was used

(Kopeinig 2004). The model was calibrated by taking measurements within an existing bare culvert and in the same culvert fitted with spoiler baffles.

Measurements for the calibration were taken in a culvert situated at Thompson Road drop structure on Cardinia Creek, Melbourne, Australia (Figure 4). The 30 m long, 1.35 m diameter ARMCO culvert, was constructed of steel with transverse corrugations of 76 x 25 mm and had a gradient of 1.19%. Wooden rectangular spoiler baffles (dimensions 0.25 m length x 0.12 m width x 0.12 m height) were placed in the culvert in a variety of arrays but for the purpose of the calibration the conformation shown in Figure 5 was used. Within this array, variations of water velocities with depth were taken at regular interval across and along the culvert with a Marsh McBurney Model 2000 flow meter. These readings were then compared with the output from the model.

Figure 4:
The test culvert at the Thompson Rd drop structure, Cardinia Creek, Melbourne, Australia.

Obtaining measures of depth and velocity at a precise location within a culvert is very difficult but overall, modelled values were in close agreement to the field measurements (Figures 6 and 7). With the model validated, it was considered appropriate to use it to simulate conditions that would exist in a culvert fitted with other conformations of spoiler baffles and other types of baffles.

Figure 5:

Plan view of the spoiler baffle arrangement used in the validation trial. The culvert was 1.35 m wide and had a slope of 1.19%. (Dimensions shown are in metres.)

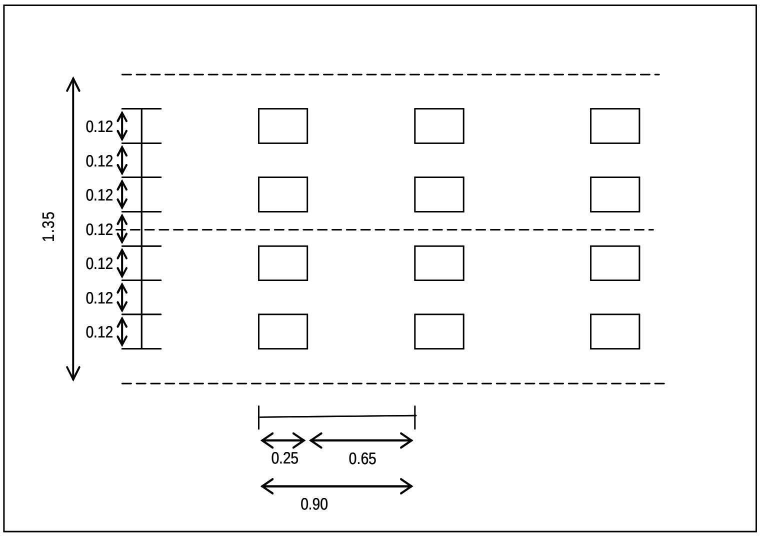


Figure 6:

Cross section through the test culvert fitted with spoiler baffles as depicted in Figure 5. The cross section is 0.05 m downstream of spoiler baffle row No. 16 and the flow is 0.11 m^3/s. The coloured band at the top of the figure gives the water velocity range modelled (red = 1.50 m/s, blue = 0 m/s). The curved black line in the middle of the flow is drawn at 0.60 x water depth and actual velocities and modelled velocities (in m/s) along this line are displayed. The occasional poor agreement between the modelled and actual values is expected to be caused by the model being more precise than it was possible to measure in the field.

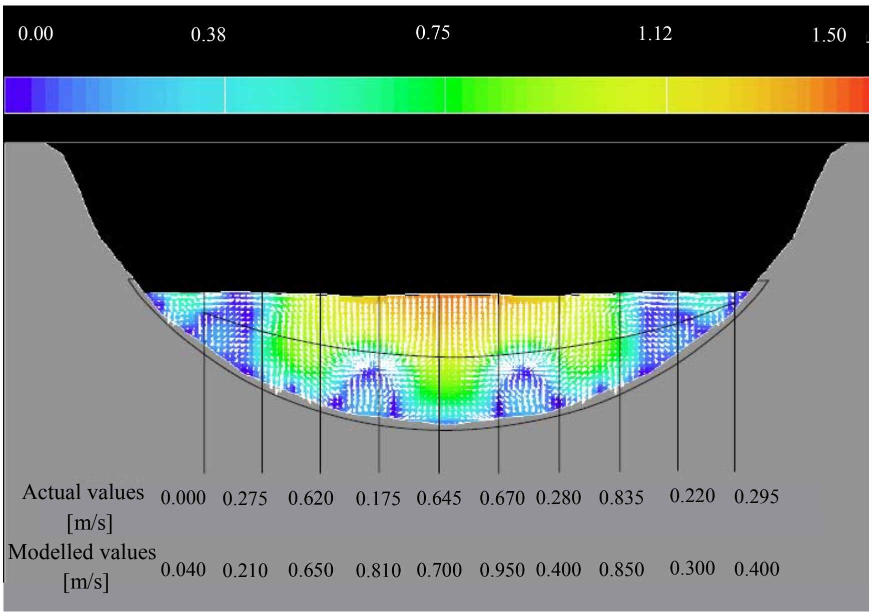
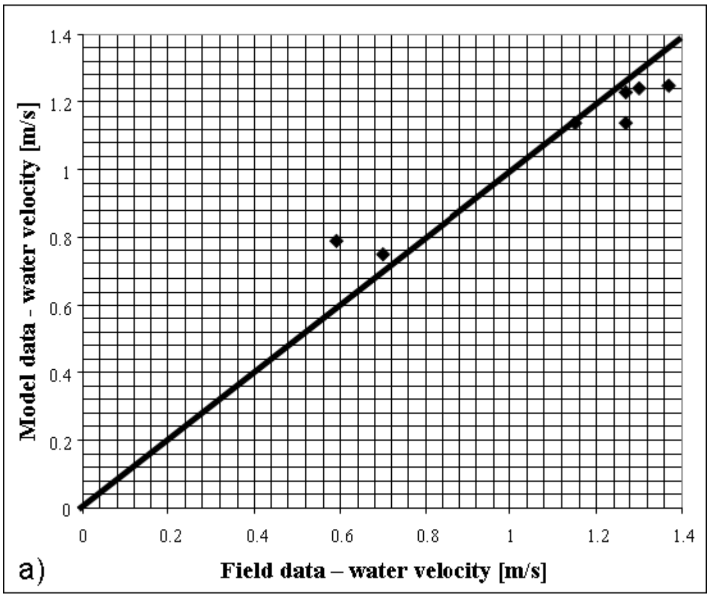
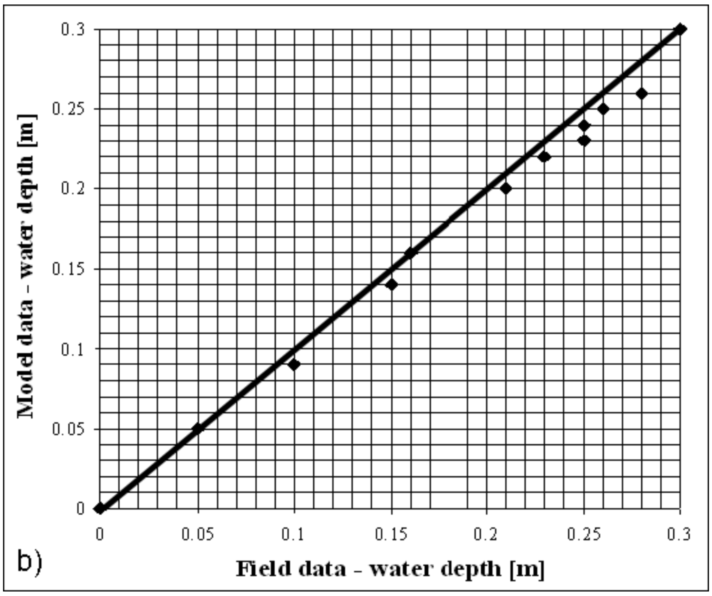


Figure 7:

Validation plots for water velocities and water depth. Plot **a)** shows water velocity in corrugated bare culvert at a cross section 1.00 m upstream of the outlet. Plot **b)** shows water depth at a cross section 0.05 m downstream of spoiler baffle row No. 16 (see Figure 5 for description of baffles).





The fish species chosen to determine if an arrangement of baffles could potentially assist the passage of small fish was again *G. maculatus*. Historical records indicated that the range of flows experienced in the chosen culvert during the September to February migration period ranged from 0.01 – 0.70 m^3/s. To ensure that spoiler baffles (or other designs) could provide passage for *G. maculatus* at this site it would be necessary to show that under such flows a 50 to 100 mm wide zone with water velocities below 0.30 m/s existed along the length of the culvert. A reduction in velocity to a level higher than this would also be acceptable but only if it was within the burst swimming capabilities of *G. maculatus* (0.47 – 1.35 m/s) and there were appropriate low velocity resting areas within the maximum burst swimming distance.

Although the model focused upon determining whether the designs reduced velocities to levels that were suitable for *G. maculatus*, the aim was to also facilitate the passage of larger fish species. For this reason, it was important to ensure that the spacing between baffle, weir or ring elements that were added to facilitate the passage of small fish did not exclude larger fish, notably other larger galaxiids (e.g. *G. fasciatus*, *G. argenteus, G. postvectis* and *G. brevipinnis*). The lateral spacing (120 mm) and longitudinal spacing (minimum of 200 mm) of the designs that were modelled recognised this.

