Passage of inanga (*Galaxias maculatus*) over artificial ramps as a means of restoring upstream access to stream habitat

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by

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Executive summary

The effects of substrate type, flow rate, and slope on fish passage over artificial ramps was evaluated for inanga (*Galaxias maculatus*); a small diadromous fish native to New Zealand, Australia, Tasmania, Lord Howe Island, Chatham Island, Chile, Argentina, and the Falkland Islands. Five substrate types (smooth, corrugated, herring-bone baffle, and two plastic moulded cores of ground drainage products Polyfo® and Stripdrain®) were tested on slopes of 3 - 5 % and flows of 4 - 6 ls^{-1}. Slope, fish size, and substrate type each had a significant influence on the mean distances swum. Stripdrain® was the most effective substrate type, enabling the greatest distances to be achieved and a maximum vertical elevation of 0.39 m to be attained. The results of this study have further highlighted the potential for ramps to provide fish passage past small in-stream barriers, as well as the need to refine ramp slopes and lengths in order to meet the specific barrier remediation needs.

Introduction

During the 19^{th} and 20^{th} centuries many waterways all over the world fitted with locks, dams, or weirs to optimise water levels for navigation, generate electricity, flood prevention, community water supplies, or agricultural land use (Knaepkens, 2006, Yasuda *et al*, 2004). Without the provision of effective/efficient fish passage, formerly continuous aquatic systems become fragmented. Human-induced habitat modification - particularly through the construction of dams and other in-stream structures - is now widely recognised as a key contributing factor in the decline of global freshwater fish biodiversity (Gosset *et al*, 2006; Baumgartner *et al*, 2006).

Habitat fragmentation can prevent, restrict or severely hinder both the upstream and downstream migration of aquatic animals between specific habitats needed during various phases of their life cycles (Knaepkens, 2006; Yasuda *et al*, 2004; Baker, 2003; Baumgartner *et al*, 2006). Long term fragmentation may cause reproductive isolation within watersheds, and it is also probable that the loss of time and energy spent waiting downstream and the changes noted in migration patterns as a result of a barrier will compromise the reproductive success of fish (Gosset *et al*, 2006). Restricted or delayed access to spawning areas or a greatly reduced species distribution is likely to result in reduced adult stock or the number of species present in an area, inevitably jeopardising the long term sustainability of fish populations (Baker, 2003; Gosset *et al*, 2006).

New Zealand has 35 species of indigenous freshwater fishes, of which 18 are diadromous and undergo migrations between fresh and salt water during their life cycle (Baker and Boubée, 2006). Some of New Zealand's indigenous migratory species can withstand periods out of water and possess the ability to climb the wetted margins of the splash-zone created as water flows over or through many in-stream structures (Boubee *et al*, 1999; McDowall, 1990). Koaro (*Galaxias brevipinnis*) and banded kokopu (*Galaxias fasciatus*) juveniles for example, are known to climb significant vertical barriers by adhering to substrates using surface tension (McDowall, 1990). Swimming species such as inanga (*Galaxias maculatus*), which have no climbing ability, must swim through high velocity areas or up vertical drops (Baker and Boubée, 2006; McDowall, 2000). Recent studies suggest that both juveniles and adults of non-climbing species such as inanga are prevented from moving upstream when they encounter vertical drops of 100mm and 200mm respectively at a velocity of $0.6ms^{-1}$ (McDowall, 1990; McDowall, 2000; Baker, 2003).

In-stream structures with relatively high velocities or drops, such as culverts or weirs will therefore differentially affect the upstream movement of New Zealand's swimming and climbing fish species, with a more significant restriction likely to be evidenced by swimming species (Baker, 2003). The fact that some species (i.e. inanga) appear to be relatively easily hindered by in-stream structures may be a warning that in addition to other human-induced habitat changes, anthropogenic barriers to migration could be significantly contributing to the decline in freshwater fish populations and biodiversity within New Zealand (Baker and Boubée, 2006; Hicks and Baker, 2003; McDowall, 2000).

Conventional fish passage structures are designed to allow the shear stress imparted by obstacles on flowing water to reduce the water velocities associated with the structure to match the swimming ability of a target fish species (Knaepkins, 2006). The considerable body of research concerning the design and efficiency/effectiveness of fish passage structures (of which there are now thousands worldwide), with few exceptions, has generally been concerned with facilitating the movement of northern hemisphere anadromous salmonids past barriers (Kowarsky and Ross, 1981; Knaepkens, 2006; Ead *et al*, 2004; Baker and Boubée, 2006). Passage of smaller fish is often impossible using conventional designs – samlonid swimming velocities far exceeding those obtainable by many other species (Ead, 2004; Baker and Boubée, 2006; Boubée *et al*, 1999). There is a clear need for New Zealand, and many other countries besides, to gather information regarding the efficiency/effectiveness of fish passage structures and the behaviour of indigenous fish towards them if a major loss of global fish diversity is to be avoided (Kowarsky and Ross, 1981; Knaepkens, 2006).

Data gathered to date on the swimming style and ability of New Zealand's native fish species has highlighted the importance of fish passage structures providing both low velocity zones to pass swimming species, and a wetted margin for species capable of climbing (Mitchell 1989, Moffat and Davison 1986, Boubée *et al*. 1999; Baker and Boubée, 2006). The large number of structures implicated also necessitates cost effective and possibly novel approaches for the provision of fish passage (Baker and Boubée, 2006).

