Fitzroy Barrage

Cone Fishway Upgrade and Monitoring Report

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Fisheries Collective

This report has been prepared by the Fisheries Collective (FC) for Fitzroy Basin Assocition (FBA).

The Fitzroy Barrage Cone Fishway, Monitoring Report has been prepared with due care and diligence using the best available information at the time of publication. FC and FBA holds no responsibility for any errors or omissions and decisions made by other parties based on this publication.

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1. Acknowledgements

The Authors would like to acknowledge the assistance and support of several groups associated with the project. Fitzroy Basin Association initiated this project as part of their larger Fish Friendly Fitzroy Project and have provided ongoing support and guidance for the project. The Australian Government provided the funding for the monitoring and construction of the Fitzroy Barrage Fishway. Fitzroy River Water provided permission to undertake the modification of their infrastructure and provided considerable knowledge of the existing fishway and barrage structure that helped with construction of the new fishway. Calibre Consulting Pty Ltd and Busby Contracting Pty Ltd capably undertook the engineering and construction of this fishway, providing great service within a difficult tidal site.

1.1. Summary

The Fish Friendly Fitzroy: Bypassing the Barrage project was initiated to improve fish passage in the lower Fitzroy Basin and restore fish communities in the lower 150 km of stream habitat. The major specific objective was to evaluate the success of an innovative new cone fishway technology as well as remediate the existing vertical slot fishway to enhance upstream passage of super-abundant small-bodied fish (<100 mm long).

From 2014-16, monitoring of the two major modifications (i) new cone fishway, (ii) tailwater stabilisation pool, to increase functionality of the new cone and existing vertical slot fishway was completed. In total, 19 species of small-bodied fish were collected with the cone fishway meeting its original design objectives of passage of very small native fish. In fact, the innovative cone design passed the most fish per hour of any Australian fishway and the work also significantly extended the functionality of the vertical slot.

The major outcomes were:

- Passage of the highest number of fish of any Australian fishway.
- Achievement of the original objective of efficient passage (>80%) of the super-abundant small-bodied fish >14 mm long which could not efficiently pass (<10%) any of the older fishway designs.
- Extension of the operational range of the cone and vertical slot fishways from 39% of tides to 95% of tides.
- Extension of the functionality of the existing vertical slot from 3 hours per tide to 24 hours per day.
- Upstream passage of an estimated 3.8M fish per year.
- An unprecedented cost-benefit estimate of at least 40 fish/per dollar investment successfully passing upstream over the 25-year fishway design life.
- Fishways that make a major contribution to restoration of native fish communities in the lower Fitzroy basin.

For Fitzroy Basin Association, the barrage fishway modifications have been a significant step forward in restoring the environmental values of the lower Fitzroy Basin. Building on these achievements, with monitoring to demonstrate outcomes and to identify new fish recovery opportunities, will be crucial in the recovery of native fish communities. The barrage fishway modifications have exceeded their design objectives but may be further complemented with:

- Minor rectification of the existing vertical slot baffles to bring the hydraulics into line with current best practice and further complement the cone fishway in restoring upstream fish passage.
- Monitoring the recovery of lower Fitzroy Basin fish communities and providing data to support any future decision for the need for interventions such as a fishway for the north bank.

2. Introduction

The Fish Friendly Fitzroy: Bypassing the Barrage project was initiated to help ameliorate the impacts of the Fitzroy Barrage on fish passage in the Fitzroy Basin. The barrage has long been recognised as a major contributing factor in detrimental changes to aquatic habitats and fish communities in the lower reaches of the Fitzroy River and tributaries. The original concept for the project was to provide fish passage past the barrage via the southern Fitzroy floodplain lagoons system.

However, engineering feasibility analysis demonstrated that the floodplain lagoon initiative would not produce the desired outcomes, due to the infrequent and short duration of connection and great expense of associated infrastructure (FBA 2014). A decision not to proceed further with these works was taken in 2015 and a focus on other activities such as improving fish passage at the Fitzroy Barrage and improved floodplain management became the focus of the project. Targets set for these new activities included the rehabilitation of 150ha of aquatic habitats, improved practices of 200ha of adjacent land, the control of 200ha of weeds and the opening of 150km of river habitat by the abatement of three barriers.

To assist with the abatement of three barriers, monitoring, modification and re-monitoring of the Fitzroy Barrage Fishway was undertaken over three years from 2014 to 2016. These works substantially contributed to the opening of over 150km of main stream habitat. The objective of this report is to detail the fishway modifications undertaken and the results of field monitoring and their implications for recovering fish communities in the lower Fitzroy River.

2.2. Fitzroy Basin

The Fitzroy River Basin encompasses an area of 142,450 km2 and is the largest river catchment on the east coast of Australia, with an average annual discharge of six million megalitres (Kowarsky & Ross, 1981). The major river basins of the catchment are the Isaac/Connors to the north, the Nogoa/Comet in the south-west, the Dawson in the south, with the Mackenzie central and the Fitzroy to the east. The Fitzroy River has a very low gradient of approximately 40 m fall per 310 km of length (Marsden & Power, 2007) and terminates at a wide alluvial plain into the Coral Sea at Broadmount.

The climate of the lower Fitzroy River is generally sub-tropical (Telfer 1995), most rainfall is received between November and February, but autumn rainfall is also common. The catchment area receives on average between 500 mm and 1000 mm of rain per year, but the high evaporation rate (2000 mm per year) ensures mostly dry conditions within the catchment and a highly variable stream flow. The catchment has a large range of temperatures with average summer high temperatures over 30^{o}C and winter low temperatures below zero degrees in some locations (Telfer 1995).

2.1. Hydrology

The location, straddling the Tropic of Capricorn, and large area of the Fitzroy Catchment has created a unique hydrology. The upper Dawson River Basin influenced by temperate weather patterns and particularly during the tropical dry season provides the bulk of inflow to the Fitzroy River. Conversely very high volume inflows may originate from the Connors and Isaac Rivers during the wet season from intense low pressure systems. The Fitzroy River at Rockhampton has a long and well documented history of flooding with records dating back to 1859 (Webster 2003). The most recent major flood for the Fitzroy River was in April 2017 which reached 8.8 metres on the Rockhampton gauge (BOM data).

Naturally the hydrology of the Fitzroy Basin consisted of non-perennial flows resulting in a fragmented chain of waterholes during the dry season. The construction and operation of dams and weirs across the catchment has transformed the flow regime of many of the streams from intermittent to perennial or near-perennial. This has had significant ecological implications for these streams. The natural flow regimes of supplemented streams have been altered from high annual summer flows and low/no flow conditions in the winter to medium to low flows continuing through the year.

The main stem Fitzroy River downstream of its confluence with both the Dawson and Mackenzie River has two major tributaries, Alligator Creek and Marlborough Creek both of which are less than 80km in length. Accordingly, the bulk of flow passing down the Fitzroy River is provided by the major river tributaries upstream.

2.2. Fish Communities

The Fitzroy River contains one of the most biodiverse and important fish assemblages in tropical eastern Australia with at least 30 species, including a variety of freshwater and estuarine/freshwater species (Berghuis and Long 1999) (Figure 1).