The dimensions of the elements tested in the computational model at flow (Q) of 0.11 m^3/s are shown in Table 2 and a selection of the designs tested is illustrated in Figure 8.

Figure 8:
Designs of some of the elements tested in the study (a) Spoiler baffles – rectangular, staggered (Variation 3 and 4); (b) Spoiler baffles – wedges (Variation 5); (c) Horizontal slot weir (Variations 6 & 7); (d) Vertical slot weir (Variation 8); (e) Ring baffles (Variation 9). All variations investigated in a bare culvert. Arrows show direction of water flow. See Table 2 for a more detailed description of the variations.

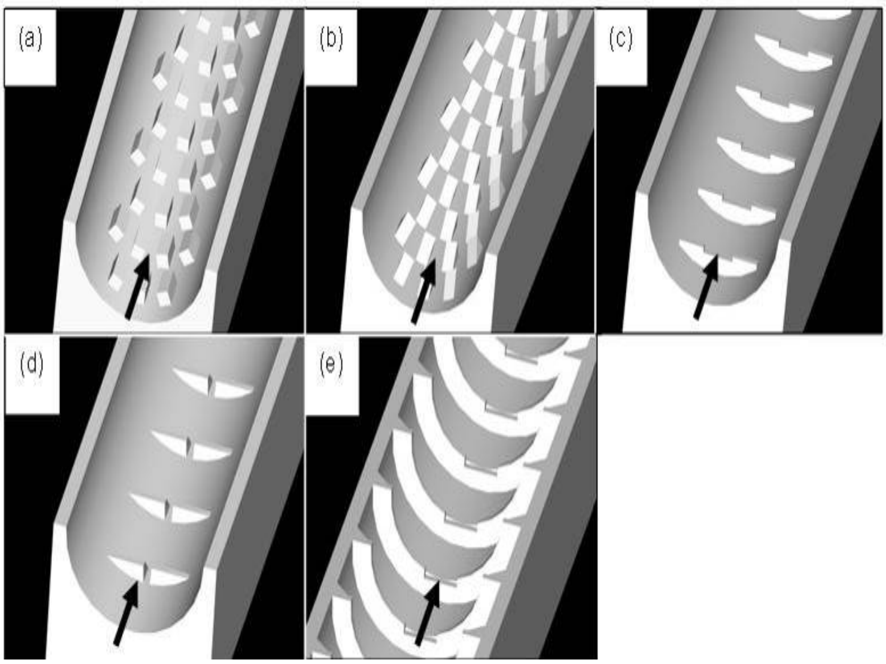


Table 2:

Dimensions of the elements tested during the study (culvert diameter = 1.35 m). Element dimensions = length x width x height.

Variation	Design	Dimensions of elements (m)	Longitudinal spacing (m)[2]	Lateral spacing (m)
1	Rows of 4 rectangular spoiler baffle blocks	0.25 x 0.12 x 0.12	0.90	0.12
2	Rows of 4 rectangular spoiler baffle blocks	0.25 x 0.12 x 0.12	0.65	0.12
3	Alternating rows of 3 and 4 rectangular spoiler baffle blocks (staggered)	0.25 x 0.12 x 0.12	0.45	0.12
4	Alternating rows of 3 and 4 rectangular spoiler baffle blocks (staggered)	0.25 x 0.12 x 0.12	0.80	0.12
5	Alternating rows of 3 and 4 spoiler baffle wedges with sloped face upstream (staggered)	0.25 x 0.12 x 0.12	0.45	0.12
6	Horizontal slot weirs with a 45º sloped face downstream	Weir height: 0.13 Gap height: 0.04 Gap width: 0.30	0.80	-
7	Horizontal slot weirs with a 45º sloped face both upstream and downstream	Weir height: 0.13 Gap height: 0.04 Gap width: 0.30	0.80	-
8	Vertical slot weir with a 45º face sloped downstream	Weir height: 0.13 Gap height: 0.13 Slot width: 0.060 (bottom)-0.08 (top)	0.80	-
9	Ring baffle with a 45º sloped face downstream	Ring height: 0.13 Gap height: 0.04 Gap width: 0.3	0.80	-

Predicted velocities with the various baffles installed are provided in Figures 9 – 15. These diagrams show the predicted velocities in a vertical plane in mid channel as well as in a horizontal plane at 0.075 m water depth (i.e. at a point mid way between 0.05 and 0.1 m, the width of the passage zone recommended by Boubée et al. 1999). Velocities in this 0.075 m horizontal plane represent the range of velocities that a fish would be required to negotiate in sustained or burst swimming mode.

All of the baffle elements tested increased water depth and reduced water velocities along the culvert base. The baffle elements which performed best for these two parameters were the rings (Variation 9) and the weirs (Variations 6, 7 and 8). However results also clearly show that whilst a continuous low velocity zone was provided on

[2] Longitudinal spacing is measured from the upstream end of one spoiler baffle to the upstream end of the next baffle.

the culvert floor by the baffles, comparatively higher velocities (up to 1.0 m/s) existed over the lip of the rings (e.g. compare Figures 9 and 13). Thus with the rings, any fish attempting to move upstream would have to ascend over the elements and repeatedly burst swim into the high velocity water flow to progress upstream. A similar situation is apparent for the weirs (Figures 10 to 12), with high velocities over the crest of the weirs. Even at a low flow of 0.11 m^3/s, and despite the lower velocities provided by the weir or ring element at the culvert floor, a small fish such as *G. maculatus* attempting to move upstream would be required to repeatedly use the burst swimming mode to negotiate each element. By definition, burst swimming cannot be maintained for a long period and repetitive bouts of burst swimming will rapidly lead to fatigue when the fish may drift downstream. Elements which require a fish to repetitively use burst swimming (or those that require burst swimming to be maintained for a long duration) are less desirable than those which require occasional short periods of burst swimming or only sustained swimming speeds. Furthermore, visual observations made under experimental conditionsand and recorded on video (see ftp://ftp.niwa.co.nz/incoming/Fish_passage/Culverts/) indicate that baffle elements which do not provide a continuous low velocity swimming path along the floor of a culvert tend to hinder fish passage. Consequently despite the ring and weir elements being effective for increasing water depth and reducing water velocities along the culvert base, they are not as 'fish friendly' as the staggered spoiler baffle designs (Figures 13 – 15). Based on these observations, modelling work with the spoiler baffle arrangement was extended[3].

[3] Since this work was completed, field studies undertaken in Australia by Macdonald and Davies (2007) have shown that following the installation of spoiler baffles, 80% of *Galaxias maculatus* and *G. truttaceus* tested passed a test section compared with only 13.5% in a smooth culvert.

Figure 9:
Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocities in a culvert fitted with ring baffles (Variation 9, Table 2). Culvert diameter = 1.35 m, height of ring = 0.13 m, height of gap in ring = 0.04 m and flow = 0.11 m^3/s. Arrows indicate the direction of flow. The coloured band at the top of the figures gives the flow velocity range (red = 1.00 m/s and blue = 0 m/s, but note that this scale is not the same as in Figure 6).

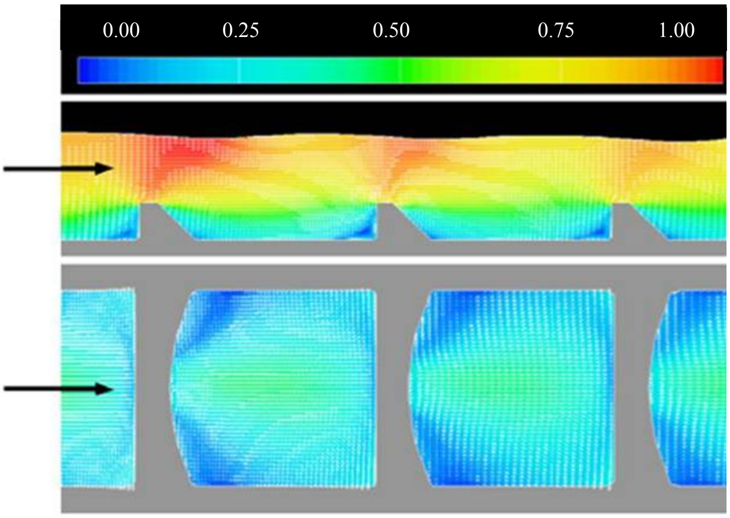


Figure 10:
Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocities in a culvert fitted with horizontal slot weirs with a 45˚ sloped face downstream (Variation 6, Table 2). Culvert diameter = 1.35 m, height of weir = 0.13 m, height of gap in weir = 0.04 m and flow = 0.11 m^3/s. Arrows indicate the direction of flow. The coloured band at the top of the figures gives the flow velocity range (red = 1.00 m/s, blue = 0 m/s).

