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Improving the upstream passage of two galaxiid fish species through a pipe culvert

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Abstract Movement between habitats in river fish assemblages is often restricted by instream structures such as culverts. The ability of diadromous common jollytail, *Galaxias maculatus* (Jenyns), and spotted galaxias, *Galaxias truttaceus* (Val.), to pass upstream through an *in situ* pipe culvert modified through the installation of baffles was assessed. Spoiler baffles (100 × 70 × 28 or 56 mm) were installed in three spatial arrangements along a 5.5-m section of the pipe, and individual fish passage assessed at three flow velocities (0.35, 0.70 and 1.0 m s^{-1}). Common jollytails (43–169 mm fork length, FL) were 10 times more successful in passing when baffles were present than under control conditions (baffles absent). Baffle size did not influence success, which increased with the spatial complexity of the baffle arrangement. Across all velocities, common jollytails (46–132 mm FL) and spotted galaxias (55–190 mm FL) were, respectively, 86 and 73 times more successful with the most complex baffle arrangement (overall 80% success) compared with control conditions (overall 13.5% success). Success for both species decreased at higher velocities under control conditions; however, when baffles were present, this trend persisted only for common jollytails. Installing small spoiler baffles may provide a simple, cost-effective solution to passage problems at culverts.

KEYWORDS: baffle, culvert, diadromous, fish passage, *Galaxias*, restoration.

Introduction

Dispersal among habitats can be critical to the ecological persistence of stream fish assemblages (Jungwirth, Muhar & Schmutz 2000). Freedom of movement over small spatial scales provides pathways to unexploited feeding habitats and shelter, minimises risk associated with predation and displacement through inter- and intraspecific competition (Harvey 1991), and allows utilisation of thermal refugia (Schaefer, Marsh-Matthews, Spooner, Gido & Matthews 2003). At larger scales, access to spawning habitat and the maintenance of genetic variability through movement of individuals, are essential processes for the expression of all life histories within populations, maximising relative fitness and adaptability to change (Schlosser 1995).

Barriers to dispersal, both physical and behavioural, may disrupt such processes, particularly in obligate migratory species. These impacts are most clearly demonstrated following construction of large-scale barriers, such as hydroelectric dams and water storage reservoirs, and have been extensively reported in Europe (e.g. Jungwirth 1996; Rivinoja, McKinnell & Lundqvist 2001) and North America (e.g. Bednarek 2001; Quinn & Kwak 2003). Fewer studies have addressed the influence of smaller-scale obstructions in shaping the dynamics of stream fish assemblages, particularly in temperate Australasian rivers (but see Baker 2003; Williams, Boubée & Smith 2005; Baker & Boubée 2006; Baumgartner 2006; New South Wales Department of Primary Industries 2006). Stream-crossing structures such as fords, low weirs and culverts make up the majority of potential physical barriers in Australian streams (Williams & Watford 1997; Pethebridge, Lugg & Harris 1998), and, like large barriers, are capable of isolation and fragmentation of previously continuous populations (Peter 1998).

Culverts are structures used to move water under a road at stream crossings. They form a rigid, hydraulically smooth boundary set into a dynamic stream environment, capable of altering local physical characteristics, hydraulic conditions and biotic linkages within streams. Although engineering guidelines for culvert design and construction are well established, the primary objective is typically to maximise the hydraulic capacity of the structure, with little atten-

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tion given to fish passage requirements (see Gibson, Haedrich & Wernerheim 2005). The steep gradients, high flow velocities and channel homogeneity typically associated with culverts, combine to form selective physical boundaries to fish movement due to inter- and intraspecific variability in swimming behaviour and performance (Baker 2003; Bates, Barnard, Heiner, Klavas & Powers 2003).

Several systems have been developed to improve the fish-passing capacity of existing culverts (see Boubée, Jowett, Nichols & Williams 1999; Bates *et al.* 2003). Baffles are one option; providing rest areas for upstream migrants and/or a continuous channel of low-velocity water. Most baffle systems are based on the swimming abilities of large-bodied species (e.g. adult salmonids) relative to the discharge velocities experienced during periods of large-scale movement and migration (Rajaratnam, Katopodis & Lodewyk 1991; Bates *et al.* 2003). Few baffle systems consider juvenile non-salmonid species, and the quantitative assessment of different fishway designs in passing such species has received little attention in Australia (but see Harris, Thorncraft & Wem 1998; Mallen-Cooper & Stuart 2007). In New Zealand, Boubée *et al.* (1999) examined swimming performance of common jollytail, *Galaxias maculatus* (Jenyns), and common smelt, *Retropinna retropinna* (Gill), and reviewed potential retrofitting options for improving upstream passage through culverts. Bowman & Rowe (2002) installed small spoiler baffles on a 2-m-long fish pass to assist upstream passage of common jollytail and smelt past a weir. More recently, Baker & Boubée (2006) explored the utility of ramps with differing surfaces and slopes in aiding upstream passage of *G. maculatus* and redfin bullies past small barriers. A baffled media (Miradrain®) was the most effective surface for passing juvenile and adult *G. maculatus* through an experimental 1.5-m-long ramp at cross-sectional velocities ≤ 1.37 m s^{-1}. With the exception of these works and a study by Nikora et al. (2003), few -quantitative published data on swimming performance in galaxiids are available. Therefore, further testing of alternative baffle systems in improving passage performance is warranted.