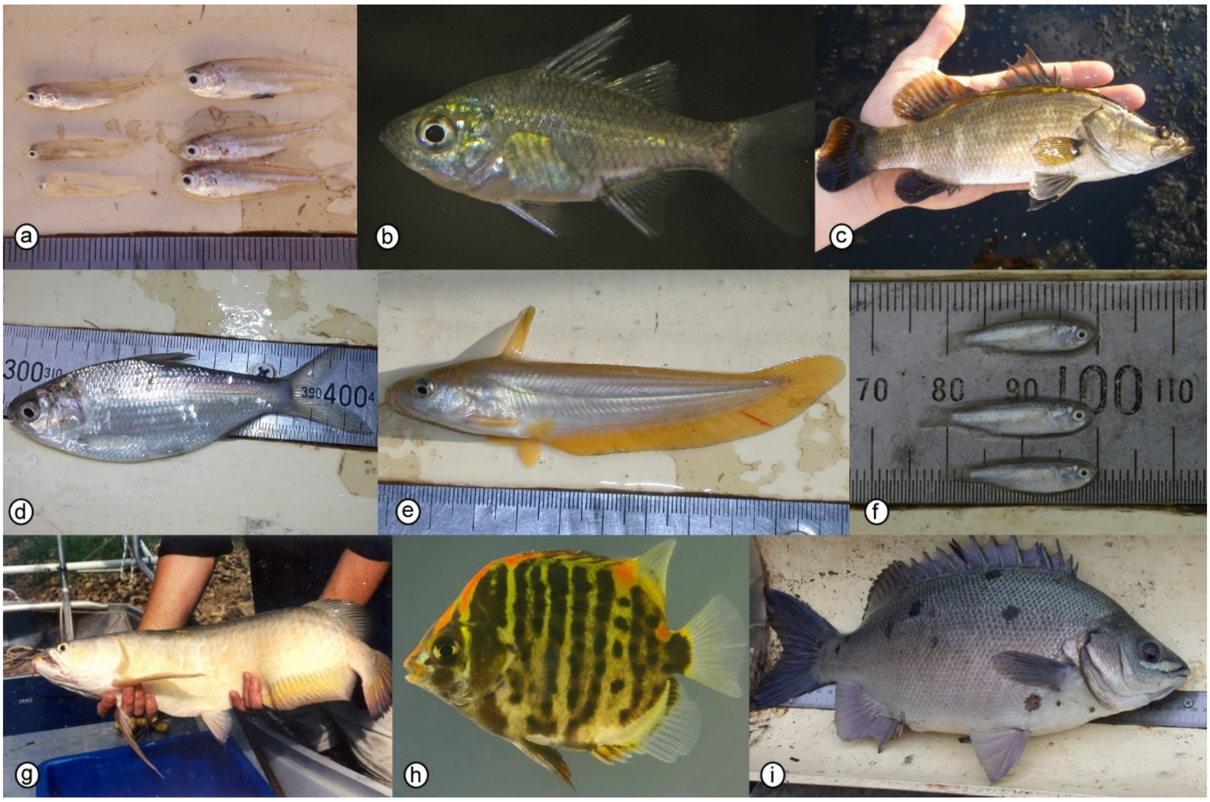

Figure 1. Migratory species of the Fitzroy Basin, a. & d. bony bream, b. olive perchlet, c. barramundi, e. hyrtl's tandan, f. striped mullet, g. saratoga, h. striped scat, i. leathery grunter.

Almost all of these fish species migrate as part of their life-history with approximately half moving between the estuary and freshwater (Stuart and Mallen-Cooper 1999). The Fitzroy River tidal barrage, 60 km from the river mouth, is a major fish passage barrier and has contributed to fragmentation of fish migration pathways between the estuary and freshwater and reduced ecosystem function (Sheaves et al. 2014). A species list compiled from the previous studies shows 34 freshwater species from 22 families are found in the Fitzroy River. In comparison Stuart (1997) identified 24 freshwater species from 17 families and 4 estuarine species at the Fitzroy River Barrage. Of the 34 freshwater species, there were six catadromous species, seven amphidromous species while the remaining 21 species are considered to be potamodromous (Table 2).

Table 1. Fish species and migration strategy from Stuart (1997) and other studies in the Fitzroy Catchment (Midgley, 1979; Stuart & Berghuis, 1997; Berghuis & Long, 1999; Long & Meager, 2000; Marsden & Thorncraft, 2000; Heidenreich & Broadfoot, 2001; Marsden *et. al.* 2005; Marsden & Powers, 2007). Migration Type - A = amphidromous, C = catadromous, P = potamodromous. ☹ = alien species, * = translocated native species

Common name	Species	Family	Migration	Stuart 1997	Other studies
long-finned eel	*Anguilla reinhardtii*	[Anguillidae]	C	✓	
mouth almighty	*Glossamia aprion*	[Apogonidae]	P	✓	✓
fork-tailed catfish	*Arius graeffei*	[Ariidae]	A	✓	✓
fly-specked hardyhead	*Craterocephalus s. stercusmuscarum*	[Atherinidae]	P	✓	✓
longtom	*Strongylura krefftii*	[Belonidae]	A	✓	✓
barramundi	*Lates calcarifer*	[Centropomidae]	C	✓	✓
olive perchlet	*Ambassis agassizii*	[Ambassidae]	P	✓	✓
bony herring	*Nematalosa erebi*	[Clupeidae]	A	✓	✓
goldfish ☹	*Carassius auratus*	[Cyprinidae]	P		✓
empire gudgeon	*Hypseleotris compressa*	[Eleotridae]	A	✓	✓
western carp gudgeon	*Hypseleotris klunzingeri*	[Eleotridae]	P	✓	✓
Midgley's carp gudgeon	*Hypseleotris sp.*	[Eleotridae]	P	✓	✓
purple spotted gudgeon	*Mogurnda adspersa*	[Eleotridae]	P		✓
sleepy cod	*Oxyeleotris lineolatus*	[Eleotridae]	P	✓	✓
flathead gudgeon	*Philypnodon grandiceps*	[Eleotridae]	P		✓
Speckled goby	*Redigobius bikolanus*	[Gobiidae]	A		✓
snub-nosed garfish	*Arrhamphus sclerolepis*	[Hemirhamphidae]	P	✓	✓
oxeye herring	*Megalops cyprinoides*	[Megalopidae]	C	✓	✓
eastern rainbowfish	*Melanotaenia s. splendida*	[Melanotaeniidae]	P	✓	✓
striped mullet	*Mugil cephalus*	[Mugilidae]	C	✓	✓
saratoga	*Scleropages leichardti*	[Osteoglossidae]	P		✓
golden perch	*Macquaria ambigua*	[Percichthyidae]	P	✓	✓
black catfish	*Neosilurus ater*	[Plotosidae]	P		✓
Hyrtl's tandan	*Neosilurus hyrtlii*	[Plotosidae]	P	✓	✓
Rendahl's catfish	*Porochilus rendahli*	[Plotosidae]	A	✓	✓
eel-tail catfish	*Tandanus tandanus*	[Plotosidae]	P		✓

Common name	Species	Family	Migration	Stuart 1997	Other studies
mosquito fish ☹	*Gambusia holbrooki*	[Poeciliidae]	P	✓	✓
Pacific blue-eye	*Pseudomugil signifer*	[Pseudomugilidae]	A		✓
bullrout	*Notesthes robusta*	[Scorpaenidae]	C	✓	
swamp eel	*Ophisternon sp.*	[Synbranchidae]	C		✓
banded grunter	*Amniataba percoides*	[Teraponidae]	P	✓	✓
sooty grunter*	*Hephaestus fuliginosus*	[Teraponidae]	P		✓
spangled perch	*Leiopotherapon unicolor*	[Teraponidae]	P	✓	✓
leathery grunter	*Scortum hillii*	[Teraponidae]	P	✓	✓

The species listed in Table 2 provide a comprehensive record of the fish community of the Fitzroy Catchment. With the exception of saratoga which is not prevalent in the lower Fitzroy, the majority of the 10 species not documented in Stuart (1997) would be expected to occur at the Fitzroy Barrage at some stage, probably only being absent due to sampling timing. The recent occurrence of noxious species tilapia (*Oreochromis mossambicus*) in the lower Fitzroy River (DAF data) adds an additional species to the list and represents the Fitzroy River's first large bodied pest species.

