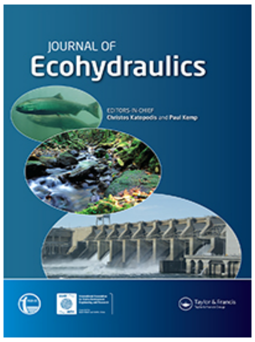

Journal of Ecohydraulics

ISSN: 2470-5357 (Print) 2470-5365 (Online) Journal homepage: https://www.tandfonline.com/loi/tjoe20

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To cite this article: Tim Marsden & Ivor Stuart (2019): Fish passage developments for small-bodied tropical fish: field case-studies lead to technology improvements, Journal of Ecohydraulics, DOI: 10.1080/24705357.2019.1646616

To link to this article: https://doi.org/10.1080/24705357.2019.1646616

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JOURNAL OF ECOHYDRAULICS
https://doi.org/10.1080/24705357.2019.1646616

Fish passage developments for small-bodied tropical fish: field case-studies lead to technology improvements

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ABSTRACT

In tropical coastal lowland rivers, there are frequently biodiverse upstream migrations of post-larval and juvenile diadromous fish from estuaries into freshwater. Tidal barriers completely block major migratory pathways for these fish and have contributed to major losses of freshwater biodiversity. In northern Australia, early efforts to improve tropical river fish passage with salmonid-style fishways completely failed. Since the mid-1990s, low gradient vertical-slot and rock fishways improved fish passage but the smallest and most abundant fish (i.e. from 10 to 100 mm long) often still failed to ascend. Since the mid-2000s, there was a paradigm shift in hydraulic design criteria for new fishways, with a renewed focus on: (i) low turbulence, (ii) maximized roughness and hydraulic boundary layers to optimise fish ascent. We used a combined methodology, firstly developing a conceptual model of fish movement to inform fishway design criteria, secondly tabulating past and present fishway design criteria, and thirdly conducting a series of brief field case-studies, at tidal barriers in tropical rivers for new technical and rock fishways. Our objective was to evaluate the success of these new designs for passage of very small (from 9 mm long) diadromous fish on low head barriers (i.e. <3 m high). We conclude that while there have been improvements in passage of small-bodied fish at tidal barriers further experimental work is still needed to test and refine current ecohydraulic fishway design criteria.

ARTICLE HISTORY
Received 4 February 2019
Accepted 18 July 2019

KEYWORDS
Fishway; fish migration; tidal barrier; cone fishway; rock ramp; Australia; Bynoe River

Introduction

In regulated rivers, fishways are often included on new infrastructure or are retro-fitted to existing dams and weirs to improve passage for migratory fish (Silva et al. 2018). Functionality varies for conventional technical pool-and-weir style fishways, from highly effective for northern hemisphere temperate anadromous salmonids (Landsman et al. 2017) and some tropical southern hemisphere species (Gutfreund et al. 2018), to highly ineffective for other temperate and tropical species (Agostinho et al. 2007; Castro-Santos et al. 2017). However, for many engineers, fisheries biologists and managers, the experience has been in-between these two extremes; where fishways have been partially effective, providing passage for some species and size classes during a sub-set of hydrological conditions (Roscoe and Hinch 2010; Bunt et al. 2012; Thiem et al. 2013).

At low-head (e.g. <3 m high) barriers, low gradient technical fishways can be reasonably effective for passage of a broad range of non-salmonid species and sizes, especially where there is a strong understanding of the complex hydraulic relationship between average pool turbulence (i.e. energy dissipation factor) and water velocity, and their effects on the local suite of fish species, sizes and behaviours (Baumgartner et al. 2014, 2018). In some cases, fishways have led directly to recovery of upstream fish communities (Marques et al. 2018), particularly for diadromous species on low-head barriers in coastal rivers (Amtstaetter et al. 2017; Rourke et al. 2019). In tropical South America, some fishways have restored connectivity (Gutfreund et al. 2018; Celestino et al. 2019). However, in other cases, fishways have not enabled adequate passage rates to support population recovery and there are calls for more transparency as to whether fishways alone can ever offset the highly detrimental impacts of new dams on a river's intrinsic ecological and hydraulic integrity (Agostinho et al. 2007; Brown et al. 2013). There is even less guidance concerning appropriate performance standards for upstream fish passage efficiency to maintain the functional integrity of riverine fish communities (Noonan et al. 2012).

Despite these varied experiences, the key advancements in fishway technology have invariably been via detailed field (and laboratory) monitoring to enable refinement of existing designs or

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occasionally development of new solutions for regional native species (Mallen-Cooper 1999; Stuart et al. 2008). Fishway hydraulics highlight this point. One field study demonstrated that passage success for small-bodied potamodromous fish (i.e. 20–100 mm long) was dramatically improved by simply altering the vertical-slot geometry to reduce discharge and pool turbulence (Mallen-Cooper et al. 2008). Other work continues to improve fishway function based on more effective combinations of internal fishway hydraulics and fish ecology knowledge (Silva et al. 2012; Bice et al. 2017; Romão et al. 2018).

Tropical rivers are under unprecedented development pressure and encapsulate some of the greatest fish passage challenges, including: (i) biodiverse and abundant fish communities, (ii) a broad range of size classes and life-stages constantly migrating upstream and downstream, (iii) highly variable stream flows with very low flows in the dry season and high flows or flooding during the wet season (Hamilton and Gehrke 2005), and (iv) significant economic, social and human nutritional benefits associated with tropical fisheries (Millar et al. 2018). The world's tropical rivers require an urgent increase in research investment to develop highly flexible fishway technology to maintain fish migrations and fisheries (Dugan et al. 2010; Birnie-Gauvin et al. 2018).

In the tropical north of Australia, these ecological challenges are underscored in coastal rivers where tidal barriers block major migrations of whole cohorts of small (from 10+ mm long) recruits of diadromous species to receiving freshwater habitats. These tidal barriers were usually installed to supply potable water for local communities and often incorporated fish passage. However, without exception, the older pool-and-weir salmonid-style fishways have completely failed in these tropical rivers and at tidal barriers major biodiversity losses have occurred upstream (Kowarsky and Ross 1981; Harris et al. 2017). The challenge of developing efficient fishways for tropical rivers remains and is further complicated by increasing scarcity of freshwater flows to estuaries and human population growth (Gillson 2011).

The early failure of salmonid-style fishways in the tropical north of Australia was partly addressed via a major paradigm shift to lower gradient (i.e. 1 vertical: 20 horizontal) and lower velocity (typically maximum 1.4 m/s) vertical-slot fishways in the mid-1990s (Stuart and Mallen-Cooper 1999). Over the next decade, many fishways were built on tidal barriers and there was a major improvement in passage efficiency over the early salmonid designs (Stuart and Berghuis 2002). Nevertheless, very small fish (i.e. 10–50 mm long) could not pass many of these fishways, remaining trapped below these tidal barriers. Studies elsewhere demonstrated that this results in greatly reduced survival due to predation by larger fish and piscivorous birds (Baumgartner 2007; Guillerault et al. 2019). To address this functional fish passage deficiency, there has been a renewed research interest in providing more suitable hydraulic conditions to improve passage for small-bodied fish (Bice et al. 2017; Rolls et al. 2018; Stuart and Marsden 2019).

Here, we synthesize 25 years of fish passage research from Australia's northern coastal tropical rivers, we: (i) conceptually outline the ecological need to provide passage for small-bodied fish, (ii) we then tabulate past and present hydrological, hydraulic and biological fishway design criteria to identify transparent fish passage performance criteria, and (iii) provide three field case-studies where there was field evaluation of three different kinds of fishways for upstream passage of small-bodied at tidal barriers. Our objective was to demonstrate a 25-year evolution of hydraulic criteria based on field evaluations that has incrementally improved passage success of small-bodied fish in coastal tropical rivers.