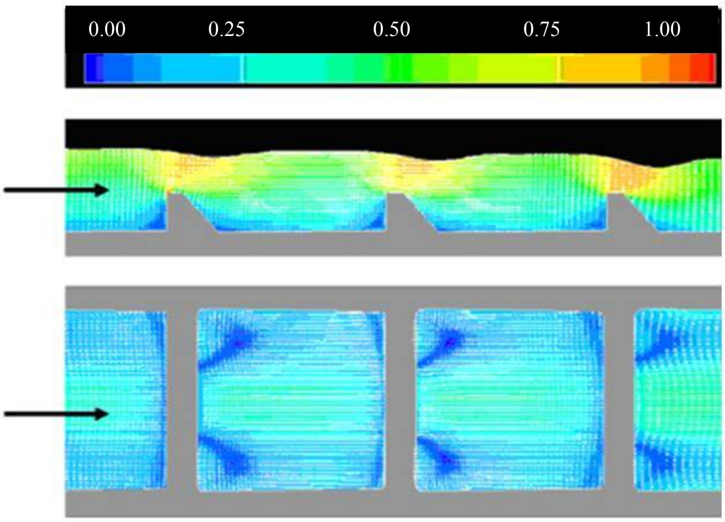


Figure 11:

Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocities in a culvert fitted with horizontal slot weirs with a 45˚ sloped face both upstream and downstream (Variation 7, Table 2). Culvert diameter = 1.35 m, height of weir = 0.13 m, height of gap in weir = 0.04 m and flow = 0.11 m^3/s. Arrows indicate direction of flow. The coloured band at the top of the figures gives the flow velocity range (red = 1.00 m/s, blue = 0 m/s).

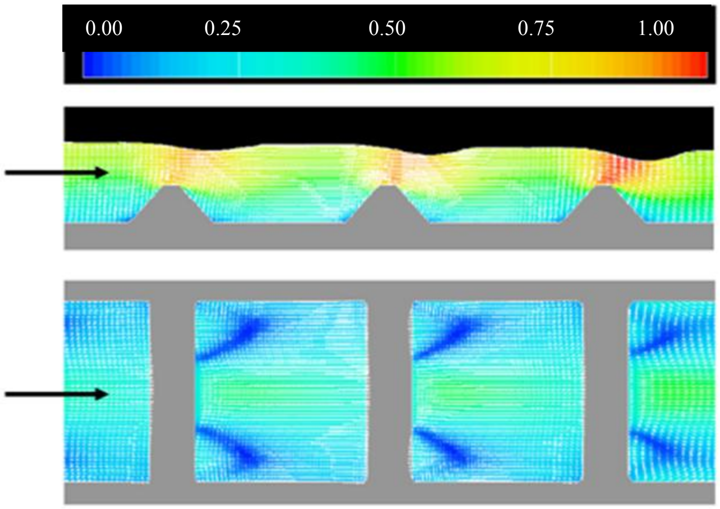


Figure 12:

Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocities in a culvert fitted with vertical slot weirs with a 45˚ sloped face downstream (Variation 8, Table 2). Culvert diameter = 1.35 m, height of weir = 0.13 m, slot width = 0.06 m – 0.08 m and flow = 0.11 m^3/s. Arrows indicate the direction of flow. The coloured band at the top of the figures gives the flow velocity range (red = 1.00 m/s, blue = 0 m/s).

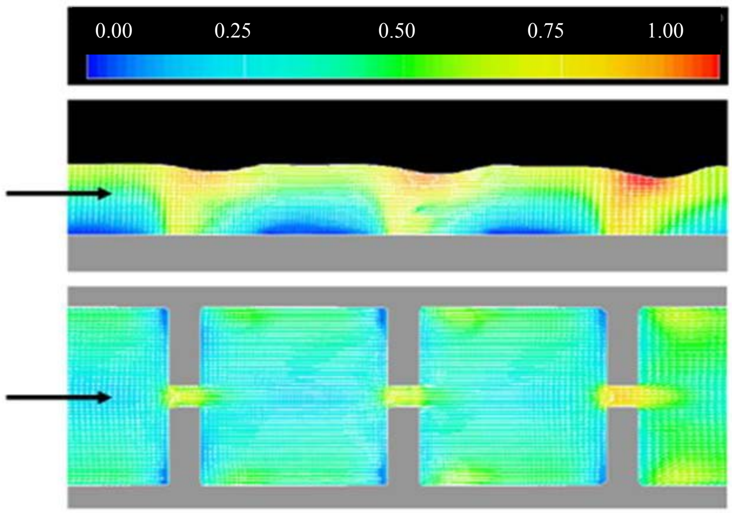


Figure 13:

Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocity in a culvert fitted with spoiler block design with alternating rows of three and four elements, spaced at 0.45m (Variation 3, Table 2) and flow = 0.11 m^3/s. Arrows indicate the direction of flow. Culvert diameter = 1.35 m and height of baffle = 0.12 m. The coloured band at the top of the figures gives the flow velocity range (red = 1.30 m/s, blue = 0 m/s).

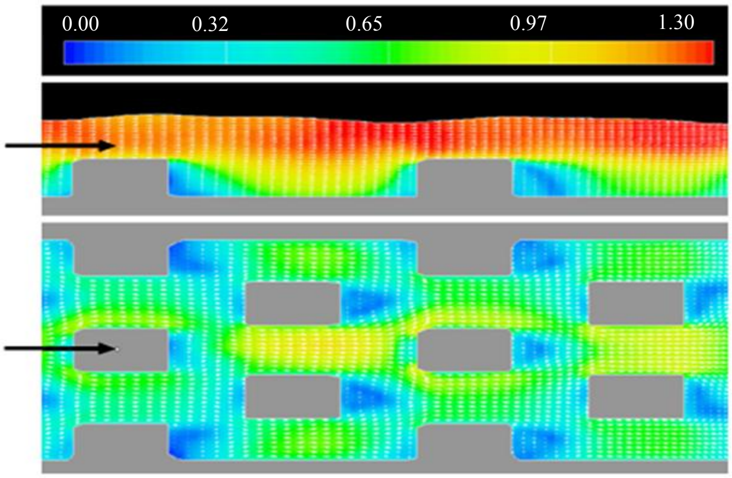


Figure 14:

Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocities in a culvert fitted with alternating rows of three and four rectangular spoiler blocks, spaced at 0.80 m (Variation 4, Table 2). Culvert diameter = 1.35 m, height of baffle = 0.12 m and flow = 0.11 m^3/s. Arrows indicate the direction of flow. The coloured band at the top of the figures gives the flow velocity range (red = 1.30 m/s, blue = 0 m/s).

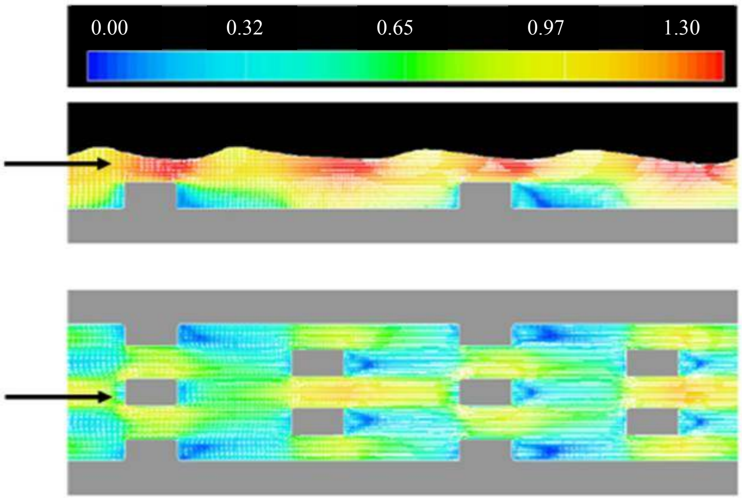
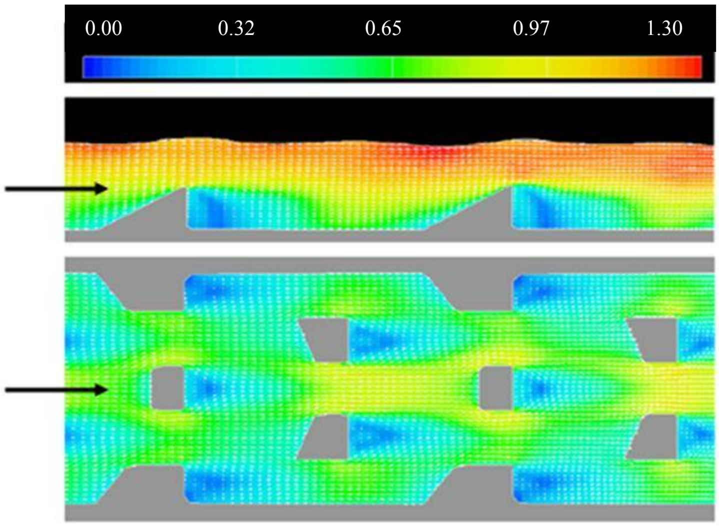


Figure 15:

Longitudinal (top) and 0.075 m depth plan (bottom) of modelled water velocities in a culvert fitted with alternating rows of three and four rectangular spoiler blocks with faces sloped upstream (Variation 5, Table 2). Culvert diameter = 1.35 m, height of baffle at highest point = 0.12 m and flow = 0.11 m^3/s. Arrows indicate the direction of flow. The coloured band at the top of the figures gives the flow velocity range (red = 1.30 m/s, blue = 0 m/s).



Results of the modelling work undertaken indicated that the shape of the spoiler baffle had a major influence on water velocities on the culvert floor. The spoilers that performed best in the model, in terms of reducing velocities and providing continuity of flow conditions, were those that were rectangular in shape. The wedge shaped spoilers produced a turbulent flow behind them (Figure 15) and were not favoured as we consider that such turbulent flow could confuse fish. Furthermore, previous work undertaken as part of the Albany-Puhoi Realignment scheme (ALPURT) found that wedge shaped spoilers resulted in faster flows and reduced water depth at low flows (SERCO 2001).