2.3. Migratory Patterns

As the Fitzroy Basin straddles the Tropic of Capricorn, the fish species within the system undertake migrations associated with both temperate and tropical streams. In tropical systems, a wide diversity of species move upstream all year-round whenever flow is available. However, the largest movements are recorded associated with the elevated flows of the wet season. Temperate migrations are generally triggered by changes to water temperature, with some species moving as temperatures rise in spring, while others undertake movement downstream as temperatures cool during Autumn.

In the Fitzroy Basin, rainfall and the associated changes in river flow and height at the beginning of the wet season are thought to be a major movement cue for species such as golden perch, leathery grunter, blue catfish, Hyrtl's tandan, black catfish and Rendahl's catfish (Marsden and Power, 2007). Low and moderate flow periods also represent a significant period for fish movement in the area for some small species such as empire gudgeon and juveniles of larger species such as striped mullet.

In order to demonstrate the triggers for upstream migration the flow record for September 2010 to June 2011 at Riverslea gauge (DNRM data) has been overlaid with the occurrence of species recorded by Stuart (1997) and provided in Figure 2. The concept behind Figure 2 is to demonstrate the use of the flow hydrograph by migratory fish at the tidal interface. In many cases separate phases of the hydrograph are utilised by the same species but for different purposes. Adults and sub-adults of catadromous species may utilise high flows to move out of the floodplain or estuarine spawning or nursery areas and into the main river channel. Whereas low flows provide an important opportunity for juveniles to enter freshwater for feeding and growth. A vital function of a fishway on a tidal barrage is the ability to provide potamodromous species with the opportunity to return to freshwater habitats following a high flow as most species cannot survive saline waters for any extended period.

Falling water temperatures following the wet season correspond with downstream migrations for catadromous and amphidromous species including striped mullet, bullrout, oxeye herring and longfinned eel. It is thought that downstream migration beyond barrages and weirs occurs during high flows or when releases are being made. However downstream migration through tidal barrage fishways does occur (Stuart and Berghuis, 2002) and may not be problematic for most species.

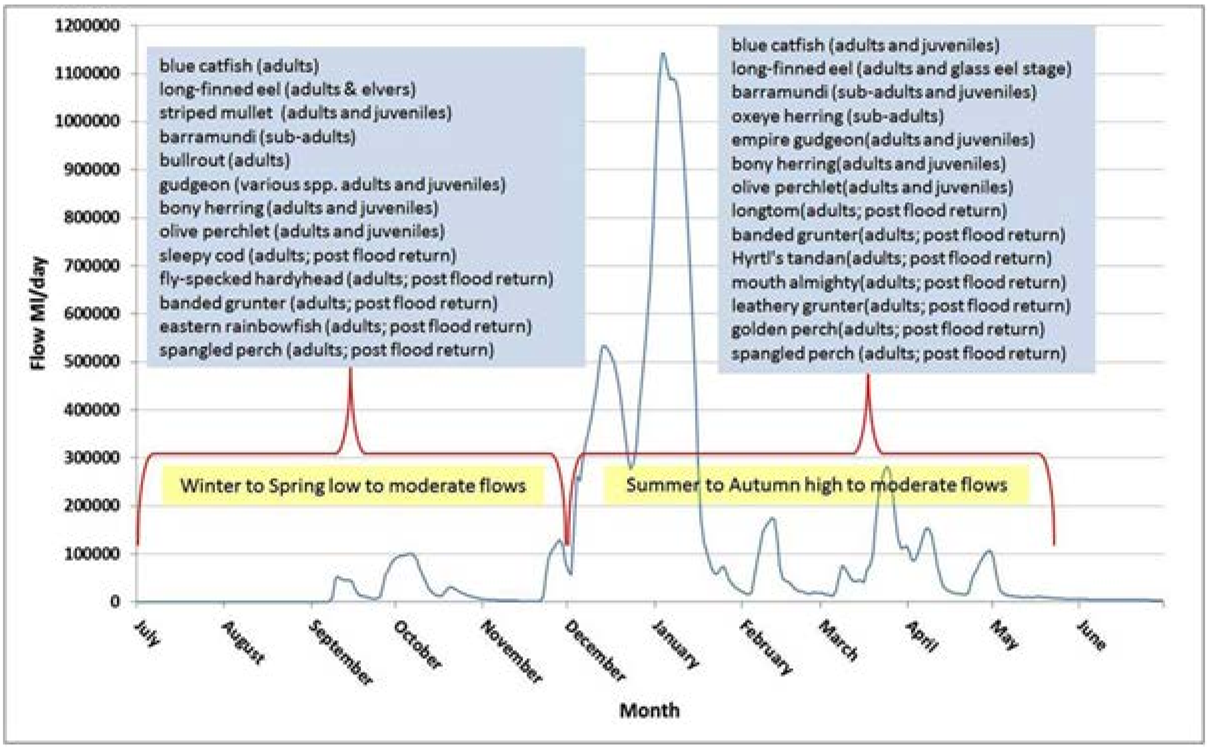

Figure 2. Upstream fish migration patterns at the Fitzroy Barrage relative to river flow. Fish data from Stuart (1997), flow data from DNRM.

2.4. The Requirement for Fish Passage

The construction of a barrier on a river can block or delay upstream fish migration and thus contribute to the decline and even the extinction of species that depend on longitudinal movements along the stream. Habitat loss or alteration, discharge modifications, changes in water quality and temperature, increased predation pressure as well as delays in migration caused by barriers are significant issues. Barriers to fish passage are identified as one of eight key threats to native fish populations (MDBC 2012). In regulated rivers throughout the world lack of fish passage is frequently identified as a major cause of the decline of freshwater fish (Barrett and Mallen-Cooper, 2006).

All fish utilise and depend on being provided with access to the aquatic habitat which supports all of their biological functions. Migratory movements of fish are described by two broad classifications; potamodromy and diadromy. Potamodromous species migrate solely within the freshwaters of a river system. Diadromous species migrate between fresh water and sea water and are further classified into catadromous, amphidromous and anadromous species. Catadromous species migrate to the sea for breeding and back to freshwater to feed and grow. Amphidromous fishes migrate between freshwater and the sea but not for the purpose of breeding. Anadromous species migrate into freshwater to spawn, with adults generally being resident in marine waters.

Regardless of migratory classification, all fish need to move along streams over scales of metres or hundreds of kilometres to:

- feed;
- spawn;
- seek shelter and refuge;
- enhance dispersal of young fish;
- counter downstream displacement following high flows;
- recolonise after droughts.

Movements can be regular seasonal migrations undertaken by much of the population or they can be less regular and less well defined. In sub-tropical and tropical environments fish movement and migration occurs throughout the year and during high and low flows. Fish often respond very quickly to subtle movement triggers such as localised rainfall events.

2.5. The Fitzroy Barrage

The Fitzroy River Barrage (Figure 3) was constructed in 1970 and is located 59.6km AMTD from the mouth of the Fitzroy River. The 3.6 m high, 340 m wide gated structure provides a 55 km long freshwater impoundment and enforces an artificial tidal limit some 46 km downstream of the historical limit (Rolfe et. al., 2004). The barrage structure contains 18 gates (12 m wide x 3.3 m high) which operate automatically to maintain the water at the full supply level of 3.78 m AHD, there are also 4 un-gated ogee crests on the right (southern) bank side.