Methods

Conceptual outline of the ecological need to effectively pass small fish

In north-eastern Australia, most fish are either catadromous or amphidromous and so upstream migrations to freshwater are dominated by small post-larvae and juveniles (10–100 mm long; Figure 1). From a brief review of the relevant literature, we developed a conceptual model for fish movement, based on prior research data, which could be used to inform fishway design for passage of these small-bodied fish.

Past and present fishway design criteria

Over the past 40 years of field-based fishway evaluation in tropical rivers, the cumulative knowledge of the migratory behaviour of Australian native fish has developed greatly. We reviewed the ecohydraulic design criteria for tropical river fishways over the past 40 years and summarise these in table form (Table 1).

Case-study field evaluations: study area

The three fishway case-study field evaluations were conducted in tropical northern Australia and consisted of: (i) a lateral rock ramp at Goosepondss

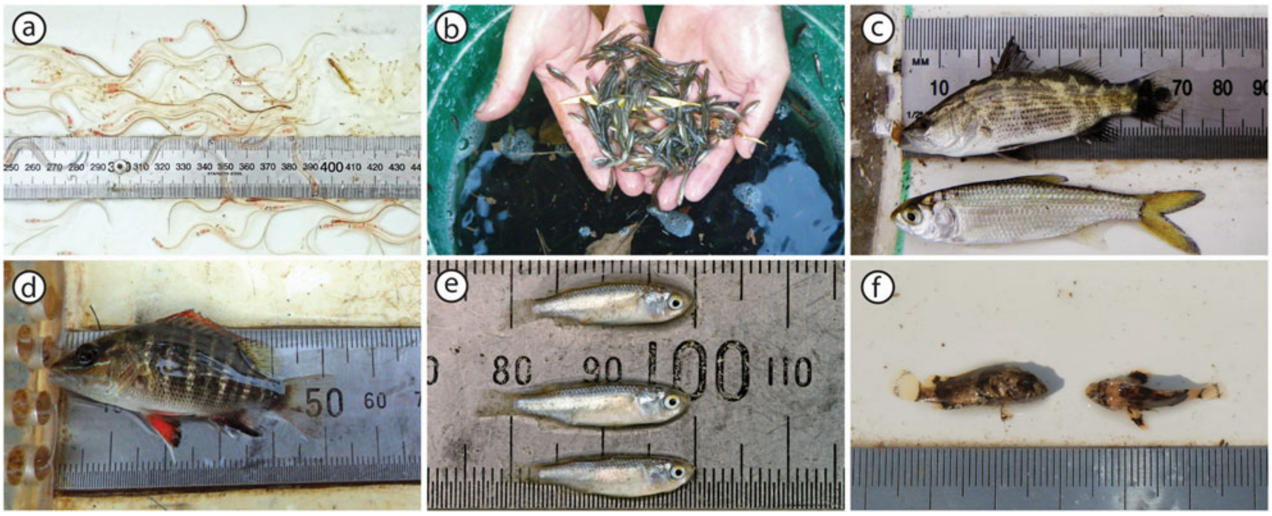

Figure 1. Small juvenile fish (i.e. 10+ mm long) commonly migrating in coastal systems of tropical northern Australia, (a) long-finned elvers (*Anguilla reinhardtii*), (b) empire gudgeons (*Hypseleotris compressa*), (c) barramundi (top; *Lates calcarifer*) and oxeye herring (bottom; *Megalops cyprinoides*), (d) mangrove jack (*Lutjanus argentimaculatus*), (e) striped mullet (*Mugil cephalus*), and (f) bullrout (*Notesthes robusta*). (Data from: Stuart and Berghuis 2002; Moore and Marsden 2010).

Creek, (ii) a vertical-slot at Waterpark Creek, and (iii) a cone fishway at the Bynoe River (Figure 2).

Gooseponds Creek Rock Fishway

The rock ramp fishway was located at the tidal interface of Gooseponds Creek, a coastal system that flows into the Pioneer River in Central Queensland. The tropical climate delivers high rainfall (mean 1.58 m annually) throughout the wet season (i.e. December to April) with a distinct dry season for the remainder of the year. Flow events are short in duration due to the relatively small catchment, however, there are low level flows for long periods of time during and after the wet season. During the dry season Gooseponds Creek often stops flowing.

In June 2012, the 0.5 m high concrete tidal barrage was retro-fitted with a rock ramp fishway consisting of seven ridges, each with a 60 mm head drop, a maximum water velocity of 1.08 $m.s^{-1}$ at the *vena contracta* and low average pool turbulence (24 W/m^3; Cd = 0.65; average volumetric dissipated power). The fishway was 15 m long, the pools were 2.0 m long, 4.0 m wide and 0.4 m deep and daily discharge was 12 ML/d.

Waterpark Creek Weir

Waterpark Creek Weir is located immediately above the tidal interface on the 35 km long system that flows into Corio Bay and the Coral Sea. The tropical climate delivers high rainfall (mean 1.45 m annually) throughout the wet season with perennial low flows during the dry season. Rainfall induced flow events are buffered by the large sand dunes and along with the relatively small catchment (1,836 km^2), results in relatively few high flow events. The average annual discharge is 138 gigalitres (GL).

In September 2010, the 1.0 m high Waterpark Weir was retrofitted with a vertical-slot fishway consisting of 10 baffles with 80 mm wide vertical-slots and 67 mm head drops between pools, creating a maximum water velocity of 1.15 $m.s^{-1}$ at the *vena contracta* and low pool turbulence (27 W/m^3; Cd = 0.65). The fishway was 18 m long, each pool was 1.2 m long by 1.2 m wide and 1.0 m deep with a daily discharge of 5.1 ML/d. This weir is the only man-made barrier on the system.

Bynoe River Crossing

The Bynoe River crossing is a causeway crossing located at the tidal interface of the Bynoe River, a coastal river system that flows into the Gulf of Carpentaria in North Queensland. The tropical climate delivers moderate rainfall (mean 0.93 m annually) throughout the wet season with high flow events often of a long duration due to the relatively large catchment. The Bynoe River causeway is inundated at low levels for long periods of time during and after the wet season but the river stops flowing for much of the dry season.

In June 2009, the 1.0 m high Bynoe River causeway was retrofitted with a concrete cone fishway consisting of 8 baffles with 50 mm head drops between pools, creating a maximum water velocity of 0.99 $m.s^{-1}$ at the *vena contracta* and low average pool turbulence (22 W/m^3; Cd = 0.65). The fishway was 22 m long, each pool was 1.5 m long by 2.0 m wide and 0.7 m deep with a daily discharge of 7.4 ML/d.

Table 1. Tropical fishways demonstrating changes to biological and hydraulic design criteria over time. P = theoretical average power, ΔH = head loss, V_{max} = maximum water velocity, and Q = discharge.