After consideration of the various factors, the most effective spoiler shape and conformation was judged to be Variation 3 (Figure 13). Although all of the staggered baffle designs created lower velocity pathways on the culvert floor, Variation 3 performed best at a discharge of 0.11 m^3/s. This variation created a zone 100 mm wide, with velocities at a level negotiable by *G. maculatus* (0.10 to 0.80 m/s). The comparatively close spacing of the spoilers (0.2 m apart) reduced the likelihood of faster water passing through the spoiler field and made it more likely that any faster water would remain above the spoiler array. The low velocity boundary layer that remained on the culvert floor and within the baffle arrangement provided fish with a continuous low velocity swimming path and resting areas behind each element. In contrast, the larger comparative distance (0.8 m) between baffles in Variation 4 meant that water was able to flow in the space between the rows of baffles more easily in comparison to Variation 3 (where the distance between rows is smaller). As a consequence, higher velocities were recorded in the boundary layer at the base of the culvert (0.10 m/s to 1.10 m/s) for Variation 4. Variation 3, therefore, provided the best conditions for facilitating the passage of small fish at low flows.

3.2.1.2 Performance of the baffle array at high flows

To assess the effectiveness of the baffle array at high flows, additional modelling was undertaken. For this, the same spacing as Variation 3 was used but the number of baffles was increased to alternating rows of seven and eight baffles (as opposed to three and four baffle rows used in Variation 3). Comparisons were then made with the bare culvert and with a culvert fitted with ring baffles (Variation 9).

Results of the modelling indicated that the expanded staggered baffle arrangement was capable of creating a continuous 100 mm low velocity layer along the culvert wall (with a maximum velocity of 0.80 m/s) for flows of up to 0.70 m^3/s. At this flow, water depth is about 0.55 m in a culvert of 1.35m diameter with 1.19% slope. Again, resting areas behind the baffles provided fish with refuges from high water velocities and the short distance between baffles meant that many flow refuges were present within the maximum burst swimming distance of *G. maculatus.*

Introducing the expanded Variation 3 spoiler array did influence culvert capacity but not to the same extent as the ring baffles (Table 3). Using staggered rows of seven and eight spoiler blocks, an increase in flow to 0.70 m^3/s only increases culvert fullness by 2% in comparison to culvert fullness when the flow is 0.50 m^3/s. This is the same increase in capacity that would be expected in a bare culvert subject to the same change in flows. Loss of capacity is therefore essentially the area occupied by the spoiler blocks plus some frictional losses. In the case of staggered rows of seven and eight spoiler baffles in a 1.35 m diameter culvert, this loss equates to about 13% of the culvert diameter.

The exact baffle conformation installed in a 1.35 m diameter culvert will be dependent upon the range of flows expected. Whilst staggered rows of three and four spoiler baffles are suitable for providing a 100 mm low velocity layer for fish up to a flow of 0.11 m^3/s, (see Section 3.2.1.1), alternating rows of seven and eight baffles will be required to provide the same low velocity zone on the margin of the same culvert at flows of 0.70 m^3/s. The effect of such an arrangement on the capacity of small culverts will be dependent on the characteristics of the catchment. Where the existing culvert is already close to capacity, the installation of baffles will not be appropriate and the only options are to either replace the existing culvert with one of a larger diameter or to install a second bare culvert to bypass high flows.

Table 3:

Changes in culvert fullness with addition of various baffle arrangements (Diameter of culvert =1.35 m). Refer to Table 2 for full description of baffle variations.

Culvert type	Flow (m^3/s)	Water depth (m)	Culvert fullness (% of culvert diameter)	% Change in fullness cf. bare culvert
Bare Culvert	0.05	0.108	8	-
	0.3	0.203	15	-
	0.50	0.220	22	-
	0.70	0.330	24	-
Culvert with staggered baffle spoilers, in 7 and 8 row arrangement (expanded Variation 3)	0.05	0.162	12	+4
	0.3	0.284	21	+6
	0.50	0.470	35	+13
	0.70	0.500	37	+13
Culvert with rings (Variation 9)	0.05	0.243	18	+10
	0.3	0.432	32	+17
	0.50	0.650	48	+26
	0.70	0.830	62	+38

3.2.2 Field testing of the pilot modelling study

3.2.2.1 Background

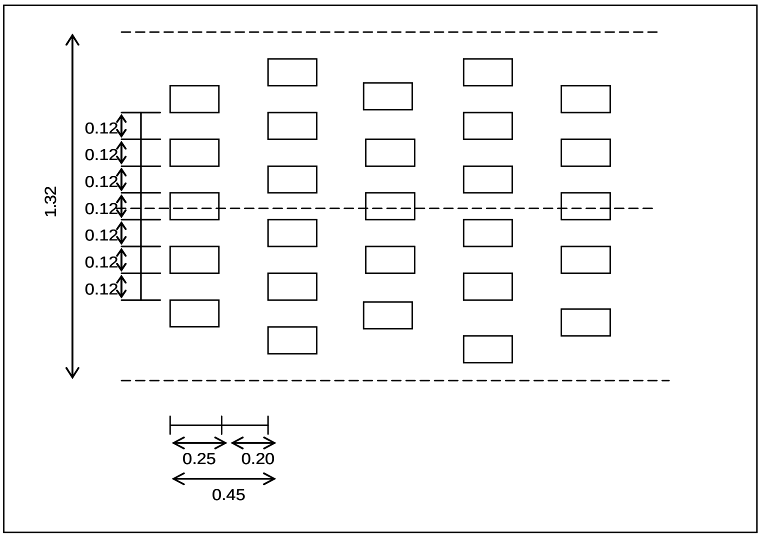
Due to corrosion, the culvert which was used to validate the pilot modelling study, at the Thompson Road drop structure on Cardinia Creek, Melbourne, Australia had to be replaced. This provided an opportunity to improve fish passage by inserting an array of spoilers in the replacement culvert and also to further test the accuracy of the model and its prediction.

To improve fish passage, the replacement culvert gradient was reduced from 1.19% to 0.76%, a bypass pipe was added to reduce peak flows in the main culvert and an open box culvert section (with a grill over the top of the culvert) inserted to allow more light to enter the structure (Figure 16). Based on results of the pilot modelling study, alternating rows of five and six spoiler baffles were installed at 0.45 m intervals (longitudinal gaps between spoilers of 0.2 m). The spoiler baffles were made of hardwood blocks of 0.25 m length x 0.12 m width x 0.12 m height. Lateral spacing between the blocks was 0.12 m (Figure 17). The culvert diameter was 1.32 m and the base of the open box section had the same curvature.

Once the changes were completed, field measurements were made to ascertain whether the model could adequately simulate the new conditions. Trapping at the culvert inlet and a limited catch and release experiment with *G. maculatus* were made to assess the effectiveness of the modifications.

Figure 16:
Outlet of the replacement culvert at the Thompson Road drop structure on Cardinia Creek, Melbourne, Australia. Photograph shows box culvert section at high flows.

Figure 17:
Plan view of culvert and spoiler baffle arrays used at the Cardinia Creek culvert. The culvert diameter where arrays were installed was 1.32 m, with a gradient of 0.76%. Dimensions shown are in metres.



3.2.2.2 Testing of the numerical model

Field measurements for testing of the numerical model predictions were undertaken following a rain event which gave the opportunity to test the effect of the spoiler baffles at different flow rates. Water velocities were obtained with a Marsh McBirney flow meter (Model 2000) at a cross section 17.65 m downstream of the inlet. The flows used to field test the numerical model[4] were 0.15 m^3/s and 0.21 m^3/s

The water velocity data collected during the field trial (Figure 18) was very similar to the flow pattern predicted by the model (Figure 19). This confirmed that the model was valid and it was judged to be appropriate to predict velocities within other sizes of culverts using similar baffle arrangements (see Section 3.2.3.1).

[4] A higher flow rate (0.74 m^3/s) was experienced during the field test but Health and Safety constraints prevented the collection of velocity data at this time.

Figure 18:

Measured water velocities (m/s) at a cross-section 17.65 m from the inlet with flow Q = 0.211 m^3/s. Culvert diameter is 1.32 m.

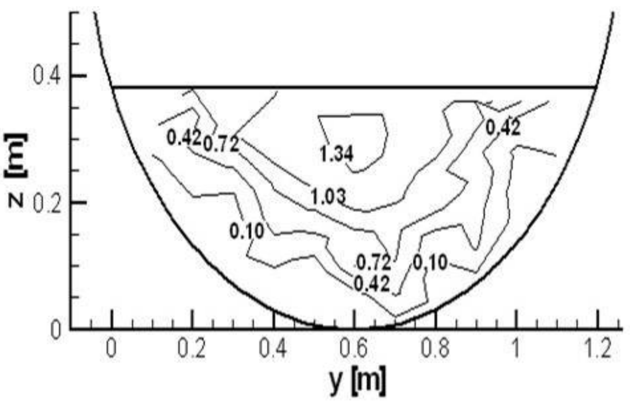
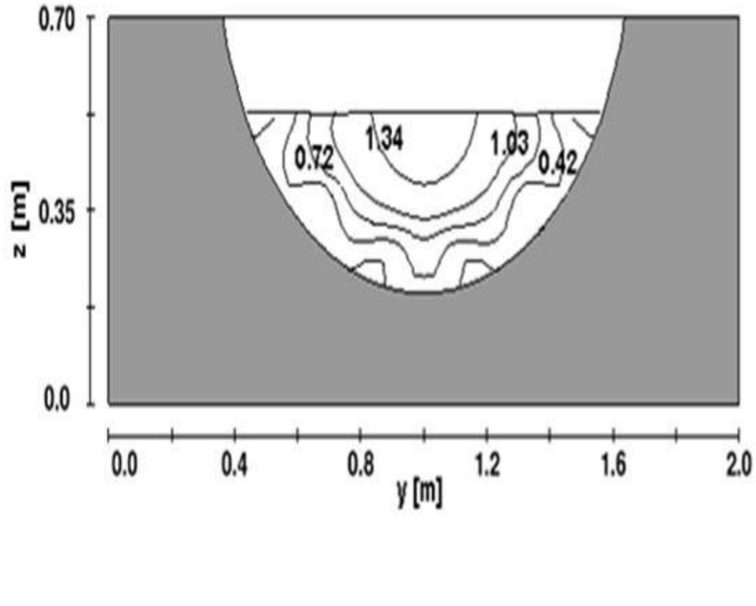


Figure 19:

Simulated water velocities (m/s) at a cross-section 17.65 m from the culvert inlet at flow Q = 0.211 m₃/s. Culvert diameter is 1.32 m.