The Fitzroy River Barrage meets the long-term water supply needs of Rockhampton (FRW 2017). The barrage separate the tidal reaches of the river from freshwater and holds back a storage of 80,300 ML when full. Water from the barrage supplies the Glenmore Water Treatment Plant which supplies up to 120 ML of drinking water each day (FRW 2017).

Figure 3. The Fitzroy Barrage, Rockhampton's main water supply.

2.6. Fitzroy Barrage Fishways

The Fitzroy Barrage has long been recognised as a barrier to fish movement and has had a number of different fishway configurations in operation since the barrage was first constructed in 1970 (Figure 4). The various fishways were constructed on the apron of the barrage, on the southern bank of the weir (Figure 5). A pool and weir fishway with downstream sloping baffles was the first fishway constructed with the weir in 1970 and this has formed the foundations for all subsequent fishways. An upgraded version of the pool and weir fishway was constructed in 1987, this replaced the baffles within the channel with an "L" shaped version and decreased the pool size within the fishway. In 1994, the pool and weir baffles were removed from the existing channel and replaced with vertical slot baffles with larger pools. This vertical slot baffles remains today, however, the baffles have been refurbished several times due to damage during flooding events.

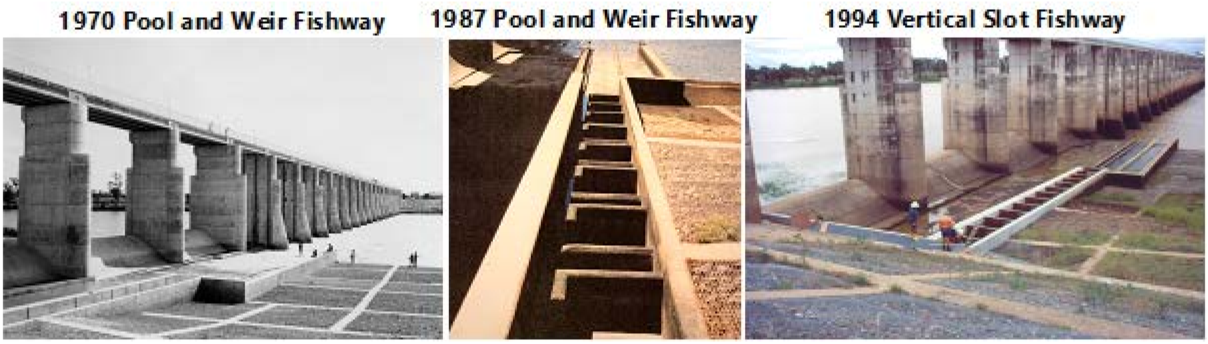

Figure 4. Three previous fishways have been installed within the original fishway channel on the Fitzroy Barrage. 1970 pool and weir fishway (left), 1987 modified pool and weir fishway (centre) and in 1997 vertical slot Fishway (right).

Figure 5. Left bank side of Fitzroy River Barrage showing the fishway, Gate 1 and ogee crest structures. Image from Google Earth.

The first two pool and weir fishway designs were largely ineffective (Kowarsky and Ross 1981, Byron and Toop 1993) and basically passed very few small to medium size fish species. It was not until the construction of the vertical-slot fishway in 1994, that passage for most species was provided. However, this fishway still could not provide passage for small fish (Stuart and Mallen-Cooper 1999, Marsden et. al. 2015) and further modifications to fish passage were recommended based on sampling in 2014-15 (Marsden et. al. 2015).

2.7. 2014-15 Fishway Monitoring

Through the period 2014 to 2015 monitoring was undertaken of the existing barrage fishway to determine the success of the existing fishway and investigate options for rehabilitation of the fishway to improve fish passage.

The experimental design for the previous FBA fishway monitoring is outlined in the project methods in the report "Fitzroy Barrage Fishway: Sampling and Recommended Upgrades". The basic experimental logic is to utilise both hydraulic and biological measurables to determine the optimal fishway design for the unique fish community and range of flows. The four specific monitoring objectives were:

i. Can the fishway be optimised to pass a greater fish species diversity, abundance and size class range by testing a range of hydraulic improvement devices (e.g. sills, keyhole slots)?

ii. What hydraulic parameters (e.g. water velocity [as indicated by headloss] and pool turbulence) influence fish passage success?

iii. Can the operational range of the fishway be extended to cover a greater range of the tailwater conditions?

iv. Can the barrage gates be integrated into the fishway function to optimize attraction of fish to the entrance?

Several configuration experiments were conducted to monitor these objectives (Figure 6). These included:

a) Unmodified slot configuration – which analysed catches from the unmodified vertical slot fishway.

b) Partial modified slot configuration – which changed configuration of the slots through the addition of a keyhole or middle sill to the slots.

c) Fully modified slot configuration – which changed the slot from a 150mm slot to a 75mm slot.

Results of these experiments demonstrated the ineffective passage of fish through the vertical slot fishway. Passage of fish within the existing barrage fishway was limited to fish >45 mm long, which in tropical biodiverse rivers can still exclude millions of individuals per year. Restricted passage of the smallest size classes confirms previous studies of vertical-slot fishways, in both tropical and temperate rivers, where small-bodied species remain as a significant design challenge (Stuart and Mallen-Cooper 1999; Stuart and Berghuis 2002; Barrett and Mallen-Cooper 2006; Stuart et al. 2008; Baumgartner et al. 2014).

Figure 6. Slot baffle configurations included slot narrowing (left) and middle sill block outs (right).

At the Fitzroy Barrage, the purpose of modifying the slots, with keyhole and mid-sill treatments, was to reduce discharge and thereby turbulence (energy dissipation) within the fishway pools. These modifications were based on recent research, on the Murray River, which showed that reduced pool turbulence enhanced passage of significantly more carp gudgeons, bony herring, unspecked hardyhead and Murray rainbowfish (Mallen-Cooper et al. 2008; Baumgartner et al. 2014). Despite the hydraulic changes at the existing Fitzroy barrage fishway the modified slots did not significantly increase small gudgeons ascending.

The hydraulic reasons which influenced the passage success of small-bodied fish were complex and related to the unique site-specific features of the Fitzroy Barrage. A major constraint was the broad tailwater tidal range which only enabled fish to enter during high tide, for a few hours per day (Figure 7), after which small-bodied fish were hydraulically ejected from the fishway (Figure 8). Hence, the improved pool hydraulics of the experimental mid-sills and keyhole slot modifications were negated by the receding high tide.

The field trials clearly demonstrated two major outcomes: (i) that a dedicated fishway specifically designed for small fish is required as the vertical slot fishway was unlikely to ever pass these fish, and (ii) slight slot modifications and continued operation of the existing fishway will continue to provide an effective passage solution for medium and large fish. The field trials provided a clear and logical path for modifications that were subsequently undertaken at the weir and have significantly increased barrage fishway operational time and improved passage conditions for small fish.

Figure 7. Large numbers of empire gudgeons below the Fitzroy Barrage fishway during sampling could only enter the fishway on high tide.

Figure 8. Fish ejected from the fishway were subject to heavy predation, with few surviving.

