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Evaluation of cone fishways to facilitate passage of small-bodied fish

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ABSTRACT

Fishways are being provided more regularly than ever before and new designs are needed to provide passage for whole fish communities. Despite recent progress, fishways have frequently performed poorly, especially for small-bodied fish (i.e. 10–100 mm long), which can form large aggregations below stream barriers. This was the genesis for the development of the cone fishway design, a new style of technical fishway which consists of a series of pre-fabricated cone-shaped concrete baffles installed laterally within a concrete channel. The cone design arose from the need to install rock ramp fishways at remote sites where rock was unavailable and where maintenance would be infrequent. The objective of the present study was to evaluate the suitability of the new cone fishway design to provide passage for small-bodied diadromous species (i.e. < 100 mm long). Cone fishways were evaluated at three low head (e.g. < 3 m high) case-study sites in tropical and temperate Australia and in total, 45 species and 28,556 fish were collected. There was passage of a broad range of the target size-classes of small-bodied fish and individuals as small as nine mm could ascend. However, further work is needed to quantify the proportion of the small-bodied fish population in the river downstream which find and pass through the cone fishways. The most suitable experimental application of the cone fishway is at sites where there is: (i) a narrow (e.g. < 0.4 m) headwater range, and (ii) where passage of small-bodied fish is a major ecological priority. Cone fishways provide a useful and novel option to improve passage of small-bodied fish, at appropriate sites, and contribute to a contemporary vision of restoration of whole fish communities.

1. Introduction

Fishways are being constructed more frequently than ever before and there is a new emphasis on adapting designs to pass a wider range of native fish species and sizes upstream and downstream (Silva et al., 2018). Passage for whole fish communities is a functional objective in the rivers of Europe (Benitez, Matondo, Dierckx, & Ovidio, 2015), North America (Pennock et al., 2017), Canada (Landsman, McLellan, Platts, & van den Heuvel, 2018), South America (Pompeu, Agostinho, & Pelicice, 2012), Australia (Mallen-Cooper & Stuart, 2007), and SE Asia (Baumgartner, Zampatti, Jones, Stuart, & Mallen-Cooper, 2014; 2018). Despite design improvements, fishways have still frequently performed poorly and this is especially true for passage of small-bodied fish (Brown et al., 2013; Bunt, Castro-Santos, & Haro, 2012; Roscoe & Hinch, 2010).

The paradigm shift from fishways for large-bodied commercial species to passage of entire fish communities began in Australia in the late 1990s. The shift came from a recognition that existing fishways were unsuitable for small-bodied and juvenile migratory fish (i.e. 10–100 mm long), with relatively poor swimming abilities (Mallen-Cooper, 1999; Barrett & Mallen-Cooper, 2006). The problem of small-bodied fish passage was most evident at tidal barriers where there were accumulations of very small and juvenile diadromous fish (10 + mm long) which often encompassed a whole year's recruitment cohort (Harris, 1983). For fishway designers, these small fish with a lower absolute burst swimming ability than large fish, determine the maximum water velocity and turbulence within the fishway and attempting to accommodate differing fish passage functions in one fishway often led to partial or wholly ineffective fishways (Harris, Kingsford, Peirson, & Baumgartner, 2017).

To improve upstream passage efficiency (i.e. percentage of fish which enter and successfully ascend a fishway) for small-bodied fish, low gradient (i.e. 1V:30H) rock ramp and vertical-slot fishways were viewed as the preferred solution in the late 1990s and 2000s (Stuart & Mallen-Cooper, 1999; Mallen-Cooper & Brand, 2007). These designs originated from German and North American fishways and in Australia were adapted to include a flatter floor gradient with lower pool-to-pool drops, and lower water velocities and turbulence (Harris et al., 2017). Hence, fishways became longer and more expensive and while there was improvement in small-bodied fish passage efficiency, the smallest

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size-classes (i.e. < 40 mm long) still failed to ascend (Stuart, Zampatti, & Baumgartner, 2008). To remediate this situation, at high priority sites, two fishways with separate hydrological and ecological functions were constructed: a high slope and high discharge fishway for strong swimming species and a low slope, low discharge fishway for poor swimming species (Baumgartner et al., 2014, 2012; Bice, Zampatti, & Mallen-Cooper, 2017).

A novel design solution to improve passage of small-bodied fish, while still passing larger fish, evolved from a uniquely Australian situation: having many sites that were so remote that transport of large quantities of rock or casting concrete *in situ* was cost prohibitive. To resolve this challenge, a pre-cast design was developed that incorporated the previous knowledge from rock ramp and vertical-slot fishways, could be transported cost-effectively and applied in a modular manner to suit the local fish ecology and hydrology. This was the genesis for the development of the cone fishway design, a new style of technical fishway which consisted of a series of pre-fabricated cone-shaped concrete baffles installed laterally within a concrete channel. The cone design was an engineered technical fishway with hydraulic similarities to step-pool nature-like fishways which are also known as lateral ridge rock fishways (Beatty, Morgan, & Torre, 2007; Franklin, Haro, Castro-Santos, & Noreika, 2012).