3.2.2.3 Fish passage trials

Fish passage trials were carried out in the newly installed structure fitted with spoiler baffles on 17 November in 2005 (Boubée et al*. in prep*) and compared to records obtained in the un-modified culvert on 21 November 2002 (Boubée et al. 2003). Water temperature was between 14.4 °C and 19.5 °C during the 2002 trial and between 16.3 °C and 19.0 °C in 2005. Flow within the culvert was about 0.1 m^3/s in 2002 and about 0.2 m^3/s in 2005.

For the experiments, *G. maculatus* were captured downstream of the culvert in fine meshed fyke nets and stained by immersion for at least half an hour in 50 litres of 25% artificial sea water containing 0.05 g per litre of Bismark brown (brown stain) in 2002 and 0.2 g per litre Rhodamine (red stain) in 2005. During staining the solution was kept well aerated and maintained at stream temperature. Once stained, fish were removed from the solution, rinsed in freshwater and released at the culvert outlet. To determine the proportion of fish passing through the culvert, a fine meshed trap was placed across the stream 20 m upstream of the culvert inlet. This net was lifted at regular intervals through the trial and fish captured were counted.

In the bare culvert, seven of the 82 *G. maculatus* (8.5%) released in 2002 were captured upstream of the culvert within ten hours of being released. With the replacement culvert with baffles added, 71 of the 172 *G. maculatus* released (41%) were captured upstream of the culvert within four hours.

During both fish passage trials, unmarked wild *G. maculatus* were caught in the trap set upstream of the culvert. The number of fish passing through the structure is expected to be influenced by the number of fish present downstream of the structure, which in turn can be gauged by the fyke net catches. In 2002, the average catch within three reaches downstream of the culvert was about 4.2 fish per hour per fyke net while in 2005 the figure was about 0.7 fish per hour per fyke net (Table 4). Therefore the population downstream of the culvert was higher in 2002 indicating either an accumulation of fish caused by passage problems and/or, there was a greater abundance of fish that year. In 2002, a total of 158 wild inanga were caught in the trap upstream of the culvert in about 77.5 hours of trapping while a similar number was captured in 2005 in only 21 hours. Thus, in 2005, and despite higher flows, more unmarked fish were successfully moving through the culvert with baffles installed than in 2002 when the unmodified culvert was in place..

In conclusion, based upon the results of the limited trials undertaken there are strong indications that fish passage at the culvert at the Thompson Road drop structure was improved by the addition of spoiler baffles. Other modifications made to the structure notably improvement to the channel at the culvert outlet, decrease in culvert slope and length, and better natural lighting, no doubt contributed to this successful outcome.

Table 4:

Comparison of average fyke net catches of *G. maculatus* obtained in three reaches of Cardinia Creek downstream of the Thompson Rd drop structure culvert during 2002 and 2005. (See Boubée et al. 2003 for map co-ordinates of reaches).

Year	Number of fish caught per net per hour		
	Lower	Middle	Upper
2002	8.3	2.98	1.23
2005	0.3	0.67	1.1

3.2.3 Further testing of the spoiler baffle design and its application

On a biological basis the ideal spoiler design for culverts would be one that provided a continuous low velocity zone along the sides and floor of the culvert, whatever the slope and diameter. Invariably, low velocity zones are created at the expense of increased water depth thus resulting in a possible conflict between biological and engineering considerations.

3.2.3.1 Modelling of the spoiler baffle array in large culverts

Further simulations were undertaken to determine if the spoiler baffle array that successfully passed small fish in a 1.3 m culvert could be used in larger culverts. Rows of six and seven spoiler baffles were modelled in a 2 m culvert, rows of 10 and 11 baffles were modelled in a 3 m culvert and rows of 13 and 14 baffles were modelled in a 4 m culvert. All spoiler baffles were of 'standard' dimension (i.e. 0.25 m length x 0.12 m width x 0.12 m height). Longitudinal spacing between the blocks was 0.2 m and lateral spacing 0.12 m. The model for each variation was run under various flow conditions to achieve approximately the same filling level for each diameter.

Results of the simulation (Table 5) indicate that spoiler baffles can create a low velocity zone along the base of large diameter culverts (see Figure 13 for an example of the resulting velocity profile). Lower velocity areas were created by the comparatively close spacing of the spoilers, which encouraged the faster top layer of water to overtop the spoilers whilst the slower bottom layer of water passed through the spoiler baffles in a sinuous manner. Whilst the velocities between the rows of spoilers were relatively low, they still range between 0.38 to 1.17 m/s. *G. maculatus* could thus 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. Low velocity zones were present to allow fish to recuperate after bouts of burst swimming.

Table 5:

Simulated velocities at different flows on the base of culverts of varying diameter fitted with baffle spoilers. Water velocities tabulated are the maximum velocity in gaps between spoilers (lateral and longitudinal). The gradient of the culvert is 1.2%. Baffle dimensions were 0.25 m length x 0.12 m width x 0.12 m height with longitudinal gap between baffles of 0.2 m and lateral space of 0.12 m).

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

Changes in culvert capacity have the potential to affect the way in which the culvert performs hydrologically and it is therefore important to know what effect the spoiler baffles have on capacity. In addition to providing water velocity predictions, the model developed allowed water depth to be estimated for varying flows (Table 6).

Table 6:

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

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

In a bare culvert, water depth increases as flow increases but the addition of spoiler baffles results in an additional increase in water depth. For a 1.3 m diameter culvert, with spoiler baffles installed, changes in flow resulted in a uniform 8% increase in culvert fullness. Essentially, therefore, once the spoilers are completely covered, the relative change in culvert fullness caused by the addition of the spoilers does not change. Furthermore, spoiler baffles of the chosen size in the chosen configuration, and covering about a third of the culvert diameter do not unduly alter culvert capacity of a 1.3 m diameter culvert.

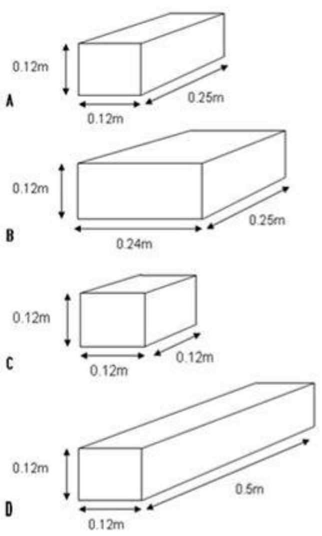
For larger culvert diameters, the addition of spoilers also increases relative culvert fullness but the effects decrease as size increases (Table 6). For example, in a 2 m diameter culvert the maximum decrease in fullness is about 7% while for a 4 m diameter culvert this is only 4%. A standard spoiler array placed over approximately one third of the base of the culvert would therefore considerably increase fish passage without unduly reducing capacity.

Previous research has suggested that baffle size (notably height and width) should differ, dependent upon the size of culvert into which the baffles will be installed (Rajaratnam et al. 1991, Ead et al. 2002). The current modelling work suggests that baffles that are sized to suit the targeted fish (in our case *G. maculatus* and adult galaxiids) can be attached to culverts of varying size to ease fish passage without unduly affecting culvert capacity. Field tests would be required to determine whether spoilers remain effective in a natural situation, particularly where there is a high sediment and debris load. The risk of barrel blockage would also need to be assessed and potential methods of reducing this risk (e.g. use of blocks made of bristle heads instead of solid blocks) need to be investigated, if required.

3.2.3.2 Modelling of spoiler baffles of differing size and effect of culvert slope

From previous work (Section 3.2.2.3), insertion of 'standard' rectangular spoiler baffles (0.25 m length x 0.12 m width x 0.12 m height) was shown to improve fish passage in the culvert at the Thompson Road drop structure culvert on Cardinia Creek. These 'standard' baffles were installed based upon results of the pilot modelling study that was undertaken in 2003 (Section 3.2.1). However, although varying spacings and shapes of spoiler had been tested, the dimensions of the rectangular spoiler baffles used had remained the same throughout the modelling exercise. If baffles of different dimensions could be shown to have the same beneficial effects as the 'standard' spoilers, this could mean that less materials would be required for baffle manufacture (if the baffles were designed to be smaller than 'standard') or may mean that a reduced number of baffles could be fitted (if the baffles were designed to be larger than 'standard'). Further modelling was carried out to investigate whether other dimensions of rectangular spoilers could be used to provide fish passage without causing additional losses in culvert capacity. This modelling was undertaken using baffle dimensions and spacing shown in Figure 20 and also investigated the effects of having these baffles installed in a culvert at slope of 1.2%, 2% and 3%

Figure 20:
The dimensions and baffle conformations used in modelling changes in velocity in relation to culvert slope. Baffles were arranged in alternating rows of three and four baffles.