3. Fishway Upgrades

As the 2014-15 sampling identified several shortcomings for fish passage through the existing vertical slot fishway, a modification process was proposed in 2015 to enhance fishway operations. Six modifications were recommended for the barrage vertical slot fishway, these included:

1. Modifying the jet alignment of the existing vertical-slot baffles in the lower leg of the existing fishway to bring the design back to the original specification.
2. Installing three extra baffles in the vertical-slot fishway exit channel and sills to reduce the hydraulic gradient of the existing fishway.
3. Installing a tailwater control pool to stabilise the tailwater of the existing fishway and extend the operating time of the part-time (3 hours/tide) vertical-slot fishway to full time (24 hours/day).
4. Installing a sloping trash-rack at the exit of the vertical slot fishway.
5. Install a cone fishway adjacent to the existing vertical slot fishway which will extend fish passage to 80% of the biodiverse small bodied-fish and exponentially increase the number of fish passing per annum, potentially to millions of fish.
6. Install an additional section of lower leg cone fishway below the existing vertical-slot fishway to increase tidal operation range from 39% to 95% of high tides.

After discussions with structure owners and funding sources, it was decided that undertaking modifications 3, 5 and 6 would be feasible within the time and funding constraints of the project. Nevertheless, in future the initiatives outlined in 1, 2 and 4 still represent solid fish passage value for money.

3.1. Vertical Slot Fishway

The recommended option to install a stabilisation pool in the tailwater of the vertical slot fishway was undertaken at the same time as construction of the new cone fishway. The stabilisation of the tailwater pool could have been provided as a standalone modification through construction of a permanent sill at the fishway entrance (Figure 9) or as a resting pool at the top of the lower leg (Figure 9) of any cone fishway installed at the site. As the second fishway was constructed, modification to the tailwater of the vertical slot fishway was the completed as part of the construction of the new small fish cone fishway (Figure 10). This configuration provided a stable tailwater for the vertical slot and cone fishways, a large area for fish to rest in at the base both fishways and a good attraction flow into the fishways on all except high tides. A control level for the first cone fishway ridge downstream of this pool was set at AHD 2.05m, which ensured the vertical-slot fishway maintained a 100 mm headloss throughout all pools at all times.

This modification has ensured that the vertical slot fishway maintains functionality at all times, independent of the tide. By providing a fixed tailwater level, turbulence levels in the existing fishway do not increase beyond the design baseline as occurred previously with the falling tide. The tailwater stabilisation pool has increased the time fish have available to ascend the fishway from approximately 6hours per day to 24hours per day.

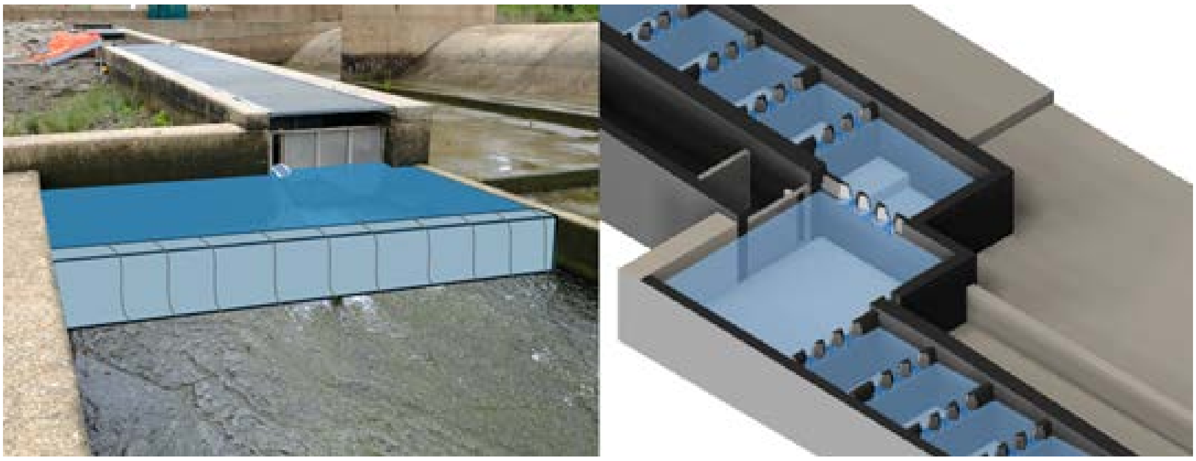

Figure 9. Proposed designs to stabilise tailwater levels, construction of a permanent sill (left) and as a resting pool in a new cone fishway (right).

The modification has been very successful, maintaining water levels at the base of the vertical slot fishway and preventing turbulence increasing within the fishway as tides recede. This has in effect created design conditions within the vertical slot fishway for 24hour fish passage as opposed to the 6 hours per day that previously occurred. A significant improvement in the fishway.

Figure 10. The priority modification to the vertical slot fishway tailwater pool that occurred as part of the cone fishway installation

3.2. New Cone Fishway

As highlighted by the previous monitoring there were significant issues with passing the abundant very small fish (i.e. <20mm long) upstream through the existing vertical slot fishway. Attempts to trial modifications that would assist these species highlighted that it was unlikely that the vertical slot fishway could ever be modified within its existing channel to provide passage for these fish. Therefore, to achieve successful passage, it was decided to use the newly emerging cone fishway design, which is designed specifically to pass these small-bodied tropical fish. The cone fishway design was chosen after consideration of a number of design options (Marsden et. al. 2015) as it had several attributes that could make it successful at this site, these included:

1. The cone fishway design had been demonstrated to be suitable for providing passage of small fish in other tropical locations.
2. The cone fishway design is still capable of passing large fish.
3. The cone fishway design could be implemented on the existing Fitzroy Barrage apron without modification.
4. The cone fishway design could fit within the footprint available and still maintain internal hydraulic conditions suitable for small fish.
5. The cone fishway design used prefabricated components that would assist in practical construction in a tidal environment.
6. The design would complement the existing vertical slot fishway as cone fishway resting pool could be used to stabilise the tailwater of the existing vertical slot fishway, improving that fishway too.
7. As much of the cone fishway design was prefabricated off-site (baffles) or already existing (outside walls) costs could be greatly reduced.

The new cone fishway was designed to have low turbulence and low head losses between pools, with micro-roughness elements and faceted cone faces that maximise optimal boundary layer conditions for the passage of small fish (Figure 11). The cone fishway channel is 2.4 m wide and contains 36 cone baffles with 1.5 m long pools between each baffle for a total length of 54 m. The headloss between each of the pools within the new fishway channel is 80 mm, which is the lowest height that could be achieved given the channel length available and the minimum pool size required.