Culverts within the Waikato Region associated with roading infrastructure have been scrutinised in terms of fish passage by several researchers (i.e. Speirs and Kelly, 2001; Takeshi Ito, *unpublished data*). Data on the location, type, and severity of barriers imposed upon fish movement are available in relatively large quantities for the Waikato Region. This database of information, currently administered by the Waikato Regional Council, has already allowed a prioritised retro-fit program to be developed, and it is anticipated that the database will also greatly facilitate the development of economical fish passage structures (Speirs and Kelly, 2001; D. Speirs, *pers comm.*). For the purposes of this report, I only report survey results for the Thames-Coromandel District. Refer to Speirs and Kelly (2001) for a detailed description of the survey results in their entirety. As at September 2005 250 culverts (66%) were still thought to pose a barrier to fish passage within the Thames-Coromandel District – far more then the 22 and 68 offending culverts in the Hauraki and Matamata Piako Districts respectively (Speirs, *unpublished data*). Half of the 52 culverts within the Thames-Coromandel District likely to be barriers to fish movement only during low flow conditions were as a result of the culvert being perched, on average 0.3 m. 97 % of the 198 culverts likely to impede fish movement at most flows within the Thames-Coromandel District were due to the culverts being perched, on average 0.6 m. Over 95 % of all culverts surveyed were concrete with an average diameter of 0.5 m.

The current study uses data obtained under laboratory conditions by Takeshi Ito (*unpublished data*), to investigate the potential for artificial ramps to provide fish passage past in-stream barriers (i.e. perched culvert outlets) reflecting those found within the Thames-Coromandel District. Inanga, generally thought to be among the weakest swimming of New Zealand's native fish, were selected as the study species for three reasons. The species is found throughout the Thames-Coromandel District, readily adapts to laboratory conditions, and the successful passage of this comparably weak swimmer is likely to provide passage for stronger swimming species as well as those capable of climbing (McDowall, 2000, Mitchell, 1989).

DESCRIPTION OF STUDY SPECIES

The inanga (*Galaxias maculatus*) is the most common of the five diadromous galaxiid species comprising New Zealand's commercial whitebait fishery, and has one of widest distributions of any fish species (Berra *et al*, 1996). Conspecific populations are known to occur in New Zealand, western and eastern Australia, Tasmania, southern South America, as well as Stewart Island, the Chatham Islands, the Great Barrier Islands, Lord Howe Island, and the Falkland Islands (McDowall, 2000; Berra *et al*, 1996). Inanga are widely distributed within New Zealand, but are usually found at low elevations near the coast. A diverse range of habitats are utilised - from clear to tannin-stained cold to warm waters, pasture or forest reaches, within a range of flow regimes. However, it most often inhabits gently flowing and still waters such as estuaries, lowland rivers and streams, and lagoons and backwaters, where it is found in loose, roving mid-water shoals of varying size. Of the 5 diadromous galaxiid species inanga are the only essentially annual species, maturing after one year, with adults being most abundant between November and March (McDowall, 1990; McDowall, 2000; Mitchell, 1989). In autumn adults (80-100 mm) undertake catadromous migration downstream on full or new moon phases to spawn in inundated vegetation upstream of the tidal wedge (McDowall, 1990; McDowall, 2000; Mitchell, 1989). A number of fish will remain in freshwater for an extra year, maybe two, but certainly no more than three (McDowall, 1990; McDowall, 2000). Larvae (c. 7 mm) are swept to sea, where they feed and grow for between 147-161 days, before returning to rivers (not necessarily from which they originated) in spring (August – November) as whitebait (c. 50-55 mm) where they will grow to maturity, never returning to the sea (Berra *et al*, 1996; Hicks and Baker, 2003; McDowall, 1990; Mitchell, 1989).

Inanga are thought to rely on 'burst' swimming to get past high velocity areas (Boubee *et al*, 1999). 50 mm inanga have been recorded to swim at a velocity of 1 ms^{-1} for between 1 and 10 s, but over shorter time periods (i.e. less than 0.5 s while negotiating a vertical drop) appear able to surpass this speed (Boubee *et al*, 1999; Baker, 2003).

Methods

STUDY SPECIES CAPTURE AND MAINTENANCE

A total of 792 adult and juvenile inanga (40 – 120 mm total length) were sourced from the Waikato River and tributaries of the Raglan Harbour. Fish were either purchased from fisherman who used traditional whitebait nets, or caught with baited G-minnow traps. Fish collection and experimental trials were performed between August and November, so as to correspond with the period of natural upstream migration (McDowall, 1990; Mitchell, 1989).

Upon capture, fish were transported to a laboratory setting at Ruakura, Hamilton. Fish were acclimated, for between 24 and 72 h, in the lower tank of the experimental set-up (Figure 1). The lower tank was kept at a constant temperature ($19^{\circ} \pm 0.5^{\circ}$ SD) and had a constant flow of aerated water entering over the experimental ramp. The experiments were conducted under a shade cloth in an open court yard so that fish experienced ambient light conditions, approximating a 12-h light 12-h dark photoperiod. Fish were not fed while in captivity.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were carried out in a recirculating freshwater flow system (Figure 1). Fresh water was pumped (via one of two pumps depending on the desired flow rate) from the storage tank, to the head tank (fitted with a baffle and a mesh net to minimise turbulence), from where it flowed on to the experimental ramp and back down to the lower tank. A permanent mesh screen installed in the lower tank prevented fish escaping into the large reservoir tank, and restricted fish access to the ramp until the start of a trial. The ramp was a 7.8 m long section of 0.65 m inside diameter commercially available corrugated plastic pipe cut in half lengthways. The ramp was supported on an 8m long metal frame fitted with a winch and four jacks that could be used to achieve the desired ramp slope.