Build date	River	Barrier	Barrier type (maximum head)	Fishway type	Hydrology range	Fishway hydraulic design criteria (assumed Cd = 0.65)	Biological design criteria
1974	Fitzroy River	Fitzroy Barrage	Tidal barrage (2 m)	Pool and Weir	Low flow	Floor slope = 1v:18h P = 292 W/m^3 (@390mm over crest) Vmax = 1.71 m/s, Q = 67.6 ML/d Pool ΔH = 0.15m	Based on passage of salmonid species
1976	Burnett River	Burnett River Barrage	Tidal barrage (2.3m)	Pool and weir	Low to Moderate flow	Floor slope = 1v:10h P = 186 W/m^3 (@100mm over crest) Vmax = 2.1 m/s, Q = 29 ML/d Pool ΔH = 0.225m	Based on passage of salmonid species
1987	Fitzroy River	Fitzroy Barrage	Tidal barrage (2 m)	Pool and weir Vertical-slot hybrid	Low to high flow	Floor slope = 1v:18h P = 105 W/m^3 (@600 mm through slot) Vmax = 2.5 m/s, Q = 52 ML/d Pool ΔH = 0.15m	Passage of local species and sizes from 100 - 600 mm long
1994	Fitzroy River	Fitzroy Barrage	Tidal barrage (2 m)	Vertical-slot	Low to high flow	Floor slope = 1v:17h P = 42 W/m^3 (@600 mm through slot) Vmax = 1.4 m/s, Q = 18 ML/d Pool ΔH = 0.10m	Passage of all species and sizes from 40 to 600 mm long
1996	Burnett River	Burnett Barrage	Tidal barrage (2 m)	Vertical-slot	Low to moderate flows	Floor slope = 1v:16h P = 36 W/m^3 (@1000 mm through slot) Vmax = 1.40 m/s, Q = 11.8 ML/d Pool ΔH = 0.10m	Passage of all species and sizes from 40 to 600 mm long
1999	Reliance creek	Habana Road	Causeway	Lateral ridge rock-ramp	Low flows	Floor slope = 1v:20h P = 54 W/m^3 (@100 mm through slots)* Vmax = 1.40 m/s, Q = 8.6 ML/d Pool ΔH = 0.10m	Passage of all species and small sizes from 20 to 300 mm long
2005	Sheepstation Creek	Highway Gauge	Regulating gate	Vertical-slot	Low to moderate flows	Floor slope = 1v:16h P = 29 W/m^3 (@900 mm through slot) Vmax = 1.11 m/s, Q = 4.5 ML/d Pool ΔH = 0.0625m	Passage of all species and small sizes from 20 to 300 mm long
2008	Tedlands Creek	Landing Road	Tidal Causeway	Lateral ridge rock-ramp	Low to moderate flows	Floor slope = 1v:25h P = 25 W/m^3 (@100 mm through slot)* Vmax = 0.89 m/s, Q = 5.7 ML/d Pool ΔH = 0.040m	Passage of all species and small sizes from 15 to 300 mm long
2009	Flinders River	Wernadinga Road causeway	Tidal Causeway	Cone	Low to moderate flows	Floor slope = 1v:30h P = 27 W/m^3 (@100 mm through slot) Vmax = 0.99 m/s, Q = 7.1 ML/d Pool ΔH = 0.050m	Passage of all species and small sizes from 15 to 600 mm long
2012	Moores Creek	Georges Street Crossing	Tidal Causeway	Lateral ridge rock ramp	Low to moderate flows	Floor slope = 1v:27h P = 12 W/m^3 (@100 mm through slot)* Vmax = 1.21 m/s, Q = 11.4 ML/d Pool ΔH = 0.075m	Passage of all species and small sizes from 10 to 300 mm long
2015	Fitzroy River	Fitzroy Barrage	Tidal barrage (2 m)	Cone	Low to high flows	Floor slope = 1v:19h P = 17 W/m^3 (@100 mm through slot)* Vmax = 1.21 m/s, Q = 8.0 ML/d Pool ΔH = 0.08m	Passage of all species and small sizes from 10 to 600 mm long
2015	Norman River	Glenore Weir	Tidal Weir	Cone	Low to high flows	Floor slope = 1v:30h P = 16 W/m^3 (@100 mm through slot)* Vmax = 1.08 m/s, Q = 17.1 ML/d Pool ΔH = 0.06m	Passage of all species and small sizes from 10 to 1000 mm long

*Theoretical turbulence for rock ramps based on technical fishway formulae and is likely an overestimate.

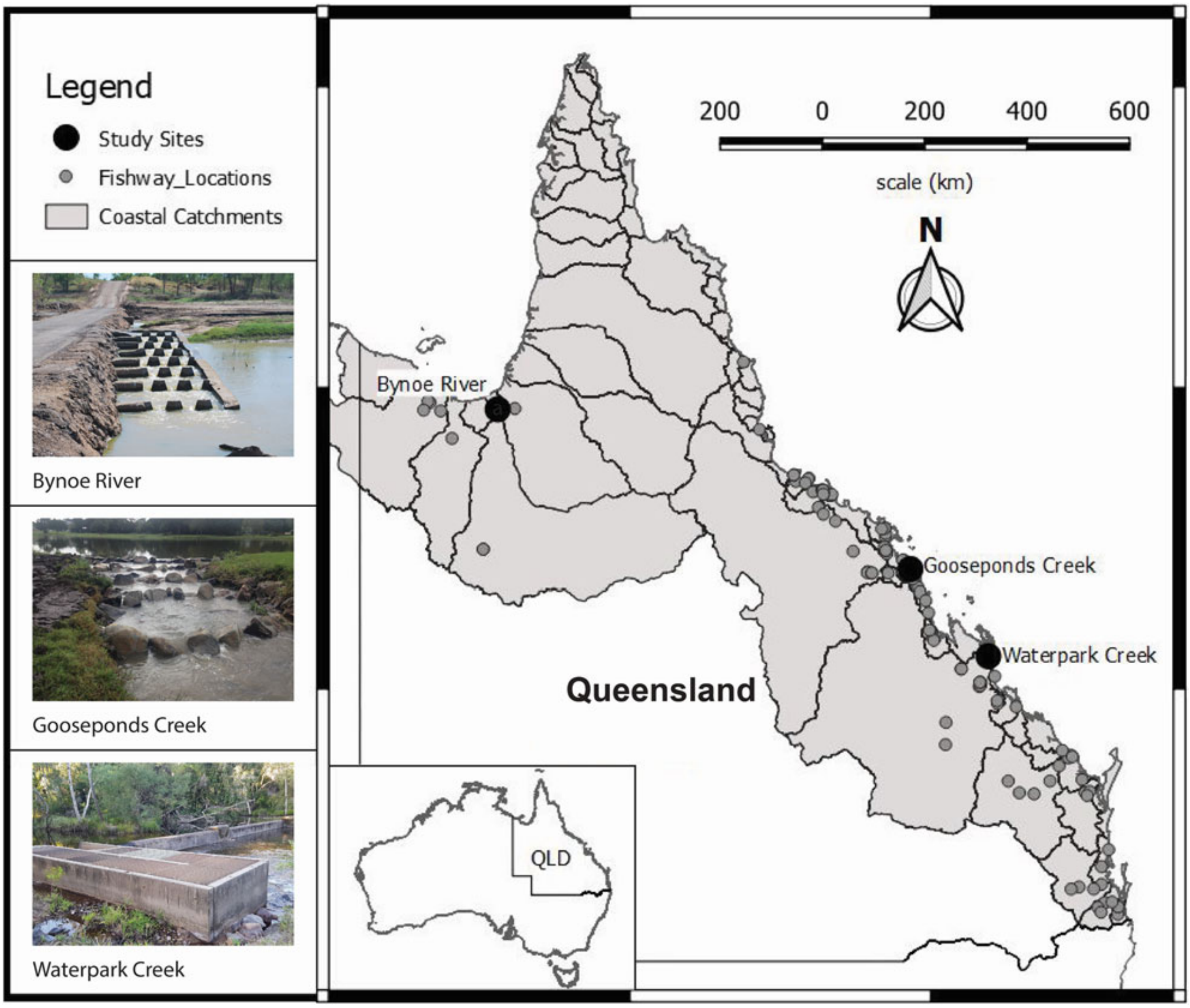

Figure 2. Fishways in the northern tropical coastal rivers of Queensland, Australia. The three case-study fishway sites at Gooseponds Creek rock ramp fishway, Waterpark Creek vertical slot fishway, and Bynoe River crossing cone fishway are shown. Source: Author and QGIS.