During the development of the cone fishway design it was important to follow four logical steps: (i) clearly identify the migratory fish community, (ii) field test wild fish within prototype cone fishways, (iii) design and build the fishway, and (iv) evaluate the fishway against clear performance standards and improve designs (Mallen-Cooper, 1999). The objective of this study was to evaluate the suitability of the cone fishway design against step four which was to facilitate passage of all size classes of small-bodied fish from 10 to 100 mm long. Field work was undertaken at three case-study sites: the Norman River in the northern tropics of Australia, the Fitzroy River in the north-eastern tropics, and the Maribyrnong River in the southern temperate zone (Fig. 1). At each site, a series of field experiments were undertaken to assess the effectiveness of each cone fishway to pass small-sized fish and to refine designs for potential application at other sites.

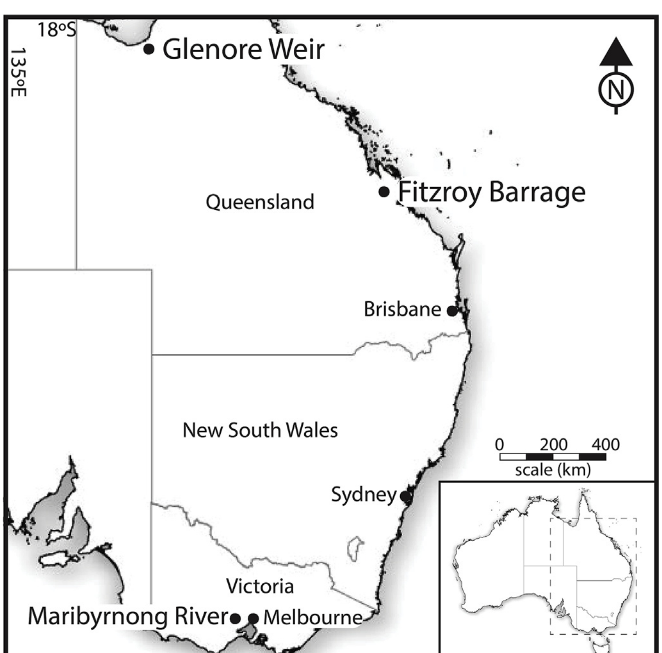

Fig. 1. Location of the three case-study sites on the northern tropical Glenore Weir (Norman River), Fitzroy River barrage and the southern temperate Maribyrnong River.

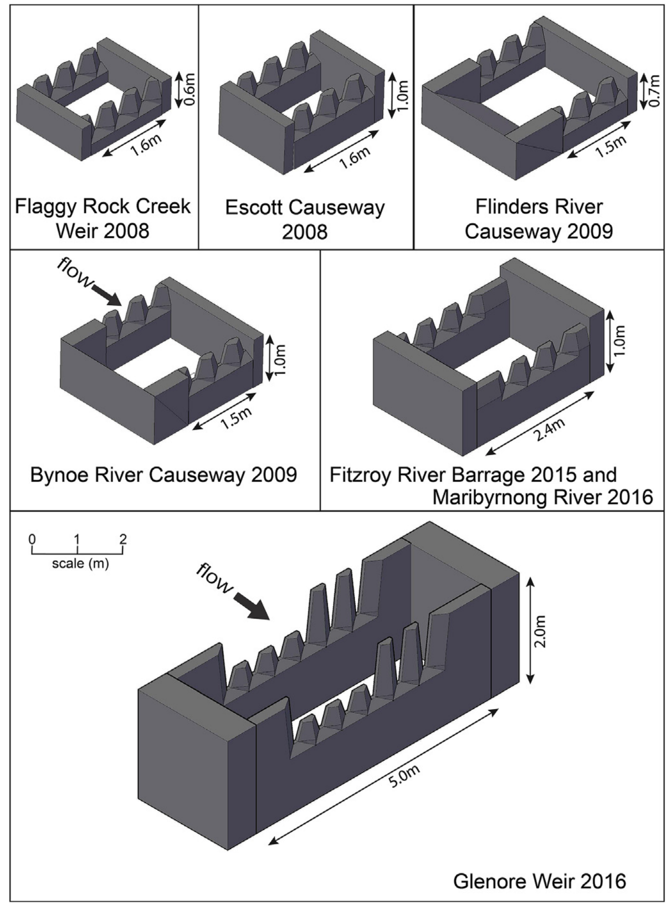

Fig. 2. Scale-drawings showing the design evolution of the cone fishway.

2. Materials and methods

2.1. Cone fishway evolution

The first prototype cone fishways were developed in 2006 and applied in four tropical coastal rivers of Queensland, north-eastern Australia. The prototype field trials tested passage of wild small-bodied migratory fish using traps at the top (upstream) and bottom (downstream) of each fishway. The early prototype cone designs were then refined to include: a deeper channel to reduce turbulence, larger gaps between the cones to reduce debris accumulation, faceted cone faces to reduce fish swimming distance, flat-backed cones to aid casting, and to create greater backwater resting areas. The cone design incorporates high turbulence and velocities in the centre of the channel, as well as low velocity and low turbulence zones on the edges, where fish can rest while ascending. The final evolution of the cone design is presented in Fig. 2.