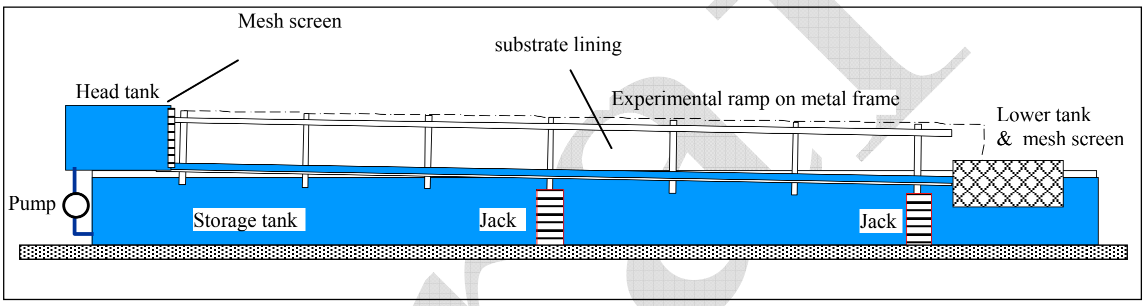

Figure 1. . ***Schematic diagram of the experimental set up located at Ruakura, Hamilton.***

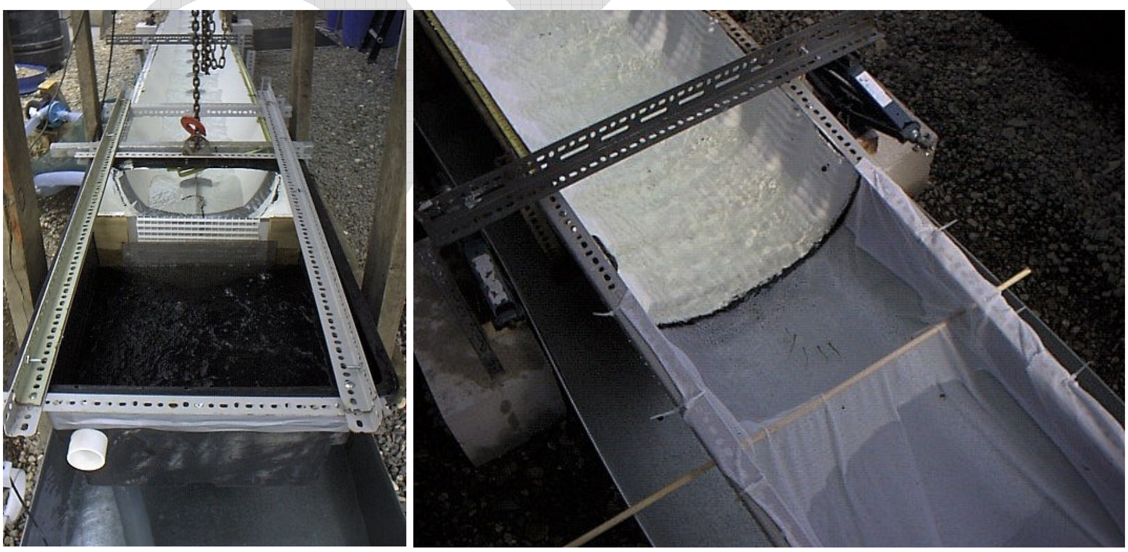

Figure 2. *The head tank was suspended with a winch, while a baffle and mesh net minimized water turbulence and prevented fish escaping (left). Each substrate lining was laid over the pipe secured to the metal frame, and the mesh screen prevented fish from entering the ramp until the start of the trial (right).*

Five linings of different substrate types, inserted into the pipe section, were tested (Figure 3); smooth control (made of flat metal sheets), corrugated, herring-bone baffle (resembling a pool-weir fish ladder, laid on top of the smooth substrate), and the plastic core of two ground drainage products: Polyflo® (a plastic sheet with trapezoidal ridges), and Stripdrain® (a plastic sheet consisting of 24 mm high cusps at 16 mm centres on a flat surface). All the five lining types were painted white to increase the visibility of fish moving on the ramps during trials.

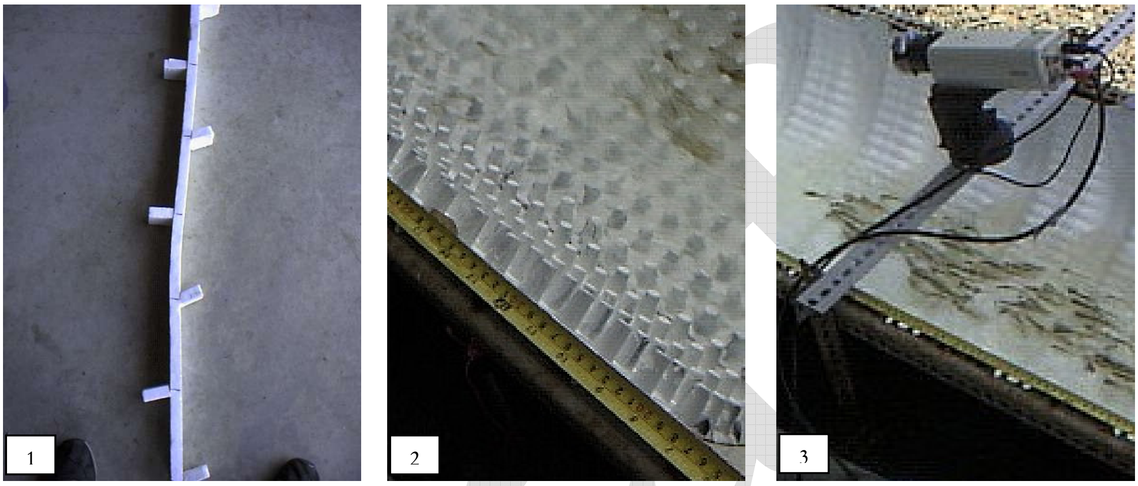

Figure 3. *Substrate types tested – 1 herringbone baffle, 2 – Stripdrain®, and 3 – Polyflo®. Smooth and corrugated substrates are not shown.*