Field methods

Individual passage at each of the three field case-study fishways was assessed by comparing the sizes (not numbers as these may be highly variable between samples due to the schooling nature of the species concerned) of small-bodied fish that located and entered the fishway (bottom of fishway), with an independent sample of those that located, entered, and successfully passed the full length of the fishway (top of fishway). Migrating fish were trapped at the top and bottom of the fishway using a cage trap which completely blocked the fishway exit (Figure 3). To reduce escapement, the cages included a funnel-trap and were covered in 3 mm diameter square mesh; these traps are efficient for small-bodied tropical fish species (Stuart and Mallen-Cooper 1999). Due to predation of small-bodied fish, all large-bodied fish (>100 mm long) were excluded from the trap with 25 mm square mesh on the funnel entry.

At each site, fishway sampling commenced when fish were migrating during the wet season, when the river was flowing and usually on the recession of the first major flow event. Fishway sampling consisted of randomized paired samples where the trap was either placed at the top or bottom of the fishway (starting location randomly selected after Mallen-Cooper 1999). Trapping began at approximately 8 am for 4 hours after which the trap was moved to the alternate location at approximately 1 pm for another 4 hours. This sampling regime constituted a paired sample. All studies at all sites were of short duration, only paired samples were used in data analysis, although other samples provided observational data used to improve fishway operation. Specifically, at Bynoe River cone fishway there were six paired samples between May and June 2011, at Gooseponds Creek rock ramp fishway there were five paired day samples between January and February 2013 and at Waterpark Creek vertical-

Figure 3. Trap like those used in the case studies, showing small mesh size and large fish exclusion mesh.

slot fishway there were seven paired day samples between November and December 2011.

Individual passage at each of the three case-study fishways was assessed by comparing the sizes of small-bodied fish that located and entered the fishway (bottom of fishway), with an in-dependent sample of those that located, entered, and successfully passed the full length of the fishway (top of fishway). Due to the brief nature of the sampling we were unable to statistically test fish passage rates with hydraulic co-variates within each fishway. Furthermore, 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 above.

During trapping, 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). Fish were released above the weir. For each species, the pooled-sample size distributions from the top and bottom of each 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 ($p = <0.05$). This computes the "D" statistic, the largest difference between two cumulative frequency distributions at any step (McKillup 2005; Stuart et al. 2008). Fish species where fewer than a total of 30 individuals were collected at a single trapping location were excluded from this analysis, this reduced the number of paired days available for analysis but improved our ability to make our inferences from the data analyses.

Results

Conceptual outline of the need to pass small-bodied fish

Australian tropical coastal rivers support high fisheries biodiversity and while many systems still retain their natural flow regime, they have severely impaired ecological function because tidal barriers disrupt connectivity (Hamilton and Gehrke 2005). Most fish are either catadromous or amphidromous and so upstream migration to freshwater are dominated by small post-larvae and juveniles (10–100 mm long; Figure 1). Conceptually, fishways that effectively attract and pass small fish have particular relevance in tropical rivers because any delay below tidal barriers can have three major impacts:

(i) migration failure for adult diadromous fish returning upstream from estuarine/marine spawning habitats, (ii) failure of freshwater dispersal migrations of whole cohorts of juvenile diadromous fish, and (iii) increased predation (Harris 1984; Sheaves et al. 2014). Diadromous fish communities have undergone dramatic declines in freshwater reaches upstream of tidal barriers and at an operational level, fishways that support the lives of small-bodied fish, add recruitment value to recipient freshwater populations (Rolls 2011; Sheaves et al. 2015). From the literature a conceptual model of fish movement was developed to help inform fishway design objectives (Figure 4).

Past and present fishway design criteria

By recognising the ecological significance of upstream passage of small-bodied fish, specific fishway hydraulic standards can be transparently determined: these relate to depth, velocity, turbulence, and hydraulic gradient. These standards are specific to biogeographic regions and to the species and sizes of fish present. For tropical rivers and passage of small-bodied fish there have been progressive reductions in technical fishway hydraulic design criteria (Table 1). In the 1970s fishways were characterized by high average theoretical turbulence (energy dissipation factor) of up to 292 W/m^3 and maximum water velocities of 2.5 m/s (calculated as per White and Pennino 1980). In the late 1990s and early 2000s, in an attempt to pass more small-bodied fish, these hydraulic design criteria were reduced to 50 W/m^3 and maximum water velocities to 1.4 m/s (Mallen-Cooper 2000; Stuart and Berghuis 2002). Further experimental work suggested even lower turbulence was required to pass small-bodied fish (Mallen-Cooper et al. 2008) and current criteria recommend $<30\ W/m^3$ and maximum water velocities of 1.2 m/s (O'Connor et al. 2015). Pool turbulence has been reduced via two main ways: (i) reducing the head drop between pools, and (ii) reducing the open area of the fishway slot to reduce pool discharge (Mallen-Cooper et al. 2008). Early fishways were based on fish passage principles for large-bodied temperate anadromous species, however research determined that most migratory tropical Australian species were diadromous and small-bodied (usually < 100 mm long) (Kowarsky and Ross 1981).

Bynoe River Cone Fishway

A total of 18 fish species and 2243 individuals were collected in 6 paired samples at the top and bottom of the cone fishway (Table 2). Five species were diadromous and 13 were potamodromous. Bony herring (*Nematalosa erebi*) formed 50% of the total catch, followed by empire gudgeons (*Hypselotris compressa*) at 21%. Three species, Rendahl's catfish (*Porochilus rendahli*), spangled perch (*Leiopotherapon unicolor*) and spotted scat (*Scatophagus argus*) were only captured in the bottom trap, while two species, longtom (*Strongylura krefftii*) and gulf grunter (*Scortum ogilbyi*) were only captured in the top trap. Each of the species only captured in one trap were caught in low numbers (<10 individuals).

Gooseponds Creek Rock Ramp Fishway

A total of 13 fish species and 847 individuals were collected in 5 paired samples at the top and bottom of the rock ramp fishway (Table 3). Five species were diadromous and eight were potamodromous. Empire gudgeons formed 40% of the total catch, followed by bony herring at 19%. Spotted scat were only captured in the bottom trap, while threadfin silverbiddy (*Gerres filamentosus*), carp gudgeon (*Hypseleotris* spp) and spangled perch were only captured in the top trap. Each of the species only captured in one trap were caught in low numbers (<3 individuals).

Waterpark Creek Vertical-slot Fishway

A total of 10 fish species and 419 individuals were collected in 7 paired samples at the top and bottom of the vertical-slot fishway (Table 4). Seven species were diadromous and three were potamodromous. Empire gudgeons formed 84% of the total catch, followed by long-finned eels (*Anguilla reinhardtii*) at 8%. Four species, pinkeye mullet (*Trachystoma petardi*), sea mullet (*Mugil cephalus*), barramundi (*Lates calcarifer*) and flathead goby (*Glossogobius giuris*) were only captured in the bottom trap, while three species, bullrout (*Notesthes robusta*), striped gudgeon (*Gobiomorphus australis*) and Hyrtl's tandan (*Neosilurus hyrtlii*) were only captured in the top trap. Each of the species only captured in one trap were caught in low numbers (<13 individuals).