The Galaxiidae are Southern Hemisphere salmoniform fishes, broadly distributed across southern temperate latitudes (McDowall 2002). The spotted galaxias, *Galaxias truttaceus* (Val.) and *G. maculatus*, or common jollytail, are relatively widespread throughout southern Australian coastal rivers and are the numerically dominant fish species in coastal Tasmanian streams (Fulton 1990; Ault & White 1994). Riverine populations are diadromous, lack climbing ability and have a regular marine larval phase (Humphries 1989; McDowall 1996, 2002). Both species formed an important component of the commercial (pre-1974) and now solely recreational (post-1990) Tasmanian whitebait fishery and the common jollytail continues to dominate New Zealand and Chile commercial and recreational whitebait catches (McDowall 1996; Chile Department of Aquacultural Sciences, unpublished data). Thus, providing adequate migration pathways in fragmented stream networks may have important implications both for the persistence of local populations and for management of the whitebait fisheries.

This paper assesses the upstream passage of post-juvenile common jollytail and spotted galaxias past an *in situ* pipe culvert modified through the installation of small spoiler baffles. The specific objective was to determine if the installation of baffles into existing pipe culverts improves upstream passage of these species. Two spoiler baffle sizes were trialled, and the effectiveness of various combinations of baffle size and arrangement to improve passage success was explored in relation to manipulated flow velocity and fish size.

Materials and methods

Experimental culvert

Field experiments were conducted between December 2001 and March 2002. An existing road culvert situated on a third-order tributary of the Picton River in southern Tasmania was adapted for this study. The culvert, located on West Picton Road (43°08′ S, 146°43′ E), is a twin-pipe with a vertical headwall inlet. The two parallel reinforced concrete pipes have identical cross-sectional diameters of 1.5 m, total lengths of 22 m and gradients of 1.3% (Fig. 1). The dimensions, construction and gradient of this culvert is representative of over 1000 road culverts on Tasmanian streams containing populations of common jollytail and spotted galaxias (Tasmanian Department of Infrastructure, Energy & Resources (DIER), unpublished data).

The twin-pipe configuration allowed manipulation of flow through either pipe via a diversion weir installed immediately upstream. The weir was constructed from a series of star-pickets overlaid with 8-mm wire mesh, and reinforced with 4-mm plastic mesh. An adjustable gate was fitted to the most downstream star-picket, and the gate was positioned to obtain the desired flow conditions for each fish passage trial. The most downstream 5.5-m section of one culvert was used for the passage trials. A V-shaped net made from 2-mm flyscreen mesh was placed across the culvert outlet immediately below the

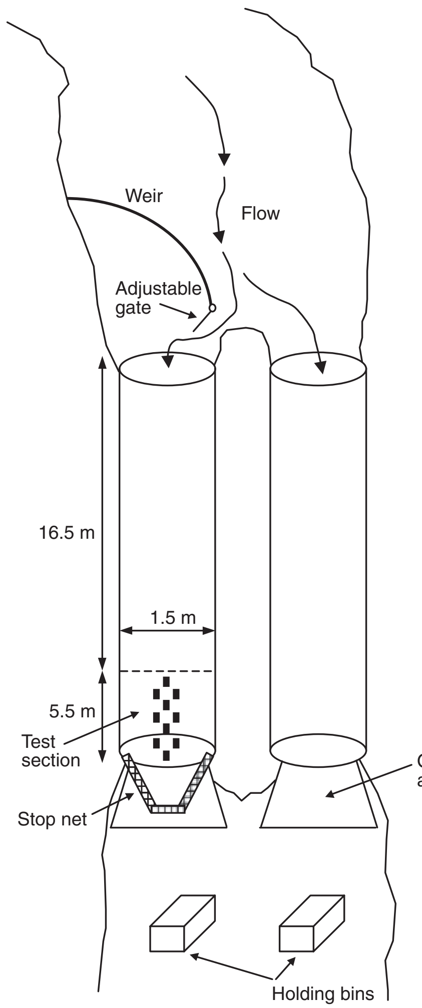

Figure 1. Schematic of the experimental culvert used for passage trials. Black rectangles represent baffles (not to scale).

test section to prevent fish escaping and to facilitate recapture (Fig. 1).