The slope of each ramp was set at 3% (1.72°, 1:34) and 5% (2.87°, 1:20) and flow rate at 3.6-3.8 ls^{-1} and 6.2-6.4 ls^{-1}. The semi-circular shape of the ramp ensured deeper water was provided in the centre for swimming and a wetted margin maintained along the water's edge for all trials. Water temperature was maintained at a mean of 19°C (standard deviation 0.55°C, minimum 17.6°C, maximum 20.0°C) with the aid of the large storage tank (0.8 m wide, 0.3 m deep, and 12 m long, reserving 2.88 m^3 of water) in conjunction with a refrigeration unit. No velocity or water depth measurements were made.

For each trial 40 fish (excluding trials of 3 % slope and smooth substrate type, in which over 60 fish were used) were placed in the lower tank, at the base of the ramp - on which one of the five substrate types to be investigated was placed. At the beginning of each trial fish were transferred (in a mesh net) in front of the mesh screen in the lower tank to allow fish access to the ramp. To avoid using coercive measures to motivate fish to swim up the ramp, the innate rheotactic behaviour (movement in response to a current of water) of inanga was utilised. No fish was used in more than one trial. Trials lasted for 3 hours, during which the time taken and distance achieved by each fish attempting passage was recorded, before the fish was removed from the trial and measured (total length). Fish still on the ramp at the end of the trial did not have measurements of time, distance swum, or length recorded. Trials were conducted between 0930 and 1930 h daily, in an outdoor setting lit with natural overhead lighting. Pilot studies performed by Baker (2003) and Baker and Boubée (2006) have confirmed the diurnal activity of inanga. Fish only exhibited movement during the day.

STATISTICAL ANALYSIS

Analysis of Variance (ANOVA) was used to determine the effects of fish size (small $<$ 60 mm, large $\geq$ 60 mm), ramp slope, and flow rate (as well as any interaction effects) on the distances fish were able to swim up the ramp on the five different substrate types tested. Post hoc tukey honestly significantly different (hsd) test was used to identify where any significant differences lay.

No data on swimming time was available from Ito (*unpublished*) to undertake an analysis of the likely swimming mode (i.e., burst or sustained) used by fish or their groundspeed during trials.

The mean temperature was higher (19°C vs 17.8°C), though less variable (0.55°C vs 0.8°C SD), in the current study than was reported by Baker and Boubée (2006). Accordingly, temperature effects (due to unwanted variation) on fish passage has not been investigated.

Results

RAMP HYDRAULICS - OBSERVATIONS

The flow rate down the ramp in all trials was uniform, i.e. parallel to the substrate along the length of the ramp, and supercritical in all cases. No velocity data were recorded, but it is expected that water velocity increased and water depth decreased as the slope of the ramps increased during both flow scenarios. Because of the semicircular shape of the ramp, water velocities would have ranged from a minimum at the water's edge/wetted margin, to the maximum velocity at the centre (deepest point). For a given slope and flow rate, velocities would be expected to decrease as the size of the surface roughness elements of the substrate type increases. Thus, water velocity is likely to have been highest on the bare ramp, and lowest on the Stripdrain® substrate type. The rougher substrate types also appeared to produce areas of low velocity immediately downstream of the substrate elements which were used as resting areas by fish.

Fish Behaviour - observations

All fish began swimming in the main current at the base of the ramp. As they swam up the ramp, fish utilised the entire range of water velocities, moving back and forth between the deeper, faster water to the shallower, slower water. The distance swum was therefore higher for fish that chose a route within their swimming ability. All substrate types, other than smooth, allowed fish (of both size classes) to rest on the wetted margin when velocities too fast to swim against were encountered.

Passage Success

Analysis of Covariance (ANCOVA) revealed that the relationship between distance swum by fish, ramp slope, and flow rate was independent of total fish length. That is, fish of all lengths were affected in the same way by changes in ramp slope or flow rate. For the purposes of simplified analysis and general applicability, fish were assigned to either of two groups ($<$60 mm small, and $\geq$60 mm large) with significantly different means. Numbers of fish in each group were similar; small (N = 435, M = 50.57 mm, SD = 5.02 mm) and large (N = 357, M = 74.06 mm, SD = 12.58 mm). This grouping is consistent with that used by Baker and Boubée (2006).

Small inanga

Figure 4 and Table 1 illustrate that the mean distance swum (and accordingly vertical elevation achieved) by small inanga on ramps with the slope set at 3% and flow rate at 4 l s^{-1} (A) was greatest when tested on the corrugated, herring-bone baffle, Polyflo®, and Stripdrain® substrate types, and significantly less when tested on the smooth substrate type ($P<0.001$). Fish swam a significantly greater distance on the Stripdain® substrate type than either the corrugated, herring-bone baffle, or Polyflo® substrate types ($P<0.001$) – which again performed better than the smooth substrate type ($P<0.001$) – when the flow rate was increased to 6 ls^{-1} while maintaining slope at 3 % (B).