The generic design elements of the cone fishway included: a low channel gradient (1V:21H; 4.7%), with a 2.4 m wide, 1.0 m deep channel and pool volume of 2.52–3.60 m^3, depending on depth. The pre-cast 0.2 m thick concrete trapezoidal cross-section baffles were set 1.5 m apart with a 0.08 m head drop between each, thus giving a maximum water velocity of 1.25 m/s^{-1} and a theoretically calculated average volumetric dissipated power (i.e. average pool turbulence) of 12 $W\,m^{-3}$ (Cd = 0.70). At each turn of the fishway channel there was a larger pool which was two times the standard pool volume. Each baffle gap was offset from the adjacent baffle gap to ensure no direct flow transfer between pools. The cones were 0.3 m high with internal gaps of 0.31 m at the cone top and 0.10 m at the cone base. There was a 0.15 m faceted sloping front cone face to maximise surface area and boundary layer conditions; the rear downstream face of the cone baffle was flat to increase manufacturing efficiency. In October 2018, each cone baffle cost AUD$900.

2.2. Glenore Weir and cone fishway

The 420 km long Norman River has a catchment area of 50,445 km^2 and flows into the Gulf of Carpentaria in northern Australia. Mean annual discharge is 137 GL (GL) but in the dry season (April–November) the system becomes intermittent with flow events only occurring after monsoonal rainfall and tropical cyclones in the wet season (December to March). Glenore Weir is 103 km from the river mouth and is immediately above the tidal influence. The concrete weir is 3.68 m high and 250 m wide with a central ogee crest and concrete and rock abutments. There are 48 species of native freshwater fish with 17 species classified as diadromous (Burrows & Perna, 2006).

The 70 m long Glenore Weir cone fishway was completed in May 2016, consisting of 40 pre-cast cone baffles. The site-specific design modifications were to extend headwater (i.e. the range of levels experienced by the impounded water upstream of the weir) functionality by widening the channel to 5 m and including high cones (0.9 m) on the side of the channel and low cones (0.3 m) in the middle (Fig. 3). At high headwater there was higher discharge down the centre of the fishway channel and the low cones became submerged, the spatial distribution of turbulence was concentrated in the middle of the channel, with lower turbulence along the sides.

Within the Glenore fishway, with tall cones for high river flows, there was a 20-fold increase in total fishway discharge, from 0.153 m^3/s to 3.2 m^3/s during a river flow event, which likely aided fish attraction. This design feature is unusual for a pool-type fishway (e.g. vertical-slot and Denil) because discharge is usually limited by the cross-sectional area of the slot or orifice. Another advantage of the wide channel with central submerged cones was to potentially facilitate passage of large-bodied species, including critically endangered largetooth sawfish (*Pristis microdon)*, which are generally > 1.0 m long when migrating upstream (Whitty, Morgan, & Thorburn, 2009, pp. 7–45). While fish could rest within each pool, there were larger resting pools, placed for every 0.68 m rise in elevation.

2.3. Fitzroy River barrage

The 480 km long Fitzroy River has a large catchment area of 142,665 km^2 and flows into the Coral Sea in north-eastern Australia. Mean annual discharge is 6,000 GL but stream flows are intermittent and heavily influenced by monsoonal rainfall and tropical cyclones. The Fitzroy River barrage is 60 km from the river mouth and the downstream tidal variation is up to 6.5 m per day. The under-shot gated weir structure was 3.6 m high and 340 m wide and a vertical-slot fishway was included which is effective for fish > 40 mm long but it has a limited tailwater range (i.e. the range of levels experienced by the river immediately downstream of the weir; Stuart & Mallen-Cooper, 1999). There are 35 species of native freshwater fish with 11 species classified as diadromous.

The 54 m long Fitzroy River barrage cone fishway was constructed in December 2015, consisting of 36 pre-cast concrete cone baffles in a 2.4 m wide channel. The upper section of the cone fishway was constructed adjacent to the existing vertical-slot fishway, while the lower section was built downstream of the existing fishway (Fig. 4). To stabilise the internal hydraulics of the vertical-slot fishway, a 4 × 5 m rectangular tailwater pool was incorporated between the upper and lower sections of the cone fishway. This created a stable tailwater pool that prevented the vertical-slot fishway from draining, maintaining low turbulence internal hydraulics as the tide (tailwater) receded. The tailwater pool also created a common entrance for the vertical-slot fishway and upper section of cone fishway. The addition of the lower section of cone fishway and the stabilised tailwater pool extended the tailwater operation range from 32% of high tides to > 95% of high tides. Average discharge from the cone fishway was approximately 0.09 m^3/s.

2.4. Maribyrnong River fishway

The 160 km long Maribyrnong River has a small catchment area of 1,450 km^2 and flows into the lower Yarra River and Port Phillip Bay in southern Australia. Mean annual discharge is 98 GL but flow often ceases over summer (December to February) with increases in discharge associated with winter-spring rainfall (June–November). The fixed

Fig. 3. (a) Glenore fishway at low and (b) high flows with low turbulence resting areas for ascent of small-bodied fish. t (c) Fitzroy River barrage cone fishway and (d) tailwater stabilisation pool which improves hydraulics in the new cone fishway and existing vertical-slot, covered by grid-deck.