Fish collection

Fish were collected from four small coastal streams: Castle Forbes Rivulet (43°08′ S, 147°58′ E), Fleurty's Rivulet (43°07′ S, 146°60′ E), Browns River (42°58′ S, 147°19′ E) and Snug River (43°04′ S, 147°05′ E) using Smith-Root backpack electric fishing gear (model 12 or 12B) during spring/summer 2001–2002. A total of 644 common jollytails (43–169 mm fork length, FL, mean FL ± SD = 86.04 ± 22.16 mm) and 126 spotted galaxias (55–190 mm FL, mean FL ± SD = 116.03 ± 27.76 mm) were captured during the sampling period, typically in batches of 30–40 individuals. Captured fish were placed immediately into flow-through holding tanks (65 × 42 × 53 cm) during collection, and transferred to aerated containers (60 × 45 × 55 cm) filled to one-third depth with water from the source stream.

Transport to the experimental culvert was completed within 2 h of capture. Water temperature and dissolved oxygen were monitored during transport and holding. Upon arrival, fish were transferred to a flow-through holding bin (65 × 42 × 53 cm), covered and darkened with two layers of shade cloth, situated directly downstream of the culvert outlet (see Fig. 1). Fish were left to acclimate to stream conditions and recover from handling stress for a minimum of 24 h prior to testing. Similar procedures were used by Baker (2003) and Nikora, Aberle, Biggs, Jowett & Sykes (2003).

Baffle design and arrangement

The spoiler baffle design was required to provide low-velocity resting refuges for the galaxiids at the flows tested, while not markedly reducing the hydraulic capacity of the pipe. Using designs first described by Rajaratnam *et al.* (1991) as a template, a range of baffle shapes was trialled in a laboratory flume to examine flow and individual fish behaviour around the baffle. One final baffle shape was adopted, with two sizes, small and large, differing in height (28 and 56 mm) but with identical widths (70 mm) and lengths (100 mm) (Fig. 2a). Baffles were spray-painted a matt dark grey to mimic the colour of the culvert floor, and were attached to the floor with screws fitted into pre-drilled holes. Screw fittings enabled repeated re-arrangement of baffles within the test section. Baffles were cut from a hard, moulded plastic (De Neefe Signs Pty Ltd).

Baffle arrangements were adapted from Baker & Votapka (1990), Rajaratnam *et al.* (1991) and Boubée *et al.* (1999), and the flow dynamics through several arrangements trialled in a laboratory flume. Three arrangements (A, B and C), incorporating different numbers and spacing of baffles, were selected for testing in the culvert (see Fig. 2b).

Culvert hydraulics

Mean flow velocity (at 0.6 × water depth) was measured using a Schiltknecht Mini Air-2 velocity meter at the midpoint of the culvert, 1, 5 and 9 m upstream of the test section. Velocities were set at 0.35, 0.70 and 1.0 m s^{-1} for passage trials. These velocities were chosen from a review of literature describing burst and prolonged swimming speed thresholds for common jollytail (Mitchell 1989; Boubée *et al.* 1999; see also

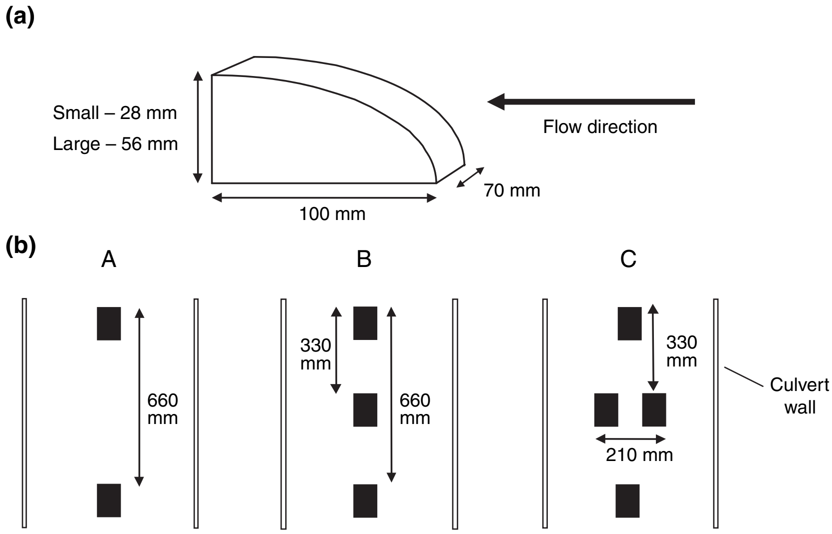

Figure 2. Baffle shape and arrangements used during fish passage trials: (a) baffle shape (plan view). (b) baffle arrangements across the culvert floor (A, B, C). Black rectangles represent baffles.