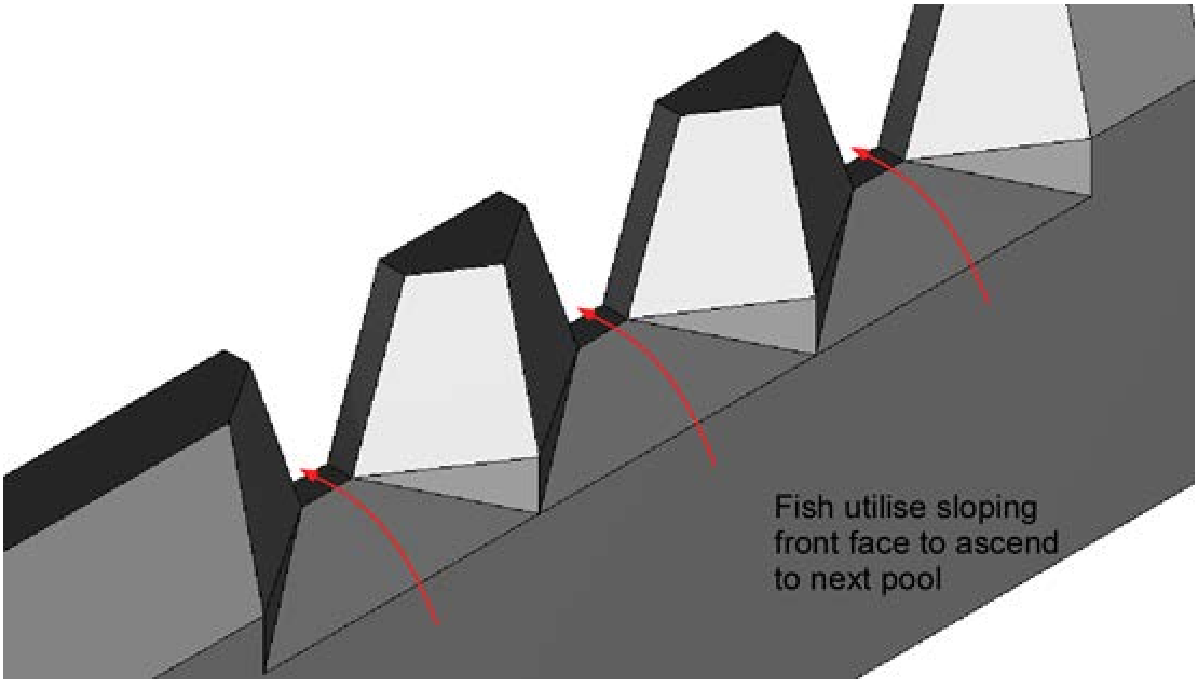

Figure 11. Cone fishway slot detail showing sloped slot faces that small fish utilise to ascend from pool to pool.

The upper leg of the cone fishway is constructed adjacent to the existing fishway on the weir apron (Figure 12), while the lower leg is constructed downstream of the existing fishway (Figure 13). The upper leg of the cone fishway has an entrance that is incorporated into the tailwater control pool that stabilises water levels at the base of the vertical-slot fishway (Figure 10). This ensures that fish which are unable to enter the vertical-slot fishway have an alternative route to the upstream weir pool. The upper leg of the cone fishway extends upstream along the inside wall of the existing fishway, exiting into the upper channel of the vertical-slot fishway via a slot cut into the side wall of the fishway (Figure 14). The cone slot is sized to ensure low velocities that do not inhibit fish leaving the fishway.

Figure 12. Walls of the upper leg of the new cone fishway are boxed up prior to pouring of concrete.

Figure 13. The lower channel and baffles of the cone fishway (below the resting pool) were mainly cast in-situ.

The cone fishway utilised prefabricated baffles that were commercially manufactured off-site. The baffles were transported to site (Figure 15) and installed into the pre-constructed fishway channel (Figure 16) with a crane. Once in place and adjusted precisely to their correct heights, the cone baffles were fixed in place with stainless steel brackets.

Figure 14. A slot to provide water for the cone fishway, was cut into the existing fishway channel wall (right), so as to not damage the main ogee crest of the barrage.

Figure 15. Baffles for the fishway were cast offsite and delivered for installation into the fishway.

Figure 16. A baffle being lowered into the fishway channel to be fixed in place on a concrete sill.

The completed cone fishway was commissioned once the upstream pool attained operational levels, with headlosses between pools checked to ensure that they were within specification limits. Hydraulically the fishway functioned well from the first flows with no adjustments required to the structure (Figure 17).

Figure 17. The completed cone fishway in operation.

3.3. Discussion

Constructability

The layout that was used for the cone fishway installation was highly efficient in terms of capital cost, footprint and functionality. The design utilised many of the features of the existing structure to provide foundations and walls for the new fishway which helped to greatly reduce the cost of the cone fishway compared to a greenfield site where no infrastructure exists. The constructability difficulties of the Fitzroy Barrage could have been considerable due to the large tidal fluctuation at the site, however, the utilisation of prefabricated baffles reduced the onsite time requirements for the construction crew. This negated the need to completely exclude water from the site and with teams working with the tides to achieve the required on-site concreting works, the construction progressed smoothly and was completed in a relatively short period of time.

Stabilisation of Existing Vertical Slot Fishway

The cone fishway construction had an added benefit of solving a major flaw in the existing vertical slot fishway design, with the installation of the tailwater stabilising pool preventing fish from being ejected from the vertical slot fishway when the tide fell below the entrance operational level. This significantly increased the time available for fish to ascend that vertical slot fishway from a few hours per high tide to 24 hours per day. It is likely that this will significantly improve the passage of fish through both the cone and vertical slot fishways. The installation of the cone fishway has also addressed a major area of weakness of the vertical slot fishway, the passage of very small fish (<50 mm long). Billions of juvenile fish attempt to pass the barrage every year with only a very small percentage having successfully ascended in the past. The new cone fishway should alleviate much of this problem, allowing many of these very small fish to successfully ascend into the weir pool upstream. A key to successful small fish passage was the cone fishway hydraulics which included significantly lower average turbulence (energy dissipation) than the vertical slot.

Cost

The cost of the construction of the new cone fishway was very competitive in comparison to the cost of fishway projects undertaken in other areas. With a total installed cost near $350,000 (around $120K per metre elevation) the fishway is at the lower end of the cost spectrum for a fishway of this size. In comparison, fishways within the Sea to Hume Project on the Murray River generally cost in the vicinity of $2M-$4M, averaging around $1M per metre of elevation (Baumgartner et al. 2014). The new cone fishway on the Fitzroy Barrage is therefore very cost effective for the potential outcomes delivered to the site.

Transferability

The successful construction of the cone fishway at the Fitzroy Barrage and the stabilisation of the tailwater of the vertical slot fishway have provided a viable demonstration of a combination of fishway types that ensures passage for small and large fish at tidal sites. The improvement of operation of the vertical slot fishway as a result of the construction of the cone fishway is directly transferable to a number of other tidal sites (e.g. Burnett and Mary river barrage fishways) where existing vertical slot fishways are affected by tidal operation ranges that increase turbulence levels on low tide.

The cone fishway design is also suitable for tidal sites where a minimum headwater level (i.e. Full Supply Level) is required that cannot be maintained by the vertical slot fishway. The prefabricated nature of the design allows the fishway to be constructed around the tidal cycle, reducing the construction de-watering costs of the project.

Approvals

Approval was sought under the State Development Assessment Provisions (SDAP) for the installation of the new fishway at the site. Approvals for the project were granted based on the application for an additional fishway to be built on the site, the fact that the construction did not damage fish habitats and that the fishway would have a positive impact on fish communities. The approvals were simplified somewhat by the already disturbed nature of the site which removed any requirements for marine vegetation/plant considerations (as there was only concrete).

The approval was successfully granted subject to a number of conditions, all of which were met during the construction process. These conditions included:

a) The development must be carried out generally in accordance with the plans provided

b) Up and downstream fish passage must be provided across the waterway barrier

c) The fish passage provided must cater for the whole fish community taking into account species, size classes, life stages and swimming abilities as well as the seasonal and flow related biomass of the fish community

d) The waterway barrier(s) and any associated infrastructure including, but not limited to intakes, walls, access structures, pipe works, spillways and dissipation devices are to be designed, constructed and maintained to avoid fish injury, mortality and/or entrapment.

e) The effective operation of the fish passage aspects of the structure must be maintained for the life of the barrier.

f) The fishway inlet must remain open when the upstream barrage water level is above EL3.2m AHD.

This report provides the final assessment of the construction works and will be submitted as the compliance document to complete the construction approvals process.