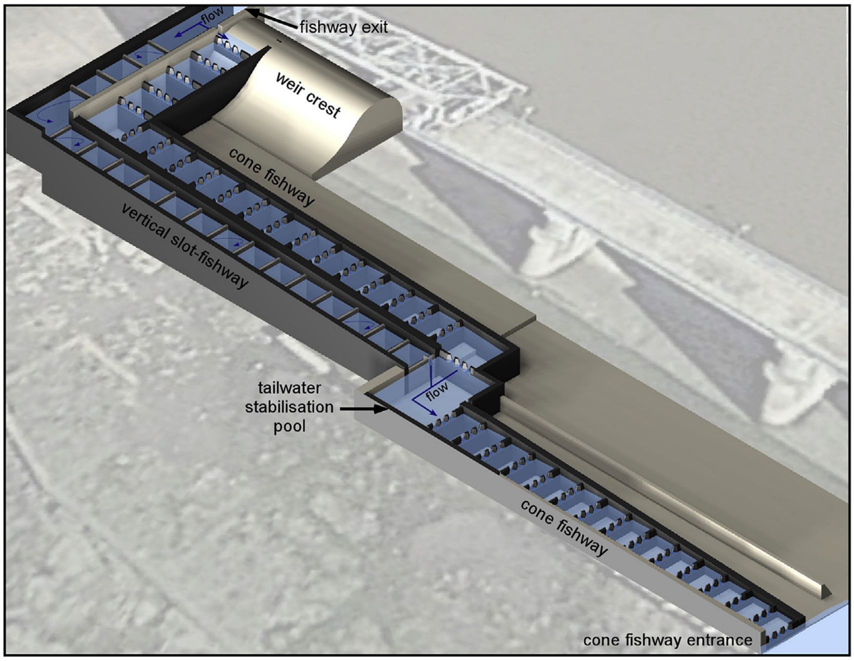

Fig. 4. Arrangement of the Fitzroy River barrage cone and vertical-slot fishways in north-eastern Australia, showing the shared tailwater stabilisation pool to improve internal hydraulics due to daily tidal tailwater variations of up to 6.5 m.

concrete crest structure was 1.2 m high and 32 m wide and included a steep ineffective rock fishway. There are nine species of native freshwater fish with five species classified as diadromous. The 43 m long Maribyrnong River cone fishway was constructed in November 2016 and consisted of 20 pre-cast concrete cone baffles and these conformed to the standard design. Average discharge was approximately 0.09 m^3/s.

2.5. *Trapping fish in the fishways*

Individual passage at each of the three case-study cone fishways was assessed by comparing the sizes (not numbers) of small-bodied fish that located and entered the fishway (bottom of fishway), with an independent sample of those that located, entered, and successfully pass the full length of the fishway (top of fishway). We did not compare among the three fishways because the timing of field sampling was different and because each site required specific sampling methods, which are described below.

The pooled-sample size distributions of each fish species from the top and bottom of each cone fishway were compared to assess if smaller fish, with a correspondingly poorer swimming ability, were unable to ascend the fishways. A Kolmogorov-Smirnov, two-tailed test was used for this comparison ($p \leq 0.05$). This test computes the 'D' statistic, which is the largest difference between two cumulative frequency distributions at any step (McKillup, 2005). Fish species where fewer than a total of 30 individuals were collected at either the top or bottom were excluded from this analysis.

At Glenore Weir, sampling was conducted from February to April 2017 during the wet season when the river was flowing. Upstream migrating fish were trapped at the top and bottom of the fishway using two adjacent cage traps which completely blocked the fishway exit. To reduce escapement, the cages included a funnel-trap and were covered in 70% shade-cloth with a 1.5 mm diameter square mesh; these traps are efficient for small-bodied tropical fish species (Baumgartner et al., 2012; Stuart & Mallen-Cooper, 1999). At the commencement of the 2 h sampling period, the cages were placed immediately above the most upstream or downstream cone baffle to sample fish that had successfully ascended or entered the fishway, respectively. The cumulative 4 h paired sample was completed in the morning (7.30 a.m.–11.30 a.m.) and afternoon (12.30 p.m.–4.30 p.m.) each day.

At the Fitzroy River barrage, sampling was conducted in March 2016 and October 2016, corresponding with periods of relatively small high tides and low river flows to maximise the effort required by fish to ascend the cone fishway. The strong tidal variation negated trapping a specific location at the bottom of the fishway, so a sub-sample of the size-classes attempting to ascend upstream were collected with a 0.3 m wide dip net (1.5 mm mesh) by scooping the dip net several times through the new tailwater stabilisation pool. The trap at the top of the fishway was set prior to the tidal tailwater rising and the 2 h sampling event occurred over high tide each day. The trap completely blocked the fishway exit and escapement rates from similar traps are low (Stuart & Mallen-Cooper, 1999). Due to high predation rates of small-bodied fish by the abundant large-bodied blue catfish (*Arius graeffei*; common maximum size 550 mm FL), all large-bodied fish (> 150 mm long) were excluded from the top trap with 25 mm galvanised square steel mesh on the funnel entry.

At the Maribyrnong River fishway, sampling was conducted from October to December 2017, encompassing Australian spring and early summer. Upstream migrating fish were collected from the river adjacent to the fishway entrance and then in an independent sample from the top of the cone fishway. The riverine sampling adjacent to the fishway entrance could potentially sample a wider size-range of fish but this still provided a useful comparison to the top samples. Both locations were trapped, over two consecutive nights, with a fine mesh double-wing fyke net (2 mm mesh) which covered the entire fishway exit. To maximise catch in the river channel downstream, two fyke nets were set. The nets were set in the late afternoon and retrieved the following morning, each fished consistently for 18 h.