Nikora *et al.* 2003) and spotted galaxias (R. Walker, unpublished data), combined with examination of velocity time-series data measured from 1.5-m-diameter pipe culverts in the Picton River catchment during 1998–1999 (R. Walker, unpublished data).

Maximum depth (±1 mm) and wetted width (±0.01 m) were recorded at five equidistant positions along the test section (0.5, 1.5, 2.5, 3.5, 4.5 m upstream from the culvert outlet) (Table 1). These variables were positively correlated with flow velocity and each other (Spearman rank correlation, all $r_s > 0.85$, $P < 0.01$). Water temperature (±0.1°C) in the culvert was recorded at the beginning of each passage trial. Temperatures over the study period (10.4–13.7°C) were substantially lower than those documented in other studies of common jollytail swimming performance (see Baker 2003; Nikora *et al.* 2003; Baker & Boubée 2006), but were considered typical for forested Tasmanian streams during the spring/summer period. Variation in mean temperature among trials within each trial series was not substantial (i.e. ≤ 1°C) (Table 1). There are no data on the influence of temperature on the swimming performance of common jollytails or spotted galaxias (Nikora *et al.* 2003), but temperature is reported to have little effect on burst swimming capacity, the primary swimming mode displayed during the current experiments (Beamish 1978).

Testing procedure

Passage testing was undertaken between 09:00 and 18:00 h daily. An individual fish was removed from the holding container by hand dip-net and introduced to the downstream end of the test section within 10 s. The fish was held within the dip-net to allow orientation to flow for a maximum of 1 min, or until it moved upstream into the test section. Active swimming and resting behaviour was then recorded and timed until passage success or failure occurred. Passage success was defined as the upstream movement of an individual fish through the full 5.5-m test section. Failure was recorded when a fish was washed-out or swam into the downstream stop net after attempting upstream movement. Each fish was tested individually and only once, with observations made by one person situated at the culvert outlet. This approach enabled a clear view of the entire test section, whilst minimising disturbance to the fish's behaviour. Fish that did not attempt to swim upstream (between 5% and 8% of individuals tested per trial) were excluded from subsequent analysis. At the completion of each test, the fish was removed by hand, either from the downstream trap, or from within the culvert, measured (FL ± 1 mm) and placed into a second flow-through holding bin. At the conclusion of all trials on each day, fish were transferred into an aerated container (60 × 45 × 55 cm), and returned to their source streams.

Passage trials were conducted to identify a combination of baffle size and arrangement that maximised successful passage for each species (Table 1). Trial series 1 incorporated 12 trials with common jollytails (n = 19–20 per trial) to assess fish passage with all combinations of the two baffle sizes (small, large),

Table 1. Numbers of fish, fish lengths (FL), baffle sizes, baffle arrangements and hydraulic variables used in testing passage performance of common jollytail and spotted galaxias