4. Fishway Monitoring

4.1. Introduction

The objective of this section of the report is to experimentally determine the success of the new cone fishway at passing small fish (i.e. < 150 mm) as compared to the existing vertical slot fishway. The main objectives of this sampling include:

- Determine if the new fishway has improved fish passage at the Fitzroy Barrage and how it compares to the vertical slot fishway.
- Determine if the modifications have improved fish passage through the existing vertical slot fishway.
- Establish the minimum size of fish that can successfully ascend each fishway
- Determine if the modifications have improved the passage of juvenile empire gudgeons, the most numerous small-bodied species.
- Determine if the modifications have improved the passage of juvenile striped mullet, one of the most commercially important species.
- Determine if other species have been assisted by the modification undertaken at the Fitzroy Barrage.

To this end, parallel sampling of the vertical slot and cone fishways was undertaken to determine the species, numbers and size ranges of all fish using the two fishways.

Sampling was undertaken over two distinct time periods, during the wet season on the recession of high flows (February to March 2016) and during low flows in spring (October 2016). Wet season sampling highlighted the passage of juveniles from species that spawn before or during the wet season, such as bony bream, empire gudgeon and eels. The dry season sampling in spring highlighted the passage of the juveniles of species that spawn during winter and early spring such as striped mullet, bullrout and empire gudgeons. The separation of sampling was required to capture migrations of the two main target species, small-bodied empire gudgeon and juvenile striped mullet and was the most efficient and cost-effective way of sampling within the time and budget constraints of the project. An important aspect to note was that medium and large fish (>100 mm long) were excluded from the traps in the present project.

4.2. Methods

The assessment at the Fitzroy Barrage vertical slot and cone fishways was based on evaluating the successful passage of small fish with a total length less than 100 mm. As these are the size classes of fish that are known to be inhibited by the hydraulics within the existing vertical slot fishway.

Two lightweight single cone traps were manufactured from steel rod and covered with standard 70% shade-cloth with an average mesh diameter of 1.5 mm. Fish greater than 100 mm in length were excluded by a mesh panel with 25 mm square openings located in the entry of the cone trap. In addition, a dip net with a 300mm opening and 1.5mm mesh was used to collect fish from the entrance of each fishway (i.e. the new stabilisation pool).

A sub-sample of fish species and sizes classes attempting to enter the fishways was collected by scooping the dip net several times through the new stabilisation pool at the entrance to the two fishways (Figure 18). This collected a representative sample of small fish attempting to move into the fishway.

Figure 18. Location of dip net samples from the stabilisation pool entrance of the two fishways.

A sample of fish that had successfully ascended and exited the fishways was obtained by placing the trap immediately upstream of the last fishway baffle as shown in Figure 19. Traps were installed to prevent fish escaping from the fishway, with a tight fit against the channel walls to prevent escape.

At the conclusion of each exit sample the trap was manually lifted out of the fishway and fish released into a 100-litre tank partly filled with aerated water. All fish captured during fishway sampling were identified to species level, counted and a sub-sample of 50 fish from each species were measured to the nearest millimetre (fork length for forked-tail species, total length for all other species). Fish were then released into the headwater pool, except for noxious species that were euthanised.

Sampling was conducted over three separate weeks, with two weeks in March 2016 and one week in October 2016, corresponding with periods of smaller high tides. These times were chosen to maximise the effort required by fish to ascend the fishway. In this way, we could establish effectiveness of passage under the worst migration conditions. If the fishway was successful under these conditions, then it could be expected that under smaller headwater/tailwater levels the fishway would pass even more fish than recorded during this sampling.

Sampling occurred over the period of high tide each day, with the trap set in the fishway prior to the bottom end of the fishway being inundated by the high tide and then checked at high tide and then again once the tide had receded below the apron of the weir.

Figure 19. Location of the exit traps for the vertical slot fishway (foreground) and cone fishway (background).

4.3. Results

Over the duration of the sampling, 19 species of small-bodied fish were captured either in the vertical slot fishway, the cone fishway or by dip netting downstream (Table 2). Empire gudgeon (*Hypseleotris compressa*) were the most abundant species overall, accounting for 83% of the catch in the wet season and 76% of the catch in the dry season (Figure 35) and were abundant during nearly every sample.

Juvenile blue catfish (*Arius graeffei*) were the second most abundant species (8.1% of catch) in the wet season, however none were captured during the dry season. Juvenile bony bream (*Nematalosa erebi*) were the third most abundant species in the wet season (3.8% of catch) and second most abundant in the dry season (15.7% of catch). They were sporadically present in large numbers and formed a greater percentage of the catch in dry season samples, as catfish were not present.

Juvenile striped mullet (*Mugil cephalus*) were mainly encountered in dry season sampling where they were the third most common species (6.9% of catch). Only very small numbers of striped mullet were encountered during wet season sampling (0.1% of catch).

Juvenile Long-finned (*Anguilla reinhardtii*) eels were observed in abundance throughout wet season sampling, however, as they could avoid or escape from the traps the number sampled was relatively low (1.2% of catch). Only adult long finned eels were detected during dry season sampling in very low numbers (0.15 of catch). All other species captured over the sampling period were present in low numbers.

a) New Cone Fishway Complements Vertical Slot Fishway

The cone fishway consistently outperformed the vertical slot fishway, with the vertical slot fishway (wet season - 1,540 fish, dry season – 777 fish) catching only a small percentage of the total small-bodied fish captured from both fishways (wet season – 14%, dry season – 7%) (Table 2). The cone fishways catch (wet season - 11,044 fish, dry season – 10,816 small-bodied fish) was much higher than the vertical slot fishway.

The catch rate at the exit of cone fishway (wet season - 147.9 fish/hr, dry season – 128.6 fish/hr) was also significantly higher than the exit of the vertical slot fishway (wet season – 22.4 fish/hr, dry season – 10.8 fish/hr). The vertical slot fishway (wet season - 14 species, dry season - 9 species) captured one less species in total than the cone fishway (wet season - 12 species, dry season - 12 species). Mouth almighty and tilapia only occurred in the vertical slot fishway, while barramundi, spangled perch, Rendhal's catfish and bullrout were only captured from the cone fishway. All of these species were captured in very low numbers (<7 individuals).

Some species showed distinct preferences for either the vertical slot or cone fishway, with generally more long-finned eel, empire gudgeon, fly specked hardyhead and bony herring captured in much larger numbers from the cone fishway than they were from the vertical slot fishway (Table 2). Conversely longtom were captured in larger numbers in the vertical slot fishway. In general, the smaller species appeared to prefer the cone fishway while larger species used the vertical slot fishway more. However small species also used the vertical slot fishway and larger species also used the cone fishway.

Table 2. Species and number of fish sampled from both the vertical slot and cone fishways.