For each trapping event, at all cone fishway sites, all fish were identified, counted and a sub-sample of 50 randomly selected fish per species measured (FL: fork length for forked-tail species and TL: total length for all others) and released above the weir.

Table 1
Total number of fish collected at the top and bottom of the Glenore Weir cone fishway between February and April 2017. Shading indicates a diadromous species and an asterisk indicates sufficient numbers for comparative length-frequency analysis.

Species	Common Name	Fishway Location	
		Bottom	Top
Ariopsis graeffei	lesser salmon catfish	1	5
Ariopsis paucus	Carpentaria catfish	2	5
Leiognathus equulus	common ponyfish	10	0
Toxotes chatareus	seven-spot archer fish	4	5
Glossogobius giuris	flathead goby	0	1
Glossogobius sp.	goby	2	0
Lates calcarifer	barramundi	7	17
*Ambassis macleayi**	Macleay's glassfish	73	44
Parambassis gulliveri	giant glassfish	1	54
Anodontoglanis dahli	toothless catfish	1	0
Ariopsis berneyi	Berney's catfish	1	2
Neosilurus hyrtlii	Hyrtl's tandan	0	1
Neosilurus sp. nov.	undescribed catfish	4	28
Amniataba percoides	barred grunter	9	2
Leiopotherapon unicolor	spangled perch	13	61
Scortum ogilbyi	gulf grunter	2	3
Liza alata	diamond mullet	3	2
Liza subviridis	greenback mullet	3	7
Oxyeleotris lineolatus	sleepy cod	1	0
Oxyeleotris selheimi	giant gudgeon	2	1
Glossamia aprion	mouth almighty	3	1
Melanotaenia splendida inornata	chequered rainbowfish	6	18
Megalops cyprinoides	tarpon	0	1
*Nematalosa erebi**	bony herring	131	180
*Nematalosa come**	bony herring	51	16
Strongylura krefftii	longtom	39	50
Thryssa scratchleyi	freshwater anchovy	2	1
	Total Number of Fish	371	505

3. Results

3.1. Glenore fishway

A total of 27 fish species and 876 individuals were collected in 15 paired samples at the top and bottom of the fishway (Table 1). Eight species were diadromous and 19 were potamodromous. Bony herring (*Nematalosa erebi* and *N. come*) formed 43% of the total catch, followed by Macleay's glassfish (*Ambassis macleayi*) at 13%. Other biota observed using the fishway were: cherabin (*Macrobrachium rosenbergii*), freshwater stingrays (*Himantura chaophrya*), file snakes (*Acrochordus arafurae*) and freshwater crocodiles (*Crocodylus johnsoni*). During the sampling period, there was a major breach in the right abutment of the weir, this likely attracted fish away from the fishway entrance as the majority of river flow passed through the breach. The breach did not lead to a major reduction in headwater or change to the fishway hydraulics.

At Glenore Weir fishway, there were no differences in the size of bony herring ($D_{194,134} = 0.12$, $p = 0.20$) and longtom ($D_{50,39} = 0.22$, $p = 0.18$) from traps at the top and bottom of the fishway, though there were significantly smaller ambassids ($D_{98,59} = 0.29$, $p = 0.0047$) at the bottom (Fig. 5). The minimum sized fish to successfully pass through the fishway was a 10 mm long Macleay's glassfish.

3.2. Fitzroy River barrage fishway

A total of 17 fish species and 15,001 individuals were collected in 16 paired samples at the top and bottom of the fishway. Seven species were diadromous and 10 were potamodromous (Table 2). Empire gudgeons (*Hypselotris compressa*) formed 73% of the catch, followed by bony herring at 15%.

At the Fitzroy River barrage there were no differences in the size of long-finned elvers (*Anguilla reinhardtii*; $D_{46,177} = 0.11$, $p = 0.77$) though there were significantly smaller empire gudgeons ($D_{1223,561} = 0.66$, $p = < 0.001$) and bony herring ($D_{812,220} = 0.33$, $p = 0.001$) at the bottom of the fishway. Empire gudgeons were abundant in the lower third of the cone fishway but were less common further upstream toward the fishway exit. The minimum sized fish to pass the fishway was a nine mm long Agassiz's glassfish (*Ambassis agassizii*). The maximum size of fish, was a 150 mm long blue catfish but this was limited by the 25 mm square mesh on the entry funnel to protect small-bodied fish from within-trap predation.