Increasing the slope to 5% while maintaining flow at 6 ls^{-1} (D) saw small inanga swim further on the Stripdain® substrate type than when tested on the Polyflo® substrate type ($P<0.001$). The mean distance achieved on the Polyflo® substrate type was comparable to that achieved on the herring-bone baffle substrate type, but significantly greater than the mean distance swum by fish tested on the corrugated substrate type ($P<0.001$). The mean distances swum on the herring-bone baffle and corrugated substrate types were similar, and significantly greater than those achieved by fish tested on the smooth substrate type ($P<0.001$). Reducing the flow rate from 6 s^{-1} to 4 s^{-1} while maintaining slope at 5% (C), confirmed the superior performance of Stripdrain® over the other substrate types tested ($P<0.001$). The mean distance swum by fish tested on the Polyfo® and herring-bone baffle substrate types were again comparable, and allowed greater distances to be swum by small inanga than either the corrugated or smooth lining types ($P<0.001$), which under these conditions produced similar mean distance values.

Large inanga

Figure 5 and Table 2 illustrates that large inanga swam significantly further than small fish in 55 % of the experiments ($p<0.001$ for all substrate types except Stripdrain® $p=0.07$), and could have been as many as 70 % but for the severe truncation of distance swum data for fish tested on the Stripdrain® substrate type (as a result of high numbers of fish passing the ramp successfully). The only experimental condition in which large fish did not consistently swim significantly farther than small fish was when fish were exposed to low flow and slope conditions (A).

The mean distance swum by large inanga on a ramp with the slope set at 3 % and flow rate at 4 ls^{-1} (A) was greatest when tested on the corrugated, herring-bone baffle, Polyflo®, and Stripdrain® substrate types, and significantly less when tested on the smooth substrate type ($P < 0.001$). These findings were the same when the flow rate was increased to 6 ls^{-1} while maintaining slope at 3 % (B). Increasing the slope to 5 % while maintaining flow at 6 ls^{-1} (D) saw large inanga swim further on the Stripdain® substrate type than when tested on the Polyflo® substrate type ($P < 0.001$). The mean distance achieved on the herring-bone baffle substrate type was comparable to that achieved on the Polyflo® substrate type, which was significantly greater than the mean distance swum by fish tested on the corrugated and smooth substrate types ($P < 0.001$). Reducing the flow rate from 6 ls^{-1} to 4 ls^{-1} while maintaining slope at 5 % (C), again (as for small inanga) confirmed the superior performance of Stripdrain® over the other substrate types tested ($P < 0.001$) with the exception of the herring-bone baffle substrate type. The mean distance swum by fish tested on the Polyfo® and herring-bone baffle substrate types were again comparable, and allowed greater distances to be swum by large inanga than either the corrugated or smooth lining types ($P < 0.001$), on which mean distance values were similar.

Substrate Type

It appears then that only a small increase in surface roughness (and associated reduction in water velocity – particularly towards the margins) significantly increases the distance which inanga are able to swim. The smooth substrate type facilitated significantly lower mean swimming distances than the other lining types in all but two experimental conditions. In experimental conditions C (for small fish) and D (for large fish), the smooth lining was comparable to the corrugated substrate type. Both the smooth and corrugated substrate types were significantly lower than the herring-bone baffle, Polyflo®, or Stripdrain® substrate types under experimental conditions C (for small fish) and D (for large fish). The performance of small and large fish was most comparable on the corrugated substrate type. This substrate type evidenced some of the lower distances swum, but only at 5% slope. At 3% slope performance on the corrugated substrate type was comparable to the other substrate types - except Stripdrain® in experimental condition B (for small fish). Herring-bone baffle and Polyflo® performed similarly in terms of facilitating fish passage – not producing significantly different results under any experimental condition. The Stripdrain® substrate type consistently contributed one of the longest, if not the longest, mean distance swum in all experimental conditions. The effect was most noticeable for small fish, for whom Stripdrain® produced significantly farther distances under all experimental conditions except 3 % slope and flow rate of 4 $l\ s^{-1}$ (A).