n	FL (mm) (mean ± SD, range)	Flow velocity (m s^{-1})	Baffle size	Baffle arrangement	Maximum depth (mm) (mean ± SD)	Wetted width (m) (mean ± SD)	Water temperature (°C)
Trial series 1: Common jollytail							
Baffle trials							
19	77.5 ± 20.5 (46–110)	0.35	S	A	19 ± 0.8	0.29 ± 0.008	10.4
20	93.2 ± 23.0 (59–121)	0.35	S	B	14 ± 0.9	0.29 ± 0.003	10.5
20	84.9 ± 22.3 (53–118)	0.35	S	C	17 ± 1.0	0.36 ± 0.01	10.7
20	83.0 ± 18.0 (62–116)	0.35	L	A	18 ± 0.9	0.29 ± 0.002	10.9
20	96.6 ± 32.2 (60–169)	0.35	L	B	12 ± 0.7	0.29 ± 0.004	10.9
20	82.3 ± 26.4 (51–132)	0.35	L	C	17 ± 1.2	0.35 ± 0.005	11.0
20	72.4 ± 16.0 (52–112)	0.70	S	A	31 ± 1.2	0.42 ± 0.006	10.7
20	87.4 ± 28.0 (43–122)	0.70	S	B	27 ± 1.1	0.45 ± 0.008	10.7
20	87.0 ± 22.5 (55–117)	0.70	S	C	29 ± 0.7	0.45 ± 0.01	10.7
19	73.2 ± 16.9 (49–103)	0.70	L	A	35 ± 0.8	0.45 ± 0.005	11.1
20	82.1 ± 25.6 (47–115)	0.70	L	B	29 ± 0.9	0.41 ± 0.01	11.2
20	90.8 ± 25.6 (55–125)	0.70	L	C	29 ± 1.0	0.44 ± 0.009	11.4
Control trials							
20	89.7 ± 17.8 (54–129)	0.35	–	–	26 ± 0.3	0.29 ± 0.001	10.8
20	85.6 ± 23.2 (50–120)	0.70	–	–	39 ± 0.7	0.41 ± 0.001	10.9
Trial series 2: Common jollytail							
Baffle trials							
40	82.6 ± 21.1 (53–118)	0.35	S	C	13 ± 0.2	0.32 ± 0.003	12.8
40	79.1 ± 20.6 (51–133)	0.70	S	C	29 ± 0.6	0.45 ± 0.02	13.3
40	88.7 ± 19.6 (54–121)	1.00	S	C	61 ± 1.1	0.62 ± 0.01	13.4
40	85.8 ± 21.8 (51–132)	0.35	L	C	17 ± 0.4	0.35 ± 0.004	13.4
40	91.3 ± 22.5 (53–127)	0.70	L	C	29 ± 0.5	0.44 ± 0.008	13.7
40	87.8 ± 19.0 (59–125)	1.00	L	C	61 ± 0.9	0.62 ± 0.02	13.7
Control trials							
40	86.1 ± 19.8 (59–105)	0.35	–	–	26 ± 1.3	0.28 ± 0.001	13.7
40	89.2 ± 24.8 (46–111)	0.70	–	–	40 ± 0.9	0.40 ± 0.002	13.7
40	94.2 ± 18.2 (62–125)	1.00	–	–	55 ± 1.0	0.59 ± 0.002	13.6
Trial series 3: Spotted galaxias							
Baffle trials							
20	116.2 ± 29.5 (69–170)	0.35	L	C	19 ± 0.4	0.35 ± 0.007	11.7
21	113.9 ± 24.5 (68–166)	0.70	L	C	28 ± 0.6	0.46 ± 0.01	12.1
21	127.2 ± 25.5 (57–190)	1.00	L	C	61 ± 0.8	0.63 ± 0.009	12.3
Control trials							
20	106.0 ± 24.4 (55–101)	0.35	–	–	26 ± 0.1	0.31 ± 0.001	12.1
20	108.5 ± 27.4 (59–159)	0.70	–	–	39 ± 0.7	0.41 ± 0.004	12.0
20	126.0 ± 31.9 (65–175)	1.00	–	–	56 ± 1.1	0.59 ± 0.004	11.9

n, the number of fish tested in each passage trial. S = small baffle; L = large baffle. For details of baffle arrangements (A, B, C), see Fig. 2b.

three arrangements (A, B and C) and two flow velocities (0.35 and 0.70 m s^{-1}). The influence of baffle size was further evaluated using only arrangement C, with larger numbers of fish ($n = 40$ per trial) and incorporating a higher flow velocity (1.0 m s^{-1}) (trial series 2). Trials were then conducted with spotted galaxias (trial series 3). Three trials ($n = 20$ per trial) were run with large baffles installed in arrangement C at three flow velocities (0.35, 0.70 and 1.0 m s^{-1}). Data from a subsample of common jollytails (53–127 mm FL, mean FL ± SD = 88.6 ± 20.31 mm, $n = 120$) tested under identical conditions, was randomly selected for comparison with performance of spotted galaxias. Eight control trials were conducted to assess fish passage in the absence of baffles, with 20 or 40 individuals per trial at three flow velocities (0.35, 0.70 and 1.0 m s^{-1}). Control trials were conducted using fish drawn from the same sample populations as trials with baffles, and accompanied each trial series. Mean FL among trials within each trial series was not significantly different (single factor ANOVA, all $P > 0.05$) (Table 1).

Statistical analysis

Stepwise multiple logistic regression was used to examine the relative importance of three categorical independent variables – baffle size, baffle arrangement and flow velocity – and a continuous variable FL, in explaining the proportions of fish succeeding or failing to pass through the test section. Fish passage was coded as a binary response variable with passage success scored as 1, and failure as 0. Logistic regression models the logit transformation of an individual's probability of success as a linear function of the independent variables. The primary output returns parameter estimates and their associated probability values, together with odds ratios (odds) for each parameter. The odds represent the change in likelihood of passage success when moving from a reference parameter level to other levels of the same parameter (see Hosmer & Lemeshow 2000 for a detailed discussion). The influence of fish length (i.e. the increase in the odds of passage success with 10 mm increases in FL) was considered for the entire data set in each trial series separately. All models were generated in SYSTAT version 10.0 (SPSS Inc., Chicago, IL, USA).

Concurrent with the present study, a detailed analysis of swimming behaviour during passage attempts was undertaken to examine variation in mean proportions of the total passage time that each fish spent in 'active' and 'resting' behaviours among trials and between species (J. I. Macdonald & P. E. Davies, unpublished data). This analysis is beyond the scope of the present study, but a summary of the main observations is presented below.