Comparison of fish sizes at the top of the fishway and at the bottom

At Bynoe River cone fishway, there were no differences in the size of empire gudgeons ($D_{54,115} = 0.088$, $p = 0.320$) and giant glassfish (*Parambassis gulliveri*) ($D_{206,106} = 0.121$, $p = 0.244$) from traps at the top and bottom of the fishway, though there were significantly larger bony herring ($D_{501,607} = 0.347$, $p < 0.005$) at the top (Figure 5). The minimum size fish to successfully pass through

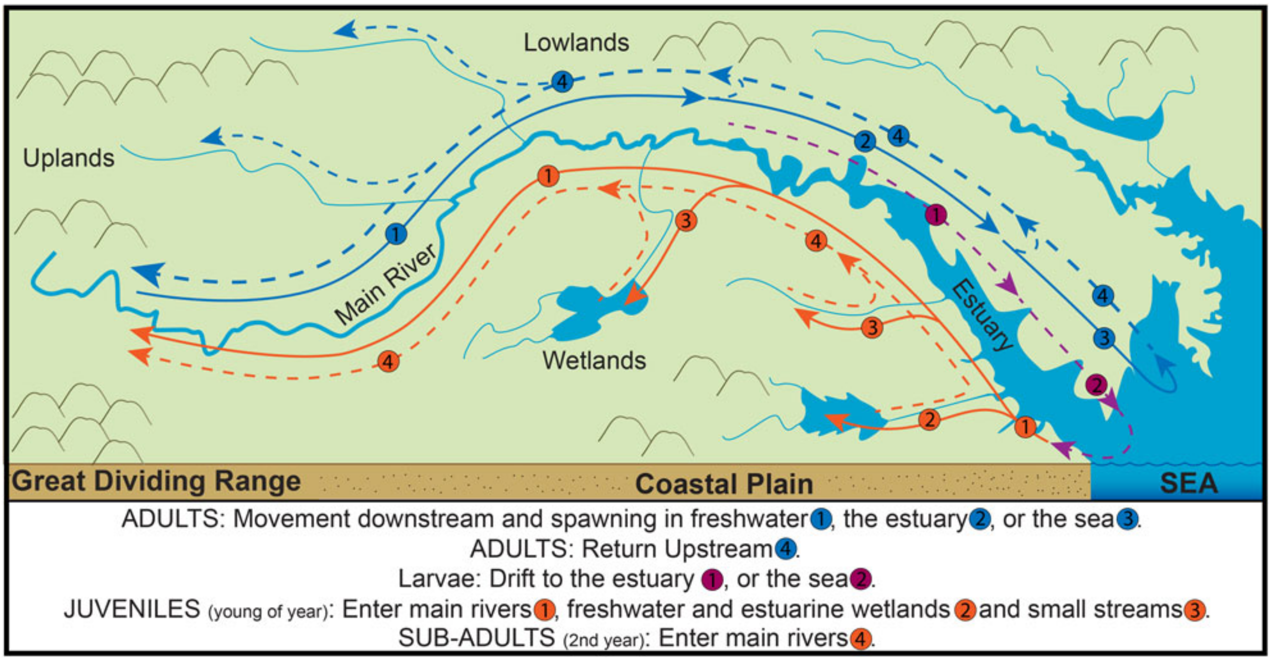

Figure 4. Conceptual model of fish movement in Australian tropical coastal streams, highlighting the return of small and juvenile fish through the tidal interface. Source: Author.

the cone fishway were a 9 mm long seven-spot archerfish (*Toxotes chatareus*) and goby (*Glossogobius sp.*).

At the Gooseponds Creek rock ramp fishway, there were no differences in the size of empire gudgeons ($D_{169,169} = 0.082$, $p = 0.590$) between the top and bottom of the fishway, although there were significantly smaller and larger bony herring ($D_{64,94} = 0.496$, $p = <0.001$) at the bottom of the fishway. The minimum size fish to pass the fishway was a 15 mm long fly-specked hardyhead (*Craterocephalus stercusmuscarum*).

At the Waterpark Creek vertical-slot fishway there were no differences in the sizes of empire gudgeons ($D_{275,50} = 0.149$, $p = 0.133$) between the top and bottom of the fishway.

Discussion

Tropical coastal rivers support high fisheries diversity, but tidal barriers disrupt connectivity and have caused direct losses to upstream biodiversity (Hamilton and Gehrke 2005; Barlow et al. 2018). In northern Australia, older fishways did not pass small amphidromous fish below tidal barriers, highlighted by millions of 10+ mm empire gudgeons aggregated below tidal barriers (Stuart and Marsden 2019). From our three case-study field evaluations, there was passage of a wide range of small-bodied fish species and sizes highlighting that modern fishways can mitigate some of the detrimental effects of stream barriers, and potentially help restore migratory small-bodied fish communities (Amtstaetter et al. 2017; Pennock et al. 2018; Rourke et al. 2019).

In the tropical rivers of northern Australia, a series of field evaluations have now demonstrated that fishways for low-head tidal barriers can help small fish (i.e. >9 mm long) to complete their upstream migration from estuaries to freshwater (Marsden et al. 2003; Ferguson et al. 2008; Moore and Marsden 2010; Stuart and Marsden 2019) and thus help to restore the original function of lowland tropical rivers and wetlands (Sheaves et al. 2014). A relatively small number of early fishway evaluations first identified the inability of salmonid fishway designs to pass native fish, especially fish <100 mm long (Kowarsky and Ross 1981; Harris 1984; Mallen-Cooper 1999). In response, a resurgence in fishway work began to develop more suitable designs which provided a platform for guidance to practitioners to design fishways for passage of fish from >40 mm long (Stuart and Mallen-Cooper 1999, Stuart and Berghuis 2002). The present case-studies now highlight that very small fish (i.e. >9 mm long) can now ascend rock and technical fishways and these designs have since been adopted for small-bodied tropical species in SE Asia (Baumgartner et al. 2018).

A key element to the development of more effective fishways was integration of ecological knowledge and hydraulic criteria. This ecohydraulic logic can be summarized as: (i) define a transparent ecological fish passage objective, (ii) from the ecology select the hydrological range of river levels over which the fishway operates, (iii) select appropriate internal hydraulic fishway design criteria, (iv) choose the fishway type that meets these ecohydraulic objectives, and (iv) field evaluation and further design

Table 2. Total number of fish collected at the top and bottom of the Bynoe River cone fishway. Shading indicates a diadromous species.

		Fishway Location	
Species	Common Name	Bottom	Top
Neoarius paucus	Carpentaria catfish	15	1
Toxotes chatareus	seven-spot archer fish	8	10
Hypseleotris compressa	empire gudgeon	292	190
Glossogobius giuris	flathead goby	23	59
Glossogobius sp.	goby	13	10
Parambassis gulliveri	giant glassfish	106	206
Porochilus rendahli	Rendahl's catfish	5	0
Craterocephalus stercusmuscarum	fly-specked hardyhead	82	60
Brachirus selheimi	freshwater sole	1	1
Neoarius berneyi	Berney's catfish	5	5
Neosilurus hyrtlii	Hyrtl's tandan	3	3
Leiopotherapon unicolor	spangled perch	1	0
Scortum ogilbyi	gulf grunter	0	1
Oxyeleotris lineolatus	sleepy cod	1	1
Melanotaenia splendida inornata	chequered rainbowfish	3	15
Scatophagus argus	spotted scat	10	0
Nematalosa erebi	bony herring	607	505
Strongylura krefftii	longtom	0	1
Total number of fish		**1175**	**1068**

Table 3. Total number of fish collected in the Gooseponds Creek rock ramp fishway. Shading indicates a diadromous species.

		Fishway Location	
	Common Name	Bottom	Top
Anguilla reinhardtii	**Species**	1	1
Gerres filamentosus	Whipfin silver-biddy	0	1
Hypseleotris compressa	empire gudgeon	169	169
Neoarius graeffei	blue catfish	23	1
Scatophagus argus	Spotted Scat	2	0
Ambassis agassizii	Agassiz's glassfish	103	4
Craterocephalus stercusmuscarum	fly-specked hardyhead	11	90
Glossamia aprion	Mouth Almighty	1	1
Hypseleotris spp	carp gudgeon	0	3
Leipotherapon unicolor	spangled perch	0	1
Melanotaenia splendida	eastern rainbowfish	7	53
Nematalosa erebi	bony herring	94	64
Gambusia holbrooki	gambusia	9	39
Total number of fish		**420**	**427**

Table 4. Total number of fish collected in the Waterpark Creek vertical slot fishway. Shading indicates a diadromous species.