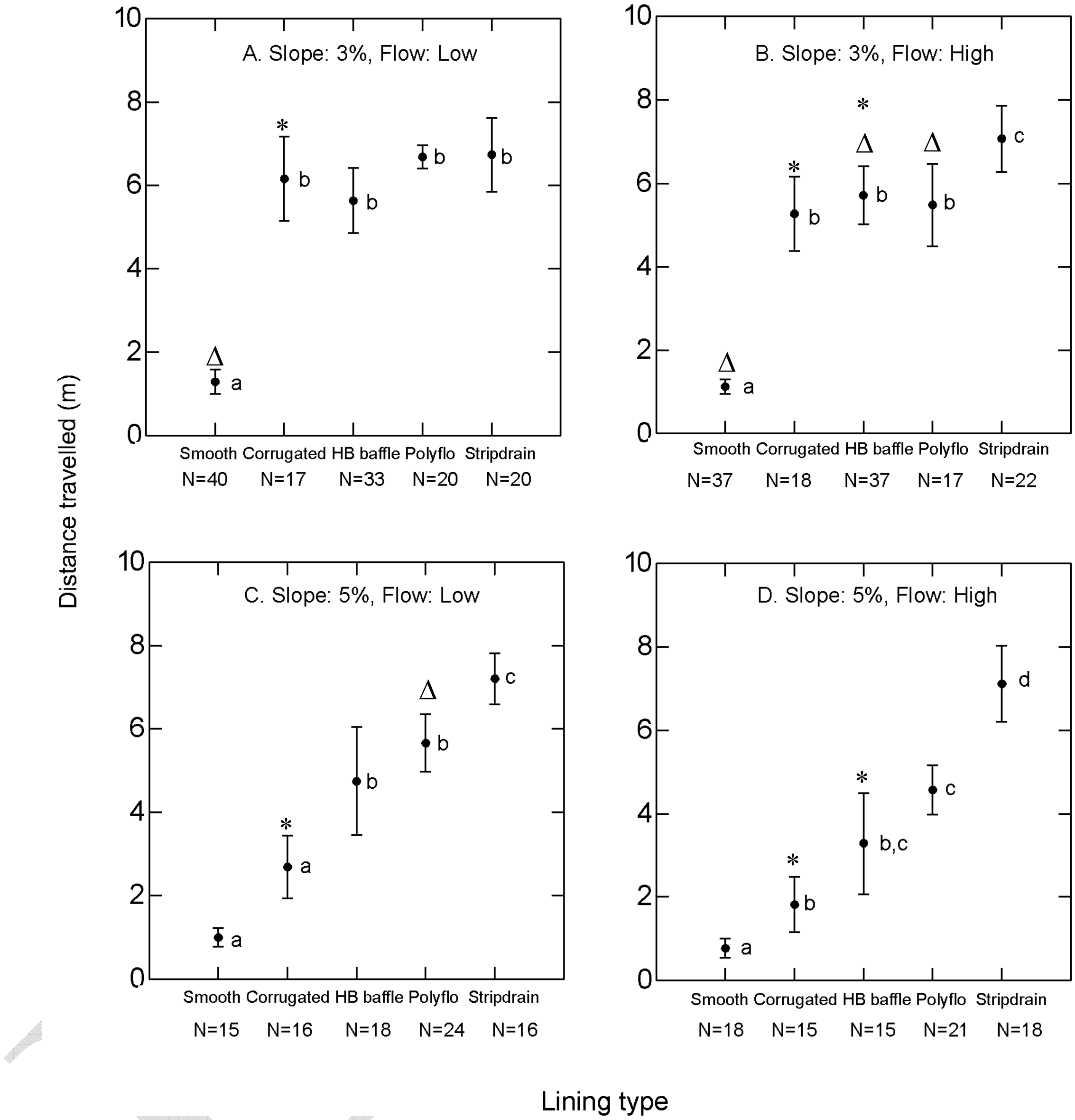

Figure 4. ***Mean distance swum by small inanga (< 60 mm), categorised by lining type, for each of the four experimental conditions. N = number of fish in each condition; vertical bars represent 95% confidence intervals. Means with the same letter are not different (ANOVA P<0.001). * and Δ represent significant differences between slope condition and fish size respectively (P<0.001).***

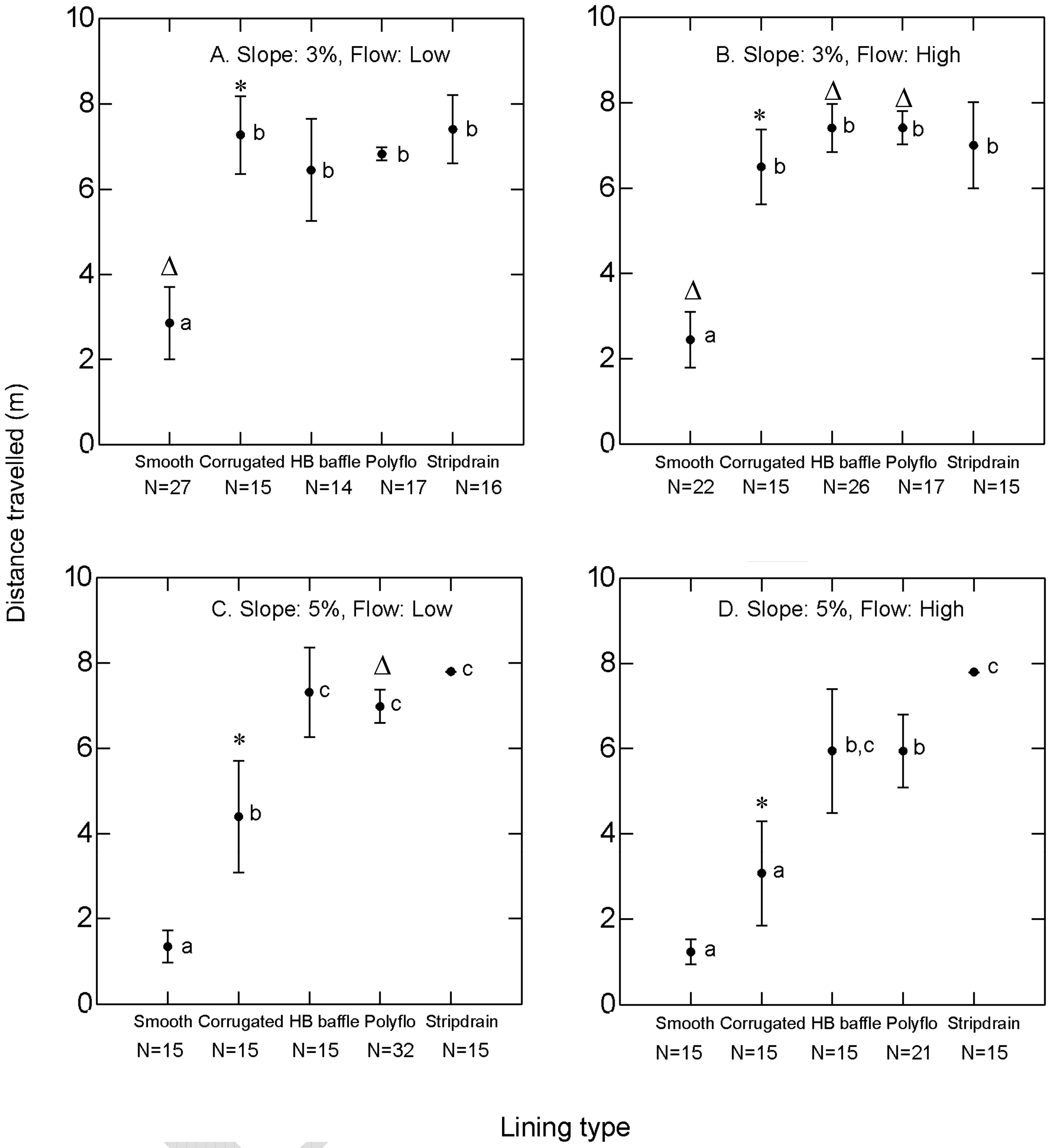

Figure 5. ***Mean distance swum by large inanga (≥ 60 mm), categorised by lining type, for each of the four experimental conditions. N = number of fish in each condition; vertical bars represent 95% confidence intervals. Means with the same letter are not different (ANOVA P<0.001). * and Δ represent significant differences between slope condition and fish size respectively (P<0.001).***