Results

Fish behaviour

Soon after release at the downstream end of the test section, fish typically sought rest at slower velocity positions directly downstream, upstream or adjacent to spoiler baffles, or less commonly at the shallow, lateral margins of the wetted area. Fish used these refuges for recovery between the active burst swimming bouts required to progress upstream or maintain a stationary position within high-velocity zones. The proportion of time spent resting near baffles increased with the number of baffles present and flow velocity for both species. Furthermore, there was a general increase in time spent in a passage attempt with the complexity of the baffle arrangement and a consistent decrease in time with increasing velocity (J. I. Macdonald & P. E. Davies, unpublished data).

During control trials, fish attempted to progress upstream along the deepest pathway near the centre-line of the test section, either in one continuous burst swimming bout, or a series of bursts interspersed with periods of passive downstream drift. Some individuals found useable resting refuges on the lateral margins, where they remained essentially stationary with their bodies partially exposed, sometimes for substantial time periods before re-entering the main flow.

There were interspecific differences in behaviour during passage attempts. Spotted galaxias utilised low-velocity resting zones around baffles for greater proportions of time than common jollytails, yet common jollytails used lateral refuges more often and for longer periods. Larger common jollytails (≥70 mm FL) rested near baffles and lateral margins more frequently than smaller individuals (< 70 mm FL), whereas fish length did not influence spotted galaxias behaviour (J. I. Macdonald & P. E. Davies, unpublished data).

Trial series 1

The presence of baffles significantly improved passage success of common jollytails (odds = 9.80, $P <$ 0.001). Individuals were approximately 10 times more successful in passing through the test section when baffles were present than when absent. A significant interaction of fish length and flow velocity (odds = 0.96, $P = 0.014$) was identified and investigated. Passage success of smaller individuals (FL < 70 mm) decreased markedly as velocity increased (odds = 0.67, $P = 0.017$), whereas success of larger specimens (FL ≥ 70 mm) was not significantly influenced by changes in velocity from 0.35 to 0.70 m s^{-1} (odds = 1.01, $P = 0.298$).

Differences in baffle size had no significant effect in determining fish passage (odds = 0.99, $P = 0.286$). However, as information on passage results when using both small and large baffles was still of interest, regressions were conducted on each baffle size separately, thus simplifying the logistic models. The influence of baffle arrangement ($P < 0.001$) and individual FL ($P < 0.001$) were highly significant in explaining fish passage with small baffles. Successful passage was positively related with the number of baffles present and the arrangement complexity. The most complex arrangement (C) was most effective (Fig. 3a), with fish tested being 21 times more likely to pass than individuals tested with arrangement A (odds = 21.34, $P < 0.001$). Fish were more successful with arrangement B than with arrangement A (odds = 1.79, $P =$ 0.037). Fish length was a significant factor in these

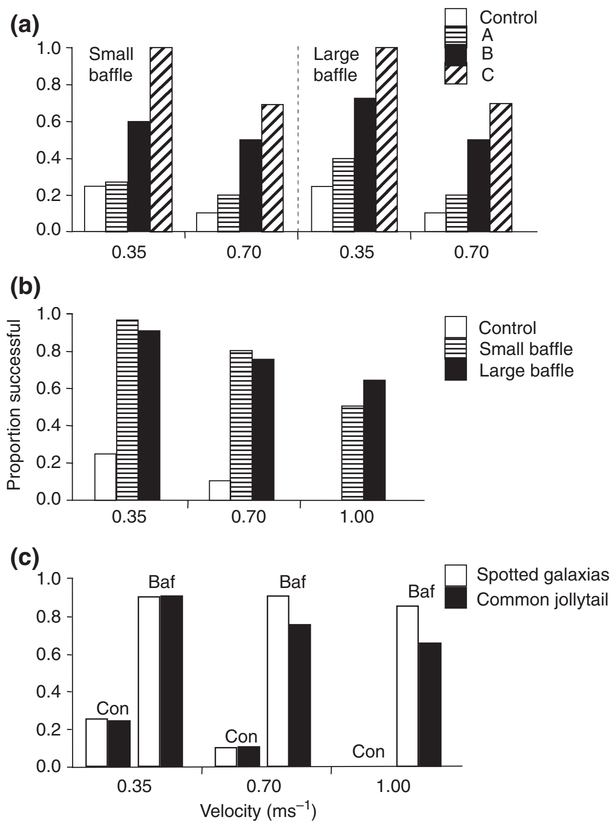

Figure 3. Proportion of individuals successfully passing the test section for: (a) Trial series 1 – common jollytails (n = 19–20 per trial). Control trials and trials with small (100 × 70 × 28 mm) and large (100 × 70 × 56 mm) baffles in three arrangements (A, B, C) at two test velocities (0.35, 0.70 m s^{-1}). (b) Trial series 2 – common jollytails (n = 40 per trial). Control trials and trials with small and large baffles in arrangement C at three test velocities (0.35, 0.70, 1.00 m s^{-1}). (c) Trial series 3. Proportions of spotted galaxias (n = 20 per trial) and a randomly selected subsample of common jollytails (n = 20 per trial) successfully passing the test section, under control conditions (Con) and with large baffles in arrangement C (Baf) at three test velocities (0.35, 0.70, 1.00 m s^{-1}).

trials. An increase of 10 mm in FL doubled the odds of successful fish passage (odds = 2.20, P < 0.001).