Experimental code	Spoiler type	Lateral spacing (m)	Longitudinal spacing (m)
d01	A	0.12	0.20
d02	C	0.12	0.20
d03	D	0.12	0.20
d04	C	0.12	0.30
d05	D	0.12	0.30
d06	A	0.24	0.20
d07	A	0.18	0.20
d08	B	0.24	0.20
d09	B	0.18	0.20

Initially the effect of changing the length of the baffle was modelled to determine if longer baffles (which would be easier and faster to install) could also produce adequate low velocity zones that small fish could use to progress upstream. Spoiler baffles with standard dimensions at longitudinal spacing of 0.2 m (code d01, Figure 20) were therefore compared to longer baffles (code d03, Figure 20). The results of the modelling are shown in Figures 21 and 22.

Figure 21:

Plan view of the modelled velocities 0.61 m from the culvert floor for standard spoiler baffles (0.25 m length x 0.12 m width x 0.12 m height). X (longitudinal) and y (transverse) axes are in metres and the coloured velocity band at the right of the figure is in m/s. Arrow shows direction of flow. Flow Q = 0.33 m^3/s, culvert diameter = 1.3 m.

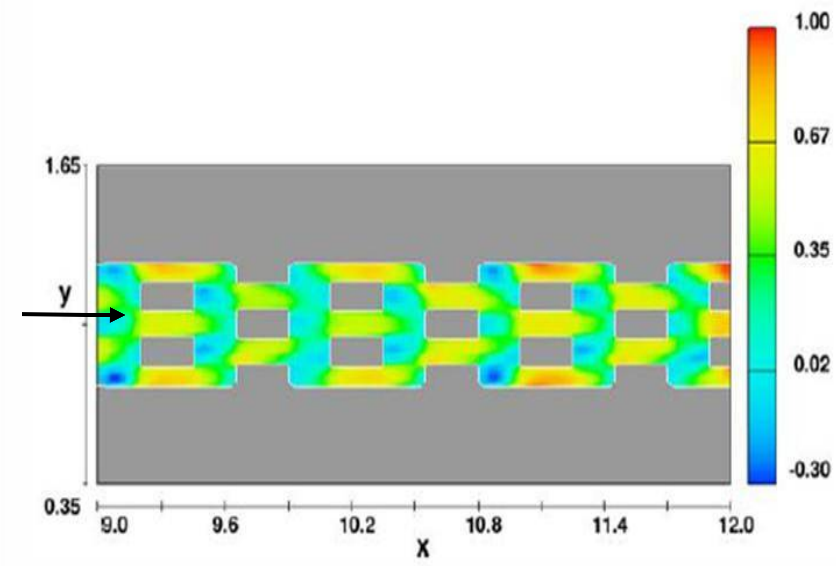
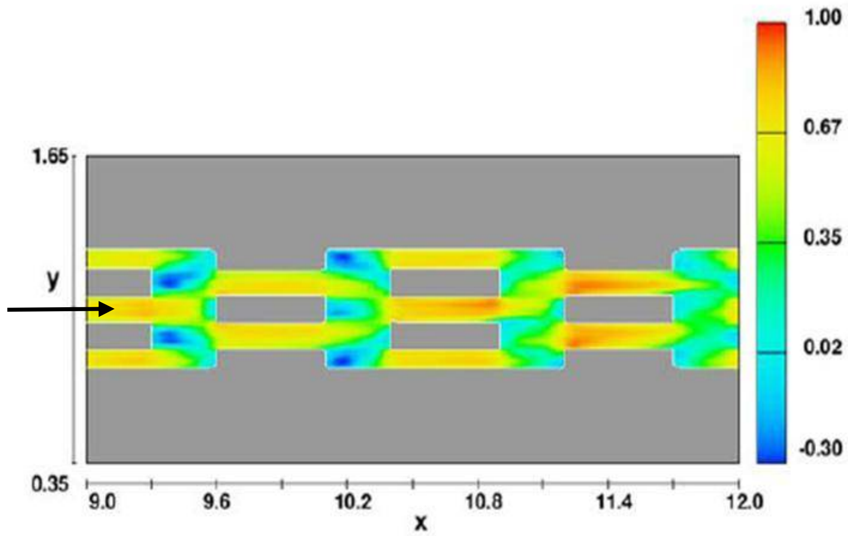


Figure 22:

Plan view of the modelled velocities 0.61 m from the culvert floor for longer spoiler baffles (0.50 m length x 0.12 m width x 0.12 m height). X (longitudinal) and y (transverse) axes are in metres and the coloured velocity band at the right of the figure is in m/s. Arrow shows direction of flow. Flow Q = 0.33 m^3/s, culvert diameter = 1.3 m.



With longer baffles, relatively longer and higher velocity zones were produced in the lateral space between the baffles in comparison to the shorter baffles. The distribution of low velocity areas was also different between the two spoiler baffle types. For the longer baffles, low velocity areas were more patchy in terms of distribution in comparison to the standard baffles, with areas downstream of the baffles displaying some very low to moderate velocities. The standard baffles produced a more even low velocity distribution, with low velocity areas of nearly uniform size behind every baffle. This indicates that the shorter spoiler baffles are better in providing a continuous low velocity zone for small fish than longer baffles.

At all slopes, the addition of baffles was found to reduce velocities in comparison to a bare culvert (Figures 23 to 25). A bare culvert represents the worst case situation for fish and resulting velocities are shown as solid black lines in these figures.

Comparing Figure 24 and Figure 25, it can be seen that for the standard baffle with standard spacing (i.e. line d01), culvert slopes higher than 2% will result in a major decrease in the low velocity area available to fish (e.g. reduction in area between pink 'd01' line and black 'bare culvert' line). This indicates that the velocity lowering capability of baffles is reduced as slope increases and strongly suggests that trials should be undertaken if baffles are proposed to be used to facilitate small fish passage in culverts with gradients greater than 2%. Closer examination of the results also shows that the denser spoiler array that results from using small spoilers (e.g. d02) can achieve a wider low velocity zone without unduly decreasing culvert capacity. Provided installation difficulties can be overcome, shorter baffles than the 'standard' spoilers installed to date may thus be a better option for improving the passage of small fish in culverts.

Figure 23:

Predicted change in water velocity u (m/s) with depth z (m) for baffles of varying dimensions and conformations (see Figure 20) at a slope of 1.2%.

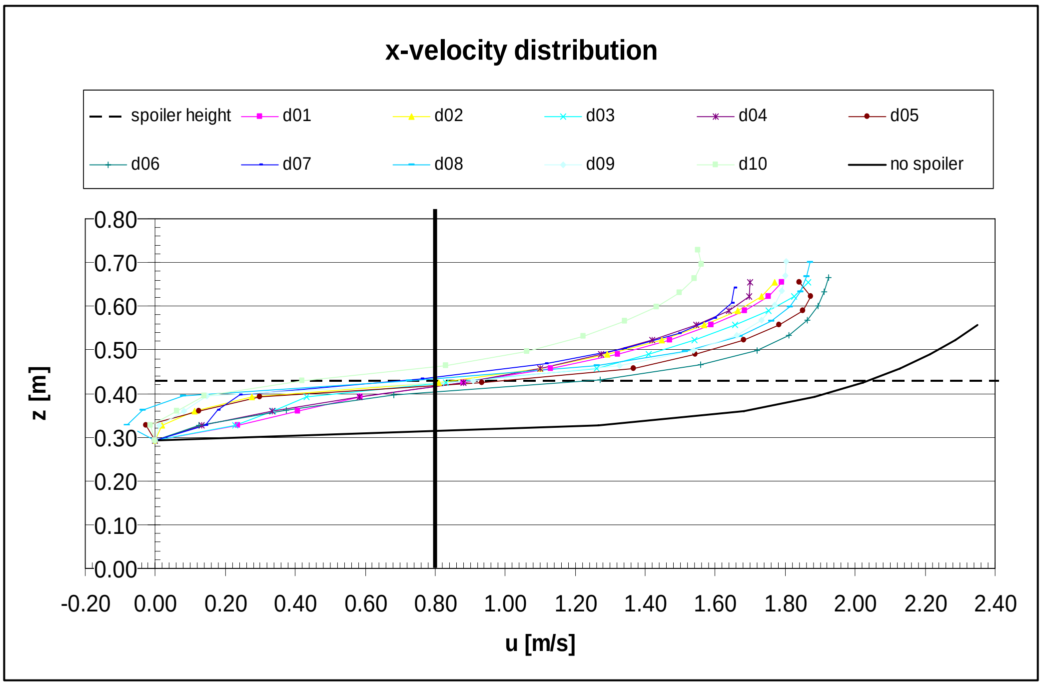


Figure 24:

Predicted change in water velocity u (m/s) with depth z (m) for baffles of varying dimensions and conformations (see Figure 20) at a slope of 2%.