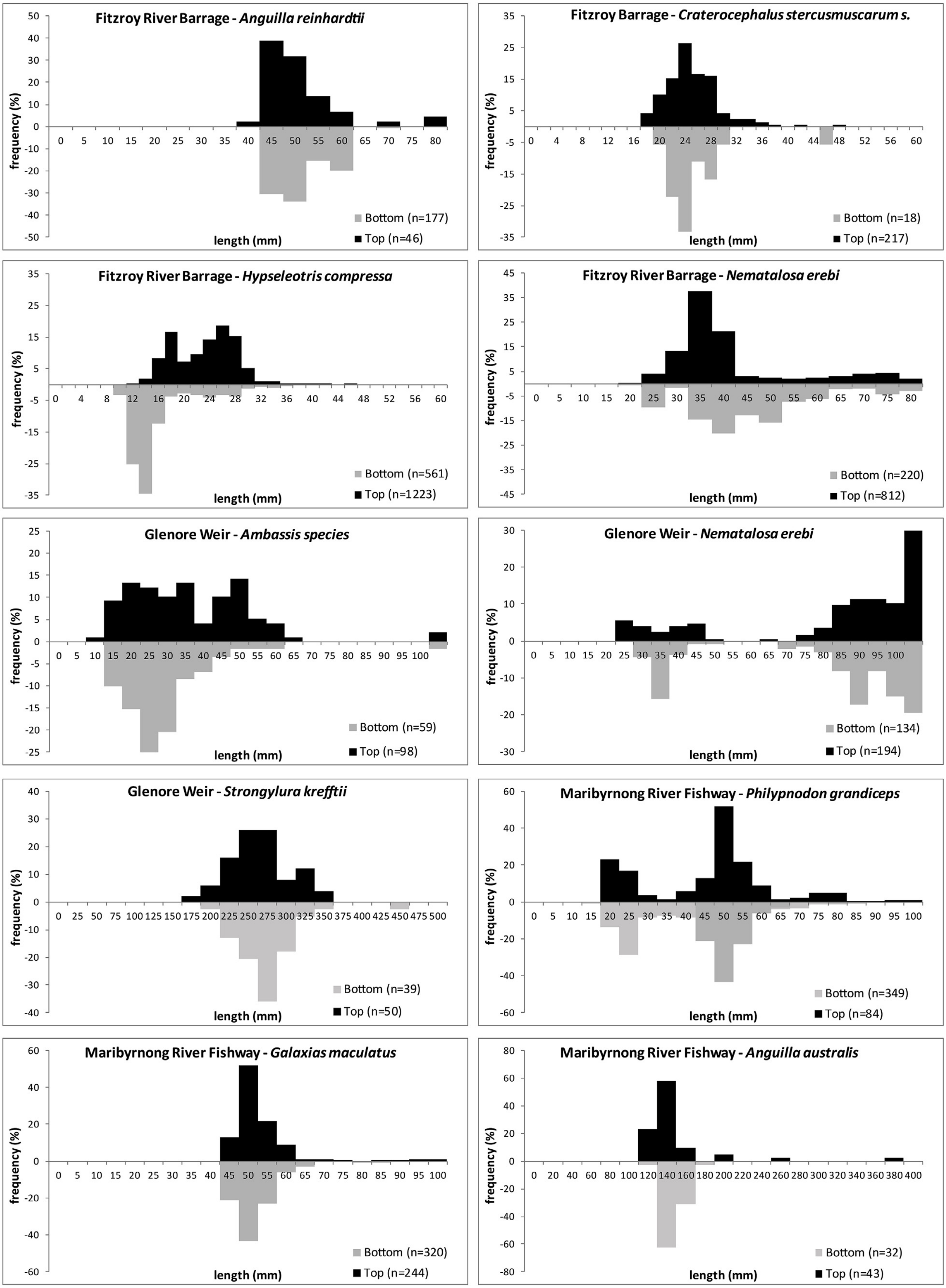

Fig. 5. Pooled size distribution of eight small-bodied (< 100 mm long) fish species from multiple sampling events at the top (upstream) and bottom (downstream) of the cone fishways. Note that the scale of the x-axis varies.

Table 2
Total number of fish collected in the Fitzroy River barrage cone fishway in March and October 2016. Shading indicates a diadromous species and an asterisk indicates sufficient numbers for comparative length-frequency analysis.

Species	Common Name	Fishway Location	
		Bottom	Top
*Anguilla reinhardtii**	long-finned eel	226	46
Arius graeffei	blue catfish	0	550
*Hypseleotris compressa**	empire gudgeon	570	10427
Lates calcarifer	barramundi	0	1
Mugil cephalus	striped mullet	0	411
Strongylura krefftii	longtom	0	1
Notestes robusta	Bullrout	0	2
Ambassis agassizii	Agassiz's glassfish	1	44
Amniataba percoides	banded grunter	0	2
Craterocephalus stercusmuscarum	fly-specked hardyhead	2	336
Hypseleotris spp	carp gudgeon	0	1
Leipotherapon unicolor	spangled perch	0	2
Melanotaenia splendida	eastern rainbowfish	1	97
*Nematalosa erebi**	bony herring	235	2043
Neosilurus hyrtlii	Hyrtl's tandan	0	1
Porochilus rendahli	Rendahl's catfish	0	1
Oxyeleotris lineolata	sleepy cod	0	1
	Total Number of Fish	1035	13966

Table 3
Total number of fish collected in the Maribyrnong River cone fishway between October and December 2017. Note that there were two fyke nets set in the river downstream of the weir and one at the top of the fishway. Shading indicates a diadromous species and an asterisk indicates sufficient numbers for comparative length-frequency analysis.

Species	Common Name	Fishway Location	
		River	Top
*Galaxias maculatus**	common galaxias	7911	3637
*Anguilla australis**	short-finned eel	32	45
Prototroctes maraena	Australian grayling	0	2
Mordacia mordax	shortheaded lamprey	1	1
Pseudaphritis urvillii	Tupong	0	10
Retropinna semoni	Australian smelt	76	27
Gambusia holbrooki[#]	eastern gambusia	0	25
Perca fluviatilis[#]	redfin perch	8	8
*Philypnodon grandiceps**	flat-headed gudgeon	812	84
	Total Number of Fish	8840	3839

[#]Non-native species.