		Fishway Location	
Species	Common Name	Bottom	Top
Anguilla reinhardtii	long-finned eel	31	4
Trachystoma petardi	pinkeye mullet	3	0
Mugil cephalus	sea mullet	1	0
Lates calcarifer	barramundi	1	0
Hypseleotris compressa	empire gudgeon	75	275
Notesthes robusta	bullrout	0	1
Glossogobius giuris	flathead goby	1	0
Gobiomorphus australis	striped gudgeon	0	13
Melanotaenia splendida	eastern rainbowfish	11	1
Neosilurus hyrtlii	Hyrtl's tandan	0	1
Total number of fish		**124**	**295**

refinements. Once passage of small-bodied fish became an explicit design objective, then hydraulic criteria including very low turbulence (i.e. 15 W/m^3), floor-slopes (e.g. 1 V:25H), and water velocities (1.0 m/s) can be selected. In this way, letting the fish ecology, fishway hydraulics and river hydrology drive the fishway design, provides for a robust and inclusive process (Mallen-Cooper 1999).

In northern Australia, older fishways where characterized by high turbulence (Kowarsky and Ross 1981) which can impact on fish stability and swimming (Lupandin 2005; Goettel et al. 2015). In temperate Australia, low turbulence fishways facilitate small-bodied fish passage (Mallen-Cooper et al. 2008) even though there is non-uniform spatial distribution of theoretical turbulence in a fishway pool (Fuentes-Pérez et al. 2018). While we were unable to statistically test the influence of ecohydraulic criteria on fish passage in our field case-studies the tabulation of tropical fishways, demonstrated that low turbulence designs (i.e. <30 W/m^3) are now common. However, to pass the smallest fish (i.e. 9–50 mm long) the latest research suggests even lower turbulence (i.e. 15 W/m^3; O'Connor et al. 2019; Stuart and Marsden 2019) may be required and further experimentation is needed to provide guidance here.

Turbulence is a function of the pool head drop, pool volume and pool discharge (Clay 1995) and for tropical small-bodied fish we used very low pool drops (i.e. 67 mm for the vertical-slot). From the three case-studies, our observations also suggest that rather than engaging the whole pool in dissipating energy, deliberately designing for non-uniform hydraulic conditions, with continuous pathways of very low turbulence, may provide a strong direction to further improve passage of small-bodied fish. This was a cost sensitive design decision because low head drops increase fishway length and highlights the need for further experimental work. By contrast, the pool head drops for the lateral ridge rock ramp fishways were greater (i.e. 100 mm), because of greater inherent roughness and boundary layers. Small fish can exploit these layers while they

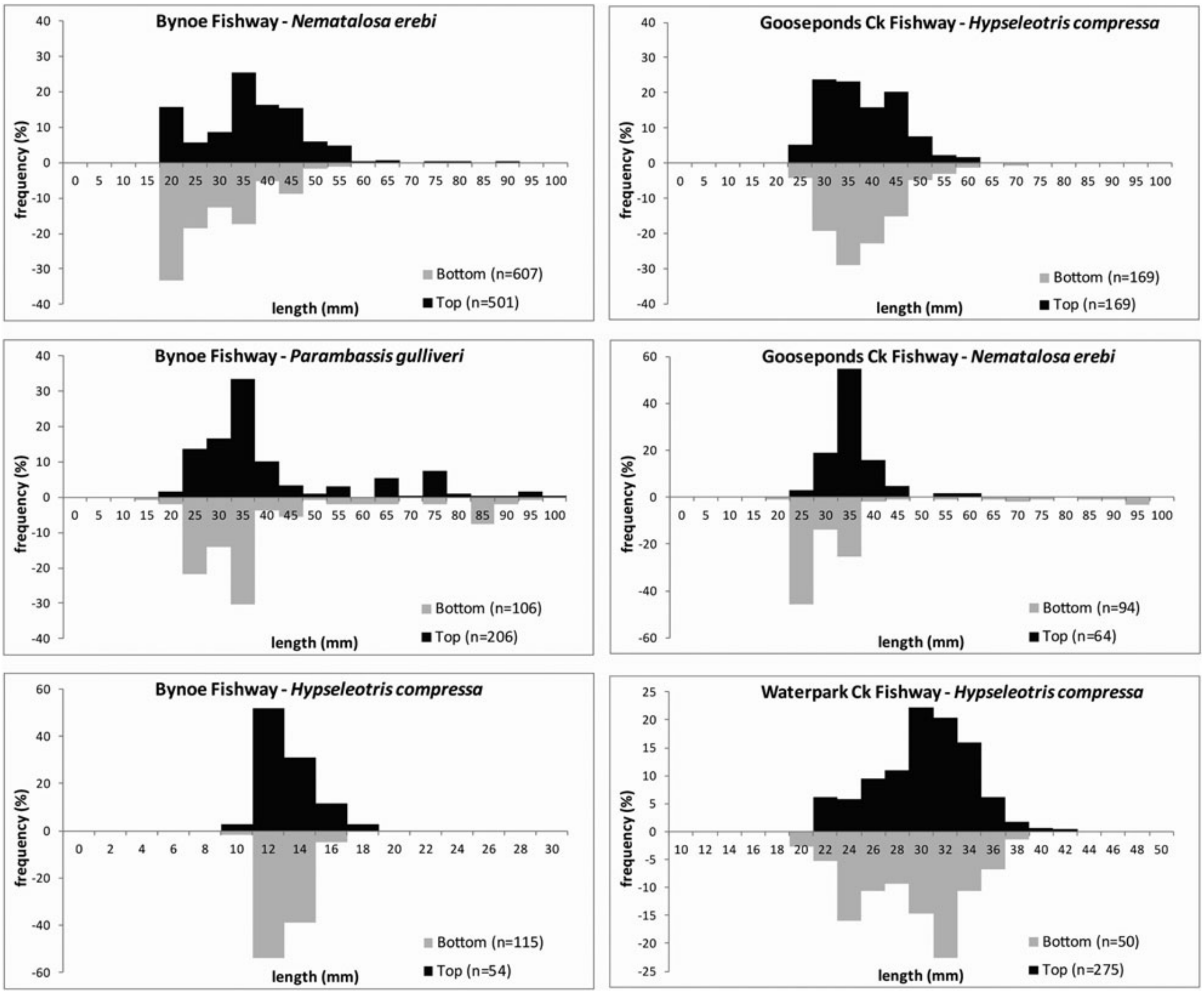

Figure 5. Pooled size distribution of six small-bodied (<100 mm long) fish species from multiple sampling events at the top (upstream) and bottom (downstream) of the fishways. Note that the scale of the *x*-axis varies.

Figure 6. Purple spotted gudgeons migrating upstream adhere to the roughened slope adjacent to high flow.

ascend, especially along the bed or shallow channel margins (Watson et al. 2018). For example, purple-spotted and empire gudgeons when migrating often partially emerge and use their pectoral fins as hydrofoils to adhere to the sloped concrete surfaces (Figure 6). To assist this type of passage, roughened concrete surfaces that create low velocity boundary layers could be incorporated into the design of technical fishways (Goodrich et al. 2018).

To maintain consistent fishway hydraulics at each of our sites, there was individual tailoring of designs to cater for local conditions, such as highly variable tidal tailwater, long periods of low flow during the dry season, or major flooding during the wet season. Design modifications included very narrow slots (e.g. 80 mm) to (i) reduce total discharge and increase operational time during the dry season, (ii) reduce theoretical pool turbulence, and (iii) improve ascent conditions for small-bodied fish (Stuart and Marsden 2019). In addition, the low profile of internal baffle elements helped to prevent blockages during high flows and enable the fishways to recommence operation, without maintenance, on the flow recession. The inclusion of a tailwater stabilization pool helped to maintain the design hydraulics even during major tidal recession of the tailwater (Stuart and Marsden 2019). Lastly, the use of low pool step heights along with roughened pools and ridge slots assisted the smallest fish sizes in their ascent of the fishway. These design decisions depend on a thorough understanding of tropical river fish ecology and fishways hydraulics and have been implemented

Table 5. Ecohydraulic fishway design criteria suitable for Australian tropical amphidromous, catadromous and potamodromous fish at pool-type fishways on low-head tidal barriers.