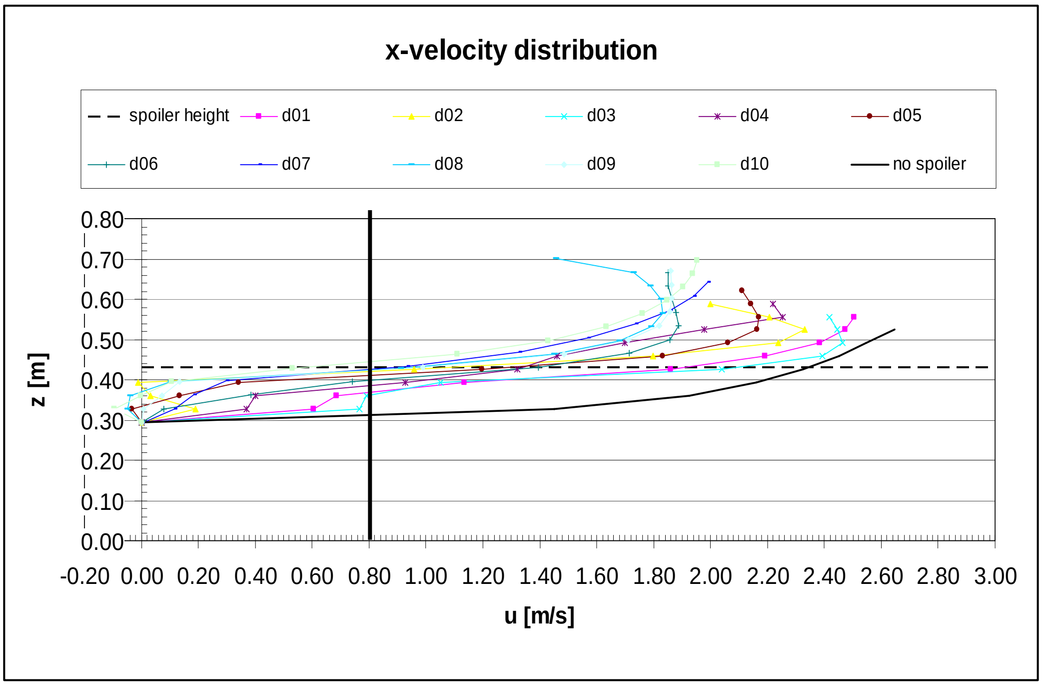
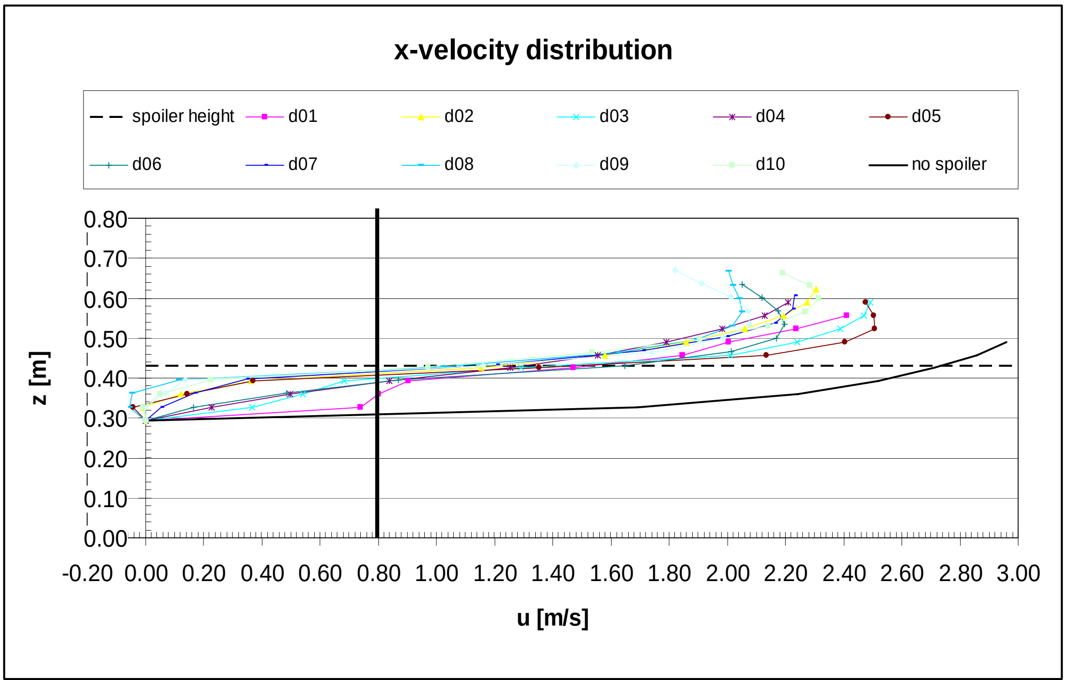


Figure 25:
Predicted change in water velocity u (m/s) with depth z (m) for baffles of varying dimensions and conformations (see Figure 20) at a slope of 3%.



3.2.4 Moulded spoiler sheets

In the current study, the addition of wooden baffles to a culvert has been successfully demonstrated to facilitate the upstream passage of small fish. Wooden baffles are low cost to manufacture but are time consuming to fit in a staggered conformation and will require replacement as the wood degrades. The cost of installing the baffles in the Cardinia Creek culvert was estimated at AU$ 23.5 per baffle. The total cost of fitting a culvert with an array of spoiler baffles, especially if these are smaller (and hence more numerous) as suggested in Section 3.2.3.2, can be substantial. There are therefore economic constraints governing the remedial retrofit work that can be carried out on culverts and improving fish passage in a durable and low cost manner is a major goal.

Since fitting individual baffles to a culvert floor can be time consuming and expensive, moulded sheets of spoilers that can be affixed to the culvert floor in one operation have advantages both in terms of initial installation and replacement.

At the suggestion of NIWA, the Northern Gateway Alliance (NGA) has installed sheets of spoiler baffles into culverts, as part of the ALPURT B2 motorway extension which connects Orewa with Puhoi. The size of the baffle used in the sheets were as recommended by SERCO (2001).

The culverts serve catchments which are relatively small (the largest is 125 hectares) but due to the steep gradient of the catchments, low permeability soils and high storm intensity, they were required to cope with sporadic flood events. As such, culverts up to 2.1 m diameter were installed.

The spoiler sheets were constructed from low density Rotathene plastic on a stiff but flexible base sheet (Figure 26) that could be manipulated to fit inside the culvert. The sheets were 2.4 m in length and the spoiler baffles were cuboid in shape (0.24 m length x 0.24 m width x 0.18 m height). The cuboids were hollow which allowed them to be transported easily by the contractors and the sheets were fitted to the culvert base using anchor bolts. The plastic cuboids, made of UV resistant material with high tensile strength (18 MPa), were considered to be more resistant to abrasion compared to steel and concrete (Leong 2007). The sheets were installed on a north branch of the Otanerua Stream where a 1.6 m diameter culvert was installed at a gradient of 2.6% (Figure 27). Fish passage through this Otanerua north culvert has not been assessed. On the main stem of the Otanerua Stream (2.1 m diameter culvert) only every third or fourth pipe section was fitted with baffles to create a 'pool-riffle' sequence similar to that of a natural watercourse. Sheets were held in place by cement mortar pads (reinforced with lightweight mesh) which were drilled into the culvert, secured with threaded rods and glued (using epoxy resin) at strategic positions. In a further development by the NGA, rocks were also wedged into the spaces between spoilers (Figure 28).

Figure 26:
Spoiler sheet with baffles of 0.24 m length x 0.24 m width x 0.18 m height ready to be fitted into the Otanerua Stream culvert (photo courtesy of John Chesterton).

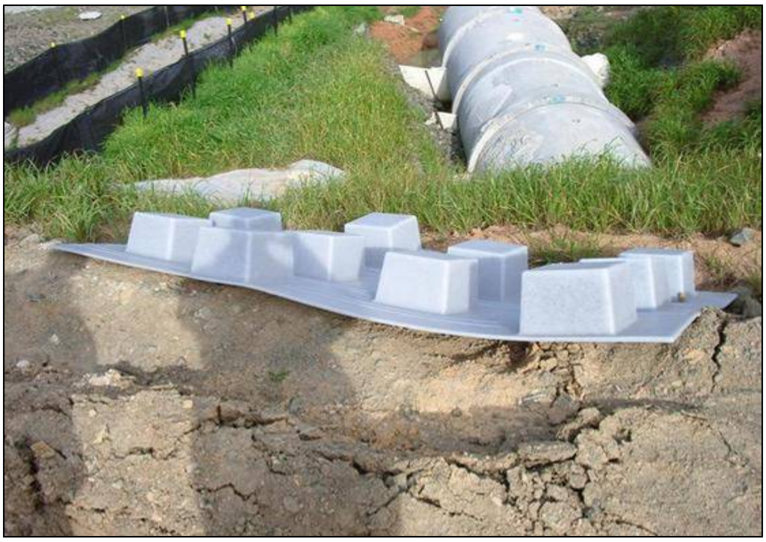


Figure 27:
Spoiler sheets with baffles of 0.24 m length x 0.24 m width x 0.18 m height installed within the 1.6 m diameter culvert on the north branch of the Otanerua Stream.