Table 1. *Mean distance swum and vertical elevation achieved by small inanga (< 60 mm) in each of the experimental trials.*

Lining Type	N	Flow Rate (ls^{-1})	Slope (%)	Mean Distance Swum (m)	Standard Deviation (m)	Elevation Achieved (m)
smooth	40	4	3	1.29	0.91	0.04
smooth	15	4	5	1.00	0.40	0.05
smooth	37	6	3	1.12	0.52	0.03
smooth	18	6	5	0.77	0.46	0.04
corrugated	17	4	3	6.16	1.95	0.18
corrugated	16	4	5	2.68	1.40	0.13
corrugated	18	6	3	5.28	1.78	0.16
corrugated	15	6	5	1.82	1.20	0.09
herring-bone baffle	33	4	3	5.63	2.20	0.17
herring-bone baffle	18	4	5	4.75	2.61	0.24
herring-bone baffle	37	6	3	5.72	2.07	0.17
herring-bone baffle	15	6	5	3.28	2.19	0.16
polyflo®	20	4	3	6.68	0.59	0.20
polyflo®	24	4	5	5.66	1.63	0.28
polyflo®	17	6	3	5.49	1.92	0.16
polyflo®	21	6	5	4.57	1.29	0.23
stripdrain®	20	4	3	6.74	1.89	0.20
stripdrain®	16	4	5	7.21	1.15	0.36
stripdrain®	22	6	3	7.08	1.79	0.21
stripdrain®	18	6	5	7.11	1.84	0.36

Table 2. *Mean distance swum and vertical elevation achieved by large inanga (≥ 60 mm) in each of the experimental trials.*

Lining Type	N	Flow Rate (ls^{-1})	Slope (%)	Mean Distance Swum (m)	Standard Deviation (m)	Elevation Achieved (m)
smooth	27	4	3	2.86	2.15	0.09
smooth	15	4	5	1.35	0.68	0.07
smooth	22	6	3	2.44	1.46	0.07
smooth	15	6	5	1.24	0.54	0.06
corrugated	15	4	3	7.28	1.64	0.22
corrugated	15	4	5	4.39	2.38	0.22
corrugated	15	6	3	6.50	1.58	0.20
corrugated	15	6	5	3.08	2.21	0.15
herring-bone baffle	14	4	3	6.45	2.07	0.19
herring-bone baffle	15	4	5	7.31	1.88	0.37
herring-bone baffle	26	6	3	7.41	1.40	0.22
herring-bone baffle	15	6	5	5.95	2.63	0.30
polyflo®	17	4	3	6.83	0.29	0.20
polyflo®	32	4	5	6.98	1.08	0.35
polyflo®	17	6	3	7.42	0.75	0.22
polyflo®	21	6	5	5.95	1.87	0.30
stripdrain®	16	4	3	7.41	1.50	0.22
stripdrain®	15	4	5	7.80	0.00	0.39
stripdrain®	15	6	3	7.01	1.81	0.21
stripdrain®	15	6	5	7.80	0.00	0.39

Ramp Slope, Flow Rate, and interaction Effects

As discussed above, the relationship between distance swum by fish, ramp slope, and flow rate was independent of total fish length. That is, fish of all lengths were affected in the same way by changes in ramp slope or flow rate.

The slope of the ramp during each experimental condition had a significant effect ($P < 0.05$) on the mean distance swum by fish on each of the substrate types tested ($p < 0.001$ corrugated) in 82% of trials (Figures 4 and 5). At higher ramp slopes, the distance swum by fish generally decreased – except for large fish tested on the Stripdrain® and herring-bone baffle substrate types at 4 l s^{-1} and 6 l s^{-1}, and Polyflo® substrate type at a 4 l s^{-1} flow rate. The greater distances swum in these trials at 5% slope were not significantly different from those achieved at 3% slope, and are likely to be influenced by the truncation of data due to fish often negotiating the entire ramp.

The rate of water flow over the ramp during each experimental condition did not have a significant effect on the distance swum by fish, except on the Polyflo® substrate type, where it was a significant factor ($p < 0.05$) during all trials (Figures 4 and 5). Increasing the flow rate generally reduced the distance swum by fish tested on the Polyflo® substrate type, but during the experimental trial of large fish at a slope of 3 %, significantly greater distances were achieved when the flow rate was increased from 4 l s^{-1} to 6 l s^{-1} ($p < 0.05$).