Baffle arrangement was again important in explaining variation in fish passage (P < 0.001) when large baffles were used (Fig. 3a). There was significant variation in passage success between velocities (P = 0.015), but no significant influence of fish size (P = 0.297). Common jollytails were 18 times more likely to pass successfully with arrangement C, than with A, when data from both velocities were pooled (odds = 18.44, P < 0.001). The odds of passage success with arrangement B were 3.7 times higher than with arrangement A (odds = 3.66, P = 0.074).

Common jollytail were only 22% as successful at 0.70 m s^{-1} compared with 0.35 m s^{-1} (odds = 0.22, P = 0.015). Flow velocity and changes in baffle arrangement, rather than baffle size, appeared to play the primary role in determining the proportion of common jollytails successfully passing through the test section. Fish performed best with arrangement C in all cases. There was no significant difference in passage success between baffle sizes.

Trial series 2

With larger numbers of common jollytails tested, the presence of baffles arranged in arrangement C increased the odds of passage success by 86 times compared with control conditions (odds = 85.56, P < 0.001, Fig. 3b). Baffle size was again not significant in determining success (P = 0.878). Flow velocity had significant influence on success (P < 0.001), which decreased with increasing velocity. Fish passage success was reduced to 19% (odds = 0.19, P < 0.006) and 6% (odds = 0.06, P = 0.001) at 0.70 and 1.0 m s^{-1}, respectively, compared with fish tested at 0.35 m s^{-1}. Although baffle size was non-significant in explaining successful passage, there was a small increase in success with large baffles at 1.0 m s^{-1}. Fish length also had a significant effect, but improvement in the odds with 10 mm increases in FL was not substantial (odds = 1.05, P < 0.001).

Trial series 3

Large baffles installed in arrangement C increased the odds of passage success by 73 times for spotted galaxias compared with control conditions (odds =72.80, P < 0.001, Fig. 3c). Successful passage of spotted galaxias through the control decreased at higher flows. When baffles were present, success was unaffected by increases in velocity from 0.35 to 1.0 m s^{-1} (P = 0.689), and fish length also had no significant influence on the odds of success (P = 0.958).

Species comparison

Despite the significant discrepancy in mean FL between species in this comparison (two-sample t-test, P < 0.01), under identical test conditions (large baffles installed in arrangement C), common jollytails and spotted galaxias displayed little difference in passage ability at 0.35 m s^{-1}. At higher velocities, however, spotted galaxias consistently outperformed common jollytails (see Fig. 3c). Among all velocities and excluding control trials, spotted galaxias were 30% more likely to pass successfully than common jollytails (odds = 1.30, P = 0.06). Success rates during control trials were uniformly low for both species, decreasing with increasing velocity (Fig. 3c).

Discussion

The installation of baffles into smooth-walled culverts increases both the structural and hydraulic complexity within them, potentially expanding the habitat available to fish moving upstream by producing low-velocity resting niches and reducing distances swum between rests at high velocities (Baker & Votapka 1990). The baffle systems trialled appeared to create such within-pipe heterogeneity, resulting in substantial improvement in successful passage of common jollytails and spotted galaxias. Fish were at least 10 times more successful in passing upstream through the test culvert section when baffles were present, with success rates for common jollytails increasing with the complexity of the baffle spacing.

The arrangement of baffles played a primary role in explaining variation in passage success rates. The most complex baffle arrangement (C) was the most effective in facilitating passage of common jollytails. It outperformed arrangements A and B at all test velocities and improved the odds of success by 86 times for common jollytails, and 73 times for spotted galaxias compared with tests without baffles. Overall, 80% of individuals successfully passed the test section with arrangement C, compared with 13.5% passing the control section. The greater available resting area associated with higher baffle densities, shorter longitudinal and lateral distances between low-velocity zones, and reduction in high-velocity areas adjacent to baffles, are all potential factors contributing to a more effective pathway for upstream movement.