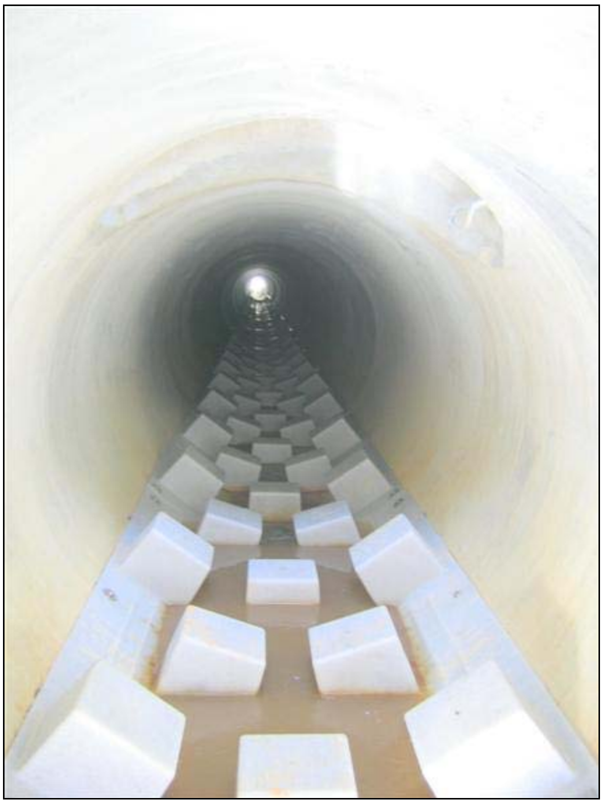


Figure 28:
Rocks positioned between the spoilers on the 2.1 m diameter culvert on the main stem of the Otanerua Stream (photo courtesy of John Chesterton).

The addition of spoiler baffles to the culvert has the potential to affect the culvert's hydraulic efficiency and flow capacity. In order to evaluate whether the addition of spoiler sheets to the culvert affected the culvert's capacity, the hydraulic efficiency of the culvert with spoilers was calculated and compared to that of a bare culvert barrel. It was found that in a full flood, the Manning's roughness value of a culvert with spoilers was around twice that of a plain barrel, indicating that the addition of spoilers decreased the culvert's capacity to deal with flood flows. In practice, however, the flow capacity of the culvert during floods was found to be limited by conditions at the inlet and not by barrel capacity (Leong 2007). The effect of the spoiler sheets on flow capacity in the Otanerua culvert was therefore considered to be negligible.

Whilst spoiler sheets with fixed dimensions were not found to reduce hydraulic efficiency in the ALPURT project due to the particular characteristics of this site, the potential for baffles to increase a culvert's resistance to flood events is a recognised issue. Theoretically, the resilience of the culvert at Otanerua to flood events was reduced by the presence of the spoilers, as they increased the culvert's roughness. Ead et al. (2002) found empirical relationships between discharge and flow depth for various spoiler and baffle configurations. The ultimate goal in spoiler baffle design is to construct a spoiler which facilitates fish passage and does not affect capacity unduly, whatever the culvert diameter. The modelling undertaken as part of the current study suggests that baffles of 'standard' dimensions (0.25 m length x 0.12 m width x 0.12 m height) may be suitable for facilitating fish passage in culverts with a range of diameters without adversely affecting capacity (Section 3.2.1.2). Smaller baffles may perform better both in terms of fish passage and effect on culvert capacity (see Section 3.2.3.2). In using these spoilers, there is no need to relate spoiler height to culvert diameter size as some authors have suggested. However, for these small baffles to be effective the culvert gradient must remain below 2%. In order to combine the benefits offered by small spoilers and the durability and ease with which spoiler sheets can be fitted, it may be worthwhile investigating the possibility of fabricating plastic spoiler sheets of the smaller baffles.

4 Summary and recommendations

The current study has successfully demonstrated that FLOW-3D can be used to model the effect of introducing spoiler baffles in a culvert, thus facilitating the assessment of changes that may result from the addition of baffle elements into culverts without the need for extensive field studies. The study has also provided information on a number of other parameters:

- Culvert slope

In general, slopes that are as close to that of the stream above and below the culvert are recommended (Clay 1995). Gradients greater than that of the natural stream will give rise to greater barrel velocities and should be avoided.

In the current series of studies, the experimental flume trials demonstrated that in small culverts (< 0.8 m diameter), small fish were able to swim a distance of between 5 and 7 m at a 3% slope when the culvert was fitted with a variety of substrates. In both modelling and field trials of culverts greater than 0.8 m diameter, rectangular wooden spoiler baffles arranged in a range of conformations were found to ease passsage at a gradient of up to 1.2%. Additional modelling indicated that spoiler baffles could be effective up to a gradient of 2%. As a general rule, therefore, in culverts where the passage of swimming fish species is required, the culvert needs to be fitted with baffles and should not be installed at a slope greater than 1 - 2%.

- Baffle size

Spoiler baffles with a 'standard' size of 0.25 m length x 0.12 m width x 0.12 m height and a longer size of 0.50 m length x 0.12 m width x 0.12 m height were tested during the current study. The longer baffles were found to create high water velocities between the baffles and a patchy distribution of lower velocity areas through the array. Longer baffles are not recommended for installation in culverts because of these issues. 'Standard' sized spoiler baffles (0.25 m length x 0.12 m width x 0.12 m height) created low velocity areas, which were regularly spaced. The research completed indicates that these smaller baffles may be suitable for facilitating the upstream passage of small fish in culverts with a range of diameters and at a range of flows.

The shorter baffles were found to be suitable for improving fish passage for *G. maculatus* of 70 mm size. Due to the space provided between baffles, it is expected that the movement of fish up to 200 mm in size will also be facilitated by the addition of these baffles. This size limit will accommodate most adult galaxiids.

Sheets of spoiler baffles have the potential to affect culvert capacity and may not be suitable for use in all situations. The current study suggests that baffles of an appropriate shape (rectangular) need only be installed in one third of the culvert base to provide suitable conditions for fish passage[5]. This has benefits in that fish passage is provided without unduly reducing flow capacity.

[5] This recommendation effectively means that rows of three and four spoiler baffles are installed in 1 m diameter culverts, rows of six and seven baffles for 2 m diameter culverts and ten and eleven baffles for 3 m diameter culverts.

- Baffle shape

From the data provided by the models, the best shape for baffles is a cube or rectangle. Rectangular baffles provided a low velocity zone along the culvert floor, refuges behind each baffle and low velocity areas along the culvert margins. The resulting low velocity zone would allow passage of small fish in the swimming mode while the slow flows along the margins of the culvert provided additional resting areas. Wedge shaped baffles were found to create turbulence at the downstream edge, which may confuse fish. Weirs and ring shaped elements created a sharp velocity gradient at each element which small fish could only surmount in the burst swimming mode. Therefore, weirs and ring elements were not considered suitable in large (>0.8 m) culverts although they do show some advantages in smaller culverts.

- Arrangement of baffles

Complex spoiler baffle arrangements appear to be best at providing continuous low velocity pathways along the culvert floor. Work undertaken in the current study has shown that in a 1.35 m diameter culvert, staggered rows of three and four baffles can successfully be used to reduce water velocities to desirable levels and provide resting areas for fish at low flows without reducing culvert capacity unduly. Modelling work also indicated that complex baffle arrangements (with rows of varying numbers of baffles) were successful in reducing velocities in culverts with diameters of 2, 3 and 4 m. As mentioned previously, in most circumstances approximately one third of the culvert should be covered by baffles but higher coverage may be necessary if base flows fill more than one third of the culvert.

- Culvert substrate for small culverts

The substrate trials undertaken in the experimental flume indicated that Stripdrain™, Polyflo™ and herring-bone were suitable for facilitating fish passage in small culverts. Due to the ease of installation and reduced maintenance requirements in comparison to the other substrates, Polyflo™ is judged to be the best substrate to use in small culverts.

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7 Appendix 1

Species	Common name
Indigenous	
Anguilla australis	Shortfinned eel *
Anguilla dieffenbachii	Longfinned eel*
Galaxias fasciatus	Banded kokopu*
Galaxias brevipinnis	Koaro *
Galaxias gracilis	Dwarf inanga
Galaxias maculatus	Inanga *
Galaxias postvectis	Shortjaw kokopu*
Galaxias argenteus	Giant kokopu*
Gobiomorphus basalis	Crans bully
Gobiomorphus cotidianus	Common bully*
Gobiomorphus huttoni	Redfin bully *
Gobiomorphus gobioides	Giant bully*
Gobiomorphus hubbsi	Bluegill bully*
Cheimarrichthys fosteri	Torrentfish*
Aldrichetta forsteri	Yelloweyed mullet*
Retropinna retropinna	Common smelt *
Mugil cephalus	Grey mullet *
Neochanna diversus	Black mudfish
Parioglossus marginalis	Dart goby*
Grahamina sp.	Estuarine triplefin*
Introduced	
Gambusia affinis	Gambusia
Scardinius erythrophthalmus	Rudd
Carassius auratus	Goldfish
Cyprinus carpio	Koi carp
Tinca tinca	Tench
Perca fluviatilis	Perch
Salmo trutta	Brown trout
Oncorhynchus mykiss	Rainbow trout
Ameiurus nebulosus	Catfish
Leuciscus idus	Golden orfe
Ctenopharyngodon idella	Grass carp

* Migratory stage within lifecycle

8 Appendix 2

Swimming ability classification	Species
Anguilliforms: 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.
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). The freshwater shrimp, a diadromous indigenous crustacean, is an excellent climber	Lamprey, elvers, juvenile kokopu, koaro and shrimp. To a limited extent redfinned bullies.
Jumpers: Able to leap using the waves at waterfalls and rapids. As water velocity increases it become energy saving for these fish to jump over obstacles.	Trout, salmon and possibly (on a scale of 20 – 50 mm) smelt and inanga.
Swimmers: 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.