3.3. Maribyrnong River fishway

A total of nine fish species and 12,679 individuals were collected in five paired samples at the top and bottom of the fishway (Table 3). Five species were diadromous and four were potamodromous. Common galaxias (*Galaxias maculatus*) formed 91% of the total catch, followed by flat-headed gudgeons (*Philypnodon grandiceps*) at 7%.

At the Maribyrnong River fishway, from a single fyke net at the top of the fishway and from two fyke nets in the river immediately downstream, there were no differences in the sizes of common galaxias ($D_{244,320} = 0.09$, $p = 0.19$) or short-finned eels (*A. australis*; $D_{43,32} = 0.29$, $p = 0.60$), though there were significantly smaller ($D_{84,349} = 0.40$, $p = 0.001$) flat-headed gudgeons at the bottom.

4. Discussion

4.1. Performance of the cone fishways

In developing the new cone fishway design it was important to follow four logical steps: (i) clearly identify the migratory fish community, (ii) field test fish within prototype cone fishways, (iii) design and build the fishway, and (iv) evaluate the fishway against clear performance standards and improve designs (Mallen-Cooper, 1999). This logic enabled the cone design to be refined from field testing of the early prototypes followed by application at several sites with different fish ecologies and hydrologies with field-based evaluation in tropical and temperate Australia.

Although there were significantly smaller fish at the bottom of the fishway for several species the cone fishways still provided passage for a broad size range of small-bodied fish. Performance standards for upstream passage efficiency, such as passage rates for migratory biomass and life-stages, for small-bodied fish in fishways are rare in the literature and further work is needed to provide quantitative metrics which can then inform fishway design (Noonan, Grant, & Jackson, 2012; O'Connor et al., 2015). Nevertheless, from the three case-study field evaluations, the cone fishways passed a wide range of small-bodied fish species and sizes highlighting the potential suitability of this design where improving passage of small-bodied fish is a priority.

While further work is needed to quantify the proportion of the downstream population that migrate, fish as small as nine mm long ascended the cone fishways; providing some assistance to migrations of entire cohorts of diadromous fish to lowland freshwater habitats, such as empire gudgeons, long-finned eels, common galaxias, tupong (*Pseudaphritis urvillii*) and striped mullet (*Mugil cephalus*). Elvers also ascended the Fitzroy River barrage cone fishway which is unusual as they rarely ascend technical pool-type fishways without additional roughness elements (Kerr, Karageorgopoulos, & Kemp, 2015). For passage of small-bodied tropical and temperate fish, the cone fishway hydraulics appear satisfactory which is particularly important for tidal barriers where fishways have frequently performed poorly (Pelicice & Agostinho, 2008; Stuart & Berghuis, 2002).

The internal hydraulics of fishways, particularly turbulence and water velocity, can be influential in terms of successful passage of small-bodied fish (Mallen-Cooper, Stuart, Zampatti, & Baumgartner, 2008; Tarrade, Texier, David, Pineau, & Larinier, 2008). We think the ability of the cone fishways to pass small-bodied fish was due to the faceted design of the cones that reduced the length of high velocity zones and increased boundary layer effects. In addition, the low pool turbulence, water velocities and large resting pools enabled fish to rest as they ascended (Mallen-Cooper et al., 2008; Tarrade et al., 2008). While the theoretical average pool turbulence was low, the Glenore cone fishway specifically incorporated higher turbulence in the centre of the channel to create very low turbulence on the edges.

For cone fishways and passage of small-bodied fish, low internal turbulence and water velocities was an important generic requirement but there was also customisation of several design aspects to suit the unique site-specific hydrology at each of the three study sites. It is illustrative to examine these aspects because they highlight how generic functional design criteria should always be adapted for the local fish ecology and site hydrology.

At Glenore Weir, the fishway was designed to operate over a broad range of river conditions, including high wet season flows. To meet this objective and still pass fish as small as 10 mm long, the design was adapted to a broad, deep fishway channel which included low cones for low flows and high cones for high flows (i.e. increased headwater). A pool-type technical fishway, with adaptive discharge is unusual because total flow is usually limited by the cross-sectional area of the slot or orifice (Clay, 1995). For the cone fishway, discharge increased 20-fold during high flows because the low cones became submerged and despite higher internal turbulence the edges of the fishway, with the tall cones, remained relatively calm and the extra discharge likely aided fish attraction; an important criterion in rivers where the river flow greatly exceeds fishway flow (Clay, 1995). The broad submerged fishway channel may also aid ascent of large migratory tropical fauna (e.g. broadtooth sawfish, freshwater stingrays and crocodiles).

At both the Fitzroy River barrage and Maribyrnong River fishways the priority was to provide passage for small-bodied swimming fish at relatively stable headwater and low river flows; often the entire river flow passed through the fishway! In these cases, high flow function was not an ecological priority, so the fishway cones were designed at the same height which helped reduce daily discharge and conserve water. The combination of local fish life-history, behaviour and hydrology supported these design decisions, where during low flows many small-bodied temperate fish move upstream (Amtstaetter, O'Connor, Borg, Stuart, & Moloney, 2017; Bice et al., 2017) and the authors have observed millions of empire gudgeons below the Fitzroy River barrage during the dry season (Fig. 6). Hence, we suggest that the relatively narrow headwater operational range and low discharge of the cone fishway was appropriate in these scenarios.