Fishway type and slot-width	Target fish size range (mm) and potential biomass	Target river flow range	Maximum water velocity (@ *vena contracta*)	Maximum head drop between pools	Turbulence (Cd = 0.65)	Distribution of turbulence	Roughness	Reference
Vertical-slot (0.1–0.18 m)	10–600 Large	Low to high flows	1.0–1.2 m/s	50–75 mm	15–25 Wm^3	Throughout pool	none required	Bice et al. (2017), O'Connor et al. (2019)
Concrete cone (0.1–0.31 m)	10–600 Large	Low to moderate flows	1.2 m/s	60–80 mm	$<$15 Wm^3	Edges and bottom low, centre high	none required	Stuart and Marsden (2019)
Rock ramp (0.1–0.25 m)	10–600 Moderate	Low flows	1.4 m/s	100 mm	$<$30 Wm^3	Edges and bottom low, surface high	maximum roughness	O'Connor et al. (2015)

at many other tropical fishways where small-bodied fish passage is a priority. From the latest research, a summary of ecohydraulic design guidance, for low-head fishways that enhance passage of small-bodied tropical fish at tidal barriers is provided in Table 5. For tropical rivers worldwide, especially where little information exists, we suggest that these criteria provide a useful guide but that further field testing and refinement for local species is still required (Baumgartner et al. 2012).

There are still many unresolved challenges in terms of optimising fish passage technology and applications, such as: (i) continuing to develop new solutions based on integrated ecological and hydraulic criteria, (ii) improving entrance attraction efficiency so that fish pass into freshwater habitats quickly (i.e. within one or two tidal cycles), (iii) developing fishways that pass the smallest and largest fish, as well as high biomass, (iv) efficient fishways for a broad range of river conditions, (iv) evaluation of small-bodied fish passage and energetic costs in long fishways (Thiem et al. 2016), and (v) ongoing evaluation as to whether fishways contribute to upstream fish recovery and long-term maintenance of viable populations (Birnie-Gauvin et al. 2018). The 25-years of fish passage experience at low-head tidal barriers in northern Australia, began with grossly inadequate fishways (Harris 1984) but is now characterized by significant progress toward recovery of freshwater fish populations (Baumgartner et al. 2012; Bice et al. 2017; Stuart and Marsden 2019).

Accumulations of large numbers of small-bodied tropical diadromous fish below low-head tidal barriers and ineffective fishways were the initial impetus for researchers to develop improved eco-hydraulic design criteria (Kowarsky and Ross 1981; Russell 1991). While there have been improvements in passage of small-bodied fish at tidal barriers (Bice et al. 2017; Stuart and Marsden 2019) further experimental work is still needed to test and refine current eco-hydraulic fishway design criteria.

Acknowledgements

We thank Darren Jennings, Matthew Moore, Alana O'Brien and Melinda Scanlon, previously staff at the Queensland Department of Agriculture and Fisheries who aided in the development, construction and monitoring many fishway designs in Queensland. Field sampling was completed under Animal Ethics Authorisation No. CA2014/08/798.

Disclosure statement

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

References

Agostinho CS, Agostinho AA, Pelicice F, Almeida DAD, Marques EE. 2007. Selectivity of fish ladders: a bottleneck in Neotropical fish movement. Neotrop Ichthyol. 5(2):205–213.

Amtstaetter F, O'Connor J, Borg D, Stuart I, Moloney P. 2017. Remediation of upstream passage for migrating Galaxias (Family: Galaxiidae) through a pipe culvert. Fish Manag Ecol. 24(3):186–192.

Barlow J, França F, Gardner TA, Hicks CC, Lennox GD, Berenguer E, Castello L, Economo EP, Ferreira J, Guénard B, et al. 2018. The future of hyperdiverse tropical ecosystems. Nature. 559(7715):517.

Baumgartner LJ. 2007. Diet and feeding habits of predatory fishes upstream and downstream of a low-level weir. J Fish Biol. 70(3):879–894.

Baumgartner LJ, Marsden T, Singhanouvong D, Phonekhampheng O, Stuart IG, Thorncraft G. 2012. Using an experimental in situ fishway to provide key design criteria for lateral fish passage in tropical rivers: a case study from the Mekong River, central Lao PDR. River Res Applic. 28(8):1217–1229.

Baumgartner L, Zampatti B, Jones M, Stuart I, Mallen-Cooper M. 2014. Fish passage in the Murray-Darling Basin, Australia: Not just an upstream battle. Ecol Manag Restor. 15:28–39.

Baumgartner LJ, Boys CA, Marsden T, McPherson J, Ning N, Phonekhampheng O, Robinson WA, Singhanouvong D, Stuart IG, Thorncraft G. 2018. Comparing fishway designs for application in a large tropical river system. Ecol Eng. 120:36–43.

Bice CM, Zampatti BP, Mallen-Cooper M. 2017. Paired hydraulically distinct vertical-slot fishways provide complementary fish passage at an estuarine barrier. Ecol Eng. 98:246–256.

Birnie-Gauvin K, Franklin P, Wilkes M, Aarestrup K. 2018. Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene. In: Aquatic conservation: Marine and freshwater ecosystems. Hoboken (NJ): Wiley-Blackwell.

Brown JJ, Limburg KE, Waldman JR, Stephenson K, Glenn EP, Juanes F, Jordaan A. 2013. Fish and hydropower on the US Atlantic coast: failed fisheries policies from half-way technologies. Cons Lett. 6(4):280–286.

Bunt CM, Castro -Santos T, Haro A. 2012. Performance of fish passage structures at upstream barriers to migration. River Res Appl. 28(4):457–478.

Castro-Santos T, Shi X, Haro A. 2017. Migratory behavior of adult sea lamprey and cumulative passage performance through four fishways. Can J Fish Aquat Sci. 74(5):790–800.

Celestino LF, Sanz -Ronda FJ, Miranda LE, Makrakis MC, Dias JHP, Makrakis S. 2019. Bidirectional connectivity via fish ladders in a large Neotropical River. River Res Appl. 35(3):236–246.

Clay CH. 1995. Design of fishways and other fish facilities. Boca Raton (FL): CRC Press.

Dugan PJ, Barlow C, Agostinho AA, Baran E, Cada GF, Chen D, Cowx IG, Ferguson JW, Jutagate T, Mallen-Cooper M, et al. 2010. Fish migration, dams, and loss of ecosystem services in the Mekong basin. Ambio. 39(4):344–348.

Ferguson M, Power T, Jennings D, O'Brien A, Marsden T. 2008. St Lawrence Wetland fish passage improvement. Report to the Fitzroy Basin Association, Queensland Department of Primary Industries and Fisheries. 22 pp.

Fuentes-Pérez JF, Silva AT, Tuhtan JA, García-Vega A, Carbonell-Baeza R, Musall M, Kruusmaa M. 2018. 3D modelling of non-uniform and turbulent flow in vertical slot fishways. Environ Modell Software. 99:156–169.

Gillson J. 2011. Freshwater flow and fisheries production in estuarine and coastal systems: where a drop of rain is not lost. Rev Fish Sci. 19(3):168–186.

Goettel MT, Atkinson JF, Bennett SJ. 2015. Behavior of western blacknose dace in a turbulence modified flow field. Ecol Eng. 74:230–240.

Goodrich HR, Watson JR, Cramp RL, Gordos MA, Franklin CE. 2018. Making culverts great again. Efficacy of a common culvert remediation strategy across sympatric fish species. Ecol Eng. 116:143–153.