No consistently significant interaction effects were discovered. However, a significant interaction effect between size (grouped) and ramp slope was apparent from data collected from fish tested on the smooth and herring-bone baffle substrate types ($p < 0.05$), but not the corrugated, Polyflo®, or Stripdrain® substrate types. Only fish tested on the Polyflo® substrate type gave evidence of an interaction effect between size (grouped) and flow rate ($p < 0.05$). These interactions suggest that at increased slopes, and on Polyflo® as flow is increased, large fish are able to swim greater distances than small fish. Size, slope, and flow rate, as well as the size and slope interaction effect have already been noted as being significant on the Polyflo® substrate type. It is not surprising then that there is a significant interaction effect between these three variables ($p < 0.05$). Interestingly, large fish tested on a ramp of 3% slope swam farther when the flow rate was increased ($p < 0.05$), and comparable distances when slope was increased at the 4 ls^{-1} flow rate. This behaviour was also evidenced on the Stripdrain® substrate type, but due to the truncation of data caused by the majority of fish successfully negotiating the ramp, no test statistics could be calculated.

DISCUSSION

Fish size (grouped as small < 60 mm, large ≥ 60 mm) and ramp slope were the most significant factors affecting the mean distance swum on any one of the five substrate types tested. Fish were able to swim farthest when ramp slope was at 3 % (as opposed to 5 %), probably as a result of the lower water velocity. As to be expected, large fish were generally able to swim farther than small fish due to their capacity for increased power production (Baker and Boubée, 2006). No significant effect of flow rate or consistent interaction effects between slope, flow rate, or fish size on the mean distance swum was evidenced. In contrast to suggestions by previous studies (Baker and Boubée, 2006) that excessive ramp length may prevent successful passage attempts, the ramp length investigated in the current study was too short to rigorously evaluate the Stripdrain® substrate type. It is likely that the use of a longer ramp would also have improved the validity of data collected on the Polyflo® and herring-bone baffle substrate types. Despite these problems with data truncation, the Stripdrain® substrate type facilitated the greatest mean distances swum for both small and large fish under each experimental condition by most effectively reducing the water velocity while increasing water depth. The maximum vertical elevation achieved during the experimental trials was 0.39 m, although this was restricted more by the length of the ramp rather than fish swimming ability.

The findings of the current study concur with Baker and Boubée (2006), who found that inanga were able to successfully negotiate ramps sloped at 15° (25 %). Significantly less could do so at 30°, and very few were successful at 45°. Redfin bullies, which are able to both swim and 'climb' past obstacles, could successfully negotiate ramps of all slopes tested, but with decreasing success as slope increased. Miradrain® (or Stripdrain® as it is now sold) allowed the highest rate of inanga passage at all slopes, and for redfin bullies only at a slope of 30° - otherwise it was comparable to the other substrate types tested (sand, gravel, Cordrain®, and brush).

The barriers present in the Thames-Coromandel District, perched on average 0.6 m for barriers at most flows, cannot be remediated with the experimental ramps examined in the current study. However, barriers at low flows only, which are perched on average by 0.3 m, could be eliminated using ramps covered in Stripdrain®. Barrier remediation based on these results is unlikely to be cost effective in some circumstances, however, as previous studies have found that the same vertical elevation can be achieved on a 1.5 m long ramp sloped at 25 % (Baker and Boubée, 2006). In order to fully address the problem of perched culverts within the Thames-Coromandel District, greater vertical elevation must be achieved by fish moving through passage structures. Due to the large number of structures required, and the often limited area available for construction at many sites, the most cost effective option is believed to be the investigation of ramps shorter and steeper than those used in the current study. A direct extension of the 15° ramp investigated by Baker and Boubée (2006) to a length of 2.3 m is a potential starting point for further investigations; which should also investigate a wider range of species.

The provision of a continuous wetted margin is considered essential where the passage of species capable of climbing is desired. Further, the reduced water velocities near this margin are likely to be crucial to the successful passage of many swimming species. Aside from velocity, the slope of the ramp should not be such that the flow becomes too turbulent or shallow, which would make it difficult for fish to maintain their balance and/or buoyancy (Yasuda *et al*, 2004). Juvenile fish have been found to suffer increased rates of mortality when exposed to highly turbulent environments, so reducing or eliminating this cause of mortality during larval development is essential to maintaining natural recruitment and ensuring the long term population sustainability for many species (Baumgartner *et al*, 2006). The provision of passage for introduced species (i.e. trout) may be more successful over a longer more gently sloping ramp than a shorter and steeper one; due to the increased water depth provided by the former (Kowarsky and Ross, 1981). However, passage for these species over steep short ramps may still be possible at elevated flow levels.

Each of the factors detailed above, including the vertical elevation to be achieved, must be considered within the context of the dynamic environment in which any fish passage structure will be required to operate. The flow rates investigated in this study and by Baker and Boubée (2006) are likely to represent only a portion of those encountered by fish in the wild. Some analysis of how the flow rates investigated to date relate to the flow regime of selected rivers and streams may therefore prove crucial to the success of ramps as a means of providing successful fish passage. It may be for example, that successful passage of native species in some streams is only possible during the peak of summer low flows, when the migration of most species has ceased. At other times of the year, when fish are actively moving upstream, the higher flows may prevent the effective operation of any fish passage structure or cause damage requiring constant maintenance.

In conclusion, the use of ramps for the provision of fish passage past small in-stream barriers such as perched culverts holds promising potential for real world implementation – both on a local, regional, and national scale. Ramps will need to be developed to address the site specific nature of the barrier (i.e. slope and length), but Stripdrain® - clearly the best performing substrate type – should always be used to reduce water velocity. A wetted margin must always be maintained, whether by using a semicircular ramp or tilting a rectangular ramp at 10° horizontally, to aid the passage of species capable of 'climbing' and to provide an area of reduced water velocity for swimming species (Baker and Boubée, 2006). The most pressing needs are to assess how flow regimes are likely to affect fish passage under natural conditions (i.e. assess periods over which successful passage is likely), and to experimentally investigate the suitability of ramps in the provision of passage for a wider range of species.

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