The improvement in fish passage for slow swimming small-bodied species, such as empire gudgeons from 14 + mm long, which passed the Fitzroy River barrage cone fishway can be gauged against the existing vertical-slot fishway which passed very few small fish (< 40 mm long; Stuart & Mallen-Cooper, 1999). Nevertheless, there were still large numbers of the smallest post yolk-sac empire gudgeons (10–12 mm long) that were unsuccessful or partially successful in ascending the cone fishway. For these fish, the cone fishway hydraulics enabled ascent of the lower third of the fishway but there was an incremental reduction in fish numbers toward the fishway exit. The mechanism of this partial passage failure is not specifically known but may simply be that small fish suffer fatigue or do not have adequate energetic resources when ascending long fishways (Romão, Santos, Katopodis, Pinheiro, & Branco, 2018). In this case, very large and deeper resting pools with mesohabitat, such as rocks/boulders or timber, may enable these fish to rest and feed during their ascent (Kilsby & Walker, 2012).

At the Fitzroy River barrage, there was an added complexity of a highly variable (6.5 m) tailwater which was influenced by twice daily high and low tides. The issue for the new cone fishway and existing vertical-slot was that as tailwater receded, the fishway entrances were stranded above water level and internal turbulence rose. Thus, optimal hydraulic ascent conditions were only present for a few hours per day at the peak of high tide. This unusual design challenge was resolved by including: (i) an additional fishway entrance channel, and (ii) a tailwater stabilisation pool. These two design inclusions enabled fish to enter the fishways over a greater range of tailwater conditions (95% of high tides instead of 32%) and stabilised the internal fishway hydraulics to enable longer periods of low turbulence ascent conditions. The tailwater stabilisation pool concept could be extended to other sites where there is rapid (i.e. hourly) tailwater variation (e.g. tidal barriers and hydropower facilities).

Fig. 6. Accumulation of millions of empire gudgeons (12 + mm long) below the Fitzroy River barrage prior to construction of the cone fishway.

4.2. Limitations and further development opportunities of cone fishways

Cone fishways function optimally for a specific set of ecological and hydrological criteria. Firstly, passage of small-bodied fish should be a major ecological priority, such as at tidal and coastal lowland sites. The site should also have fixed crest and a low headwater range with rapid (i.e. < 48 h) drown out, such as at weirs with a low total head differential (e.g. usually < 3 m high). The cone fishway design functions optimally over a narrower range (i.e. < 0.4 m) of headwater than some other designs (i.e. vertical-slot) and internal turbulence varies with headwater level. The narrow headwater range, however, may be useful at low fixed weir-crest sites where draining of the weir pool below crest level is undesirable. While small fish may have reduced passage at high flows, the ability of the cone design to operate with very low discharge can be an advantage at sites where small fish are migrating at low flows (Stuart & Mallen-Cooper, 1999).

The present study focused on quantifying passage of small-bodied fish and although the numbers of fish entering the cone fishways appear large, they are still an unknown proportion of total fish population in the river downstream. Hence, quantifying the migratory biomass and fishway entrance attraction efficiency within the context of the broader population remains as a priority. Passive integrated transponders (PIT) telemetry would likely be helpful for monitoring small-bodied fish and their behaviour as they approach and ascend cone fishways but this may be limited to the larger size-classes (e.g. > 60 mm long; Roscoe & Hinch, 2010; Silva et al., 2018).

A wide range of species, including surface- and bottom-dwelling fish, and a broad range of size-classes passed through the cone fishways and this included small numbers of benthic species, such as tupong, bullrout and stingrays. Nevertheless, a potential functional disadvantage of cone fishways is passage efficiency for demersal and large-bodied fish species. The cone fishways required these species to swim over the baffles where in a vertical-slot fishway fish can select their swim depth (Clay, 1995). While these species have been observed regularly ascending over the cone ridges, to optimise conditions for demersal fish there is potential to add a slot or submerged orifice to the future designs, though this would require further physical modelling to confirm hydraulic conditions.

The cone design arose from the need to install rock ramp fishways at remote sites where rock was unavailable and where maintenance would be infrequent. Pre-fabricated concrete, or in another example high density polyethylene (HDPE) cone baffles, have provided an innovative, low cost and modular solution for remote river systems. The cone design has now been extended to urban sites because of the advantages pre-fabricated concrete baffles provide over rocks, such as far greater constructability. In addition, there has been some uptake of cone fishways in South East Asia where they are known as ‘dragon's tooth’ fishways (Baumgartner et al., 2018). The cone design, however, should only be applied where headwater is relatively stable and where small-bodied fish passage is the priority. With further experimentation there may be an opportunity to extend the scope of the biological and hydrological application of cone fishways.

5. Conclusion

Cone fishways provide a useful and novel alternative to improve passage for small-bodied fish, at appropriate sites, and contribute to a contemporary vision of restoration of whole fish communities. The cone design has most application where small-bodied fish are an ecological priority and where there is a relatively stable headwater. Further work is needed to quantify the proportion of the motivated small-bodied fish population in the river downstream which find and pass through the cone fishways.

Declaration of interest

The authors work for agencies or consultancies who provide professional fishway and fish passage advice.

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