Guillerault N, Boulêtreau S, Santoul F. 2019. Predation of European catfish on anadromous fish species in an anthropised area. Mar Freshwater Res. 70(5):682–686.

Gutfreund C, Makrakis S, Castro-Santos T, Celestino LF, Dias JHP, Makrakis MC. 2018. Effectiveness of a fish ladder for two Neotropical migratory species in the Paraná River. Mar Freshwater Res. 69(12):1848–1856.

Hamilton SK, Gehrke PC. 2005. Australia's tropical river systems: current scientific understanding and critical knowledge gaps for sustainable management. Mar Freshwater Res. 56(3):243–252.

Harris JH. 1984. A survey of fishways in streams of coastal Southeastern Australia. Aust Zool. 21:219–234.

Harris JH, Kingsford RT, Peirson W, Baumgartner LJ. 2017. Mitigating the effects of barriers to freshwater fish migrations: the Australian experience. Mar Freshwater Res. 68(4):614–628.

Kowarsky J, Ross AH. 1981. Fish movement upstream through a central Queensland (Fitzroy River) coastal fishway. Mar Freshwater Res. 32(1):93–109.

Landsman SJ, Wilson ADM, Cooke SJ, van den Heuvel MR. 2017. Fishway passage success for migratory rainbow smelt *Osmerus mordax* is not dictated by behavioural type. River Res Applic. 33(8):1257–1267.

Lupandin AI. 2005. Effect of flow turbulence on swimming speed of fish. Biol. Bull. 32(5):461–466.

Mallen-Cooper M. 1999. Developing fishways for non-salmonid fishes; a case study from the Murray River in Australia. In: Odeh M, editor. Innovations in fish passage technology. Bethesda (MD): American Fisheries Society; pp 173–195.

Mallen-Cooper M. 2000. Review of fish passage in New South Wales–Public distribution copy. St Ives: Fishway Consulting Services.

Mallen-Cooper M, Stuart I, Zampatti B, Baumgartner L. 2008. Innovative fishways—manipulating turbulence in the vertical-slot design to improve performance and reduce cost. Murray-Darling Basin Commission.

Marsden T, Thorncraft G, Woods K. 2003. Reconstruction of Culverts and causeways to assist migrations of adult and juvenile fish project. Report to the Natural Heritage Trust, Queensland Department of Primary Industries and Fisheries. 34 pp.

Marques H, Dias JHP, Ramos IP. 2018. Is there evidence of connectivity restoration by fishways? The case of Porto Primavera Hydropower Plant, Paraná River, Southeastern Brazil. Acta Limnol Bras. 30.

McKillup S. 2005. Statistics explained. An introductory guide for life scientists. Cambridge: Cambridge University Press.

Millar J, Robinson W, Baumgartner L, Homsombath K, Chittavong M, Phommavong T, Singhanouvong D. 2018. Local perceptions of changes in the use and management of floodplain fisheries commons: the case of Pak Peung wetland in Lao PDR. Environ Develop Sust: 1–18.

Moore M, Marsden T. 2010. Amity and bridge creeks fish passage project. Report to Fitzroy Basin Association, Queensland Department of Employment, Economic Development and Innovation. 41 pp.

Noonan MJ, Grant JW, Jackson CD. 2012. A quantitative assessment of fish passage efficiency. Fish Fish. 13(4): 450–464.

O'Connor J, Pickworth A, Fanson B, Lovric D. 2019. Assessment of a vertical slot fishway in south-eastern Australia designed to pass numerous species and size classes of fish. Ecol Man Rest. 20(2):151–155.

O'Connor J, Mallen-Cooper M, Stuart I. 2015. Performance, operation and maintenance guidelines for fishways and fish passage works. Arthur Rylah Institute for Environmental Research Technical Report No. 262 for the Water and Catchments Group, Department of Environment, Land, Water and Planning. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Pennock CA, Bender D, Hofmeier J, Mounts JA, Waters R, Weaver VD, Gido KB. 2018. Can fishways mitigate fragmentation effects on Great Plains fish communities? Can J Fish Aquat Sci. 75(1):121–130.

Rolls RJ. 2011. The role of life-history and location of barriers to migration in the spatial distribution and conservation of fish assemblages in a coastal river system. Biol Cons. 144(1):339–349.

Rolls RJ, Faggotter SJ, Roberts DT, Burford MA. 2018. Simultaneous assessment of two passage facilities for maintaining hydrological connectivity for subtropical coastal riverine fish. Ecol Eng. 124:77–87.

Romão F, Branco P, Quaresma AL, Amaral SD, Pinheiro AN. 2018. Effectiveness of a multi-slot vertical slot fishway versus a standard vertical slot fishway for potamodromous cyprinids. Hydrobiol. 816(1):153–163.

Roscoe DW, Hinch SG. 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisher. 11(1): 12–33.

Rourke ML, Robinson W, Baumgartner LJ, Doyle J, Growns I, Thiem JD. 2019. Sequential fishways reconnect a coastal river reflecting restored migratory pathways for an entire fish community. Restor Ecol. 27(2): 399–407.

Russell DJ. 1991. Fish movements through a fishway on a tidal barrage in sub-tropical Queensland. Proc Roy Soc Queen. 101:109–118.

Sheaves M, Brookes J, Coles R, Freckelton M, Groves P, Johnston R, Winberg P. 2014. Repair and revitalisation of Australia's tropical estuaries and coastal wetlands: Opportunities and constraints for the reinstatement of lost function and productivity. Mar Pol. 47:23–38.

Sheaves M, Baker R, Nagelkerken I, Connolly RM. 2015. True value of estuarine and coastal nurseries for fish: incorporating complexity and dynamics. Est Coasts. 38(2):401–414.

Silva AT, Lucas MC, Castro-Santos T, Katopodis C, Baumgartner LJ, Thiem JD, Aarestrup K, Pompeu PS, O'Brien GC, Braun DC, et al. 2018. The future of fish passage science, engineering, and practice. Fish Fish. 19(2):340–362.,

Silva AT, Katopodis C, Santos JM, Ferreira MT, Pinheiro AN. 2012. Cyprinid swimming behaviour in response to turbulent flow. Ecol Eng. 44:314–328.

Stuart I, Mallen-Cooper M. 1999. An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical/subtropical river. Regul Rivers: Res Mgmt. 15(6):575–590.

Stuart IG, Berghuis AP. 2002. Upstream passage of fish through a vertical-slot fishway in an Australian subtropical river. Fisheries Manage. 9(2):111–122.

Stuart IG, Zampatti BP, Baumgartner LJ. 2008. Can a low-gradient vertical-slot fishway provide passage for a lowland river fish community? Mar Freshwater Res. 59(4):332–346.

Stuart IG, Marsden TJ. 2019. Evaluation of cone fishways to facilitate passage of small-bodied fish. Aqua Fish.

Thiem JD, Binder TR, Dumont P, Hatin D, Hatry C, Katopodis C, Stamplecoskie KM, Cooke SJ. 2013. Multispecies fish passage behaviour in a vertical slot fishway on the Richelieu River, Quebec, Canada. River Res Applic. 29(5):582–592.

Thiem JD, Dawson JW, Hatin D, Danylchuk AJ, Dumont P, Gleiss AC, Wilson RP, Cooke SJ. 2016. Swimming activity and energetic costs of adult lake sturgeon during fishway passage. J Exp Biol. 219(16):2534–2544.

Watson JR, Goodrich H, Cramp RL, Gordos MA, Franklin CR. 2018. Utilising the boundary layer to help restore the connectivity of fish habitats and populations. Ecol Eng. 122:286–294.

White DK, Pennino BJ. 1980. Connecticut river fishways: model studies. J Hydraul Div, Am Soc Civ Eng 7(198): 1219–1233.