High flow velocity has been widely considered the principal determinant in impeding fish movements through culverts. Within-culvert velocities commonly exceed the swimming capabilities of local species, causing rapid fatigue during burst swimming bouts, and resulting in temporary or permanent barriers to movement (e.g. Belford & Gould 1989; Toepfer, Fisher & Haubelt 1999). In the present study, successful passage of common jollytails and spotted galaxias through the unmodified culvert was greatly reduced at higher velocities. In the absence of baffles, the uniformity of flow and absence of low-velocity rest areas, particularly at 0.70 and 1.0 m s^{-1}, necessitated a shift to extended burst swimming bouts, commonly ending in downstream drift into the stop net as individuals fatigued after only short gains in distance upstream.

For small fish to burst swim against higher velocity currents over extended distances requires reduced space between low-velocity resting refuges. In New Zealand, Mitchell (1989), Boubée *et al.* (1999) and Nikora *et al.* (2003) independently estimated the maximum burst, and prolonged swimming speeds and distances before muscular fatigue of common jollytails. All reported burst velocities within the range 0.47–1.35 m s^{-1}. At 0.35 m s^{-1}, Boubée *et al.* (1999) predicted a maximum burst distance of 6.2 m for an average 70 mm individual. At 0.70 m s^{-1} the expected distance reduced to 3.3 m with a further decrease to 2.1 m at 1.0 m s^{-1}, the highest velocity tested in the present study. Furthermore, Baker & Boubée (2006) reported very limited passage of juvenile and adult common jollytails past a short, 1.5-m-long bare ramp of 15° slope, at cross-sectional velocities of approximately 1 m s^{-1}. These results correlate closely with the distances travelled by common jollytails during passage attempts in the absence of baffles (J. I. Macdonald & P. E. Davies, unpublished data), and suggest that successful passage through longer (over 4 m), unmodified culverts would be severely limited at velocities that require constant burst swimming (e.g. 0.70 and 1.0 m s^{-1}).

The general positive relationship between fish size and burst swimming performance has been widely documented (e.g. Nikora *et al.* 2003; Ojanguren & Braña 2003), with both morphological (e.g. fin shape and size – Weihs 1989; Plaut 2000), and physiological (e.g. increased anaerobic capacity with size – Kieffer 2000) factors suggested in determining its scale. For common jollytails, Nikora *et al.* (2003) related burst swimming velocity to the fish's Reynolds and Froude numbers in describing a positive relationship between fish length and burst performance. The higher passage success observed for larger common jollytails during the present study reflects this positive relationship, yet, unlike common jollytails, successful passage of spotted galaxias did not change with fish length. If this result reflects more powerful burst swimming bouts for this latter species at the smaller size classes tested (R. Walker, unpublished data), and/or the more effective use of rest refuges around baffles that was observed during passage attempts, or is simply an artefact of sampling and experimental design remains in question. To address these issues adequately, a detailed flume-based study into the swimming performance of spotted galaxias is recommended, incorporating small 'whitebait' juveniles, and examining allometric relationships between physiological processes, body dimensions, shape and condition.

In fast flow environments, preferential selection of resting refuges by fish that reflect their body size is well known (e.g. Gerstner & Webb 1998; Harding, Burky & Way 1998). In the present study, however, the height difference between small and large baffles had no affect on passage of common jollytails or spotted galaxias at any test velocity. There are several possible explanations for this. At all three test velocities (0.35, 0.70 and 1.0 m s^{-1}) the near-bed flow regime within the test section was characterised by chaotic flow, according to the classification scheme developed by Davis & Barmuta (1989). Chaotic flow is a category of hydraulically rough flow encountered when water depth is less than or equal to three times the mean height of bed roughness elements. Under these conditions, the flow structure is complex, and near-bed velocities are determined by local flow boundary characteristics (Young 1992). The mean maximum water depths for the three test velocities ranged between 12 and 61 mm, and the small baffles were overtopped at 0.70 and 1.0 m s^{-1}. Despite marked variation in hydraulic conditions and potential differences in turbulence energy within the test section between baffle sizes, particularly at 1.0 m s^{-1}, the fusiform, low body profile of the common jollytails and spotted galaxias tested appeared to permit exploitation of low-velocity refuge zones immediately downstream of both small and large baffles. Thus, the two baffle sizes appeared to provide adequate shelter in a range of flow conditions for all sizes of fish tested, suggesting that an approximate scaling of baffle size to fish size may be sufficient to generate a useable refuge.

In summary, this paper has demonstrated the utility of spoiler baffles in offering a simple, cost-effective option for improving the passage of post-juvenile galaxiids at relatively low flows. The findings can be applied to any culvert of similar construction at the range of flow velocities tested, but caution is required when extrapolating these results to passage of upstream migrating juveniles (whitebait), which were not tested here. Future experiments incorporating smaller size classes, and investigating the influence of temperature and hydrodynamic variables such as turbulence energy and intensity within retrofitted culverts, will provide valuable information for the development of optimal passage solutions for target species.

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