Common Name	Species	Vertical Slot		Cone Fishway	
		Wet Season	Dry Season	Wet Season	Dry Season
Diadromous					
long-finned eel	*Anguilla reinhardtii*	30	2	121	2
blue catfish	*Arius graeffei*	470	0	550	0
empire gudgeon	*Hypseleotris compressa*	865	265	9592	8569
barramundi	*Lates calcarifer*	0	0	1	0
striped mullet	*Mugil cephalus*	7	391	0	411
longtom	*Strongylura krefftii*	27	0	5	0
bullrout	*Notestes robusta*	0	0	0	2
Potadromous					
Agassiz's glassfish	*Ambassis agassizii*	17	4	43	1
banded grunter	*Amniataba percoides*	2	2	2	0

Common Name	Species	Vertical Slot		Cone Fishway	
		Wet Season	Dry Season	Wet Season	Dry Season
fly-specked Hardyhead	*Craterocephalus stercusmuscarum*	4	2	324	12
mouth almighty	*Glossamia aprion*	1	0	0	0
Western carp gudgeon	*Hypseleotris klunzingeri*	0	1	1	1
spangled Perch	*Leipotherapon unicolor*	0	0	2	0
eastern rainbowfish	*Melanotaenia splendida*	18	19	14	83
bony bream	*Nematalosa erebi*	89	91	389	1732
Hyrtl's tandan	*Neosilurus hyrtlii*	5	0	0	1
Rendahl's catfish	*Porochilus rendahli*	0	0	0	1
sleepy cod	*Oxyeleotris lineolata*	2	0	0	1
tilapia*	*Oreochromis mossambicus*	3	0	0	0
	Total Number of Fish	1540	777	11044	10816
	Total Sampling Time (hrs)	67.75	71.66	74.66	84.08
	Catch Rate (Fish/Hour)	22.4	10.8	147.9	128.6
	Total Number of Species	14	9	12	12

* Introduced species

b) Length Frequency Comparisons

March

The data from the March 2016 sampling of the exit of the vertical slot and cone fishways were compared to determine differences in size classes for abundant species entering and exiting the two fishways (empire gudgeons and long-finned eels) and between the vertical slot and cone fishway exits (bony bream and Agassiz's glassfish).

Empire Gudgeon

Data from the length frequency graph for empire gudgeons indicates a distinct variation among the size classes at the entrance, the exit of the cone fishway and the exit of the vertical slot fishway (Figure 20). Smaller fish were found at the entrance of the two fishways, with fish between 10 and 14mm common. The cone fishway successfully passed fish as small as 12mm, but in low numbers, while by 16mm most fish successfully passed the cone fishway. The vertical slot fishway passed fish as small as 18mm in low numbers, but fish needed to be greater than 20mm before ascending in any great numbers. This indicates that the new cone fishway is passing smaller fish than the vertical slot fishway, however some very small fish (i.e. 10-12 mm long) still cannot ascend.

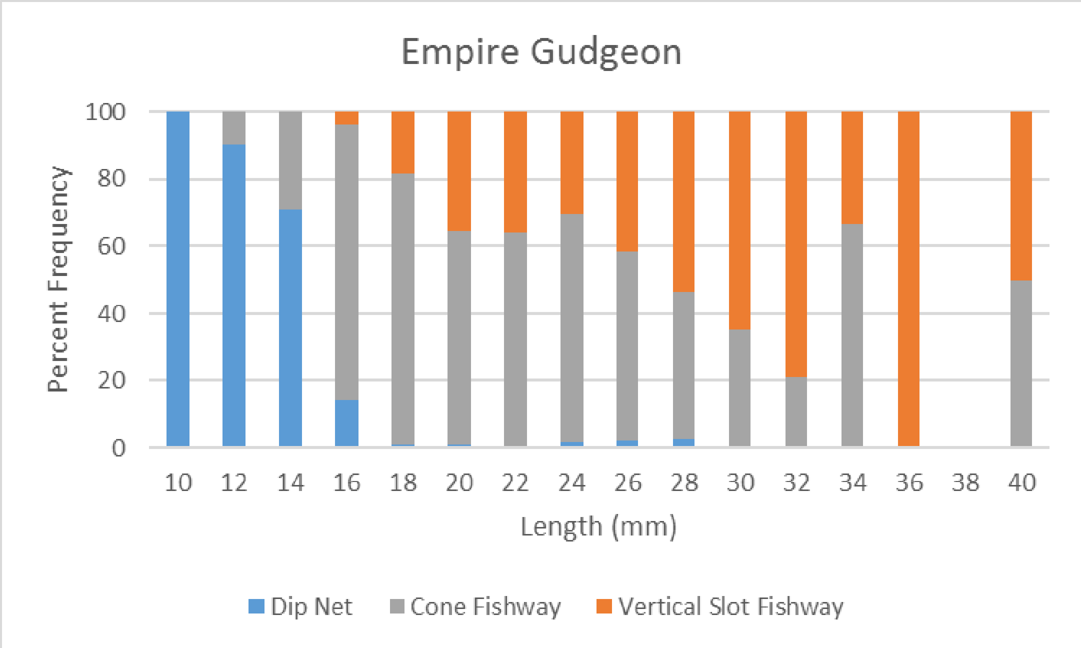

Figure 20. Length frequency of empire gudgeon captured in the March 2016 entrance and exit trap samples.

Long-finned Eels

Data from the length frequency graph for juvenile long-finned eels indicated that most fish were less than 70 mm in length and that fish were ascending both the cone fishway and the vertical slot fishway (Figure 21). There were generally more fish at the entrance to the fishways and in the cone fishway than there was in the vertical slot fishway. Data from these samples would have been be affected by the ability of long-finned eels to avoid or escape from the traps.

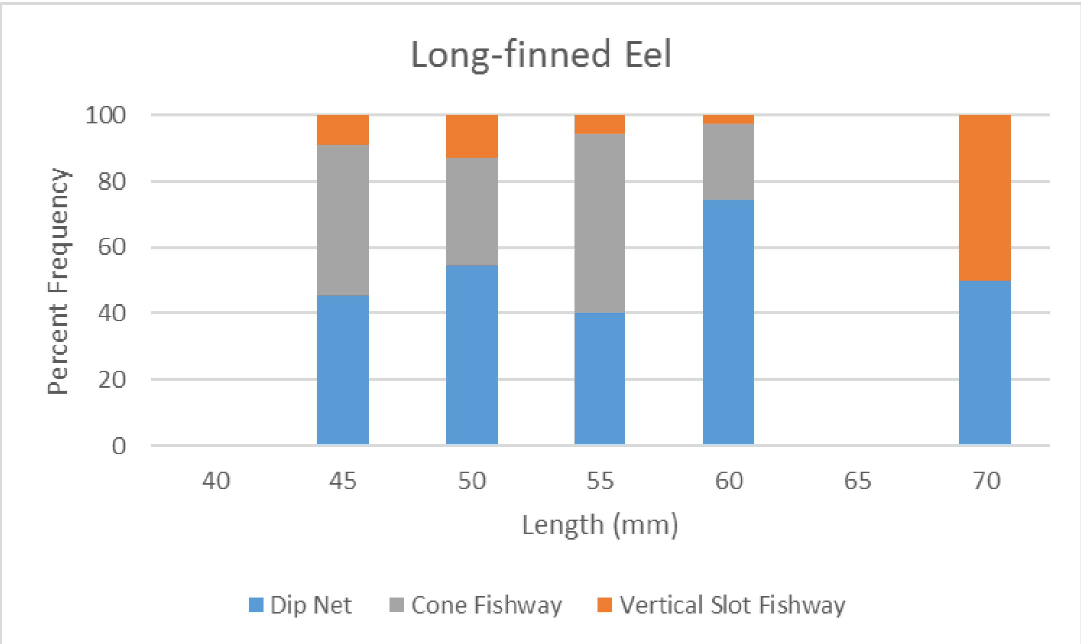

Figure 21. Length frequency of long-finned eels captured in the March 2016 entrance and exit trap samples.

Bony Bream

Data from the length frequency graph for juvenile bony bream indicated that most fish passed through the cone fishway and that the cone fishway passed much smaller fish than the vertical slot fishway. In the vertical slot fishway bony bream needed to be larger than 50mm to pass in any great numbers, while the cone fishway passed fish as small as 20mm (Figure 22). No bony bream were recorded from dip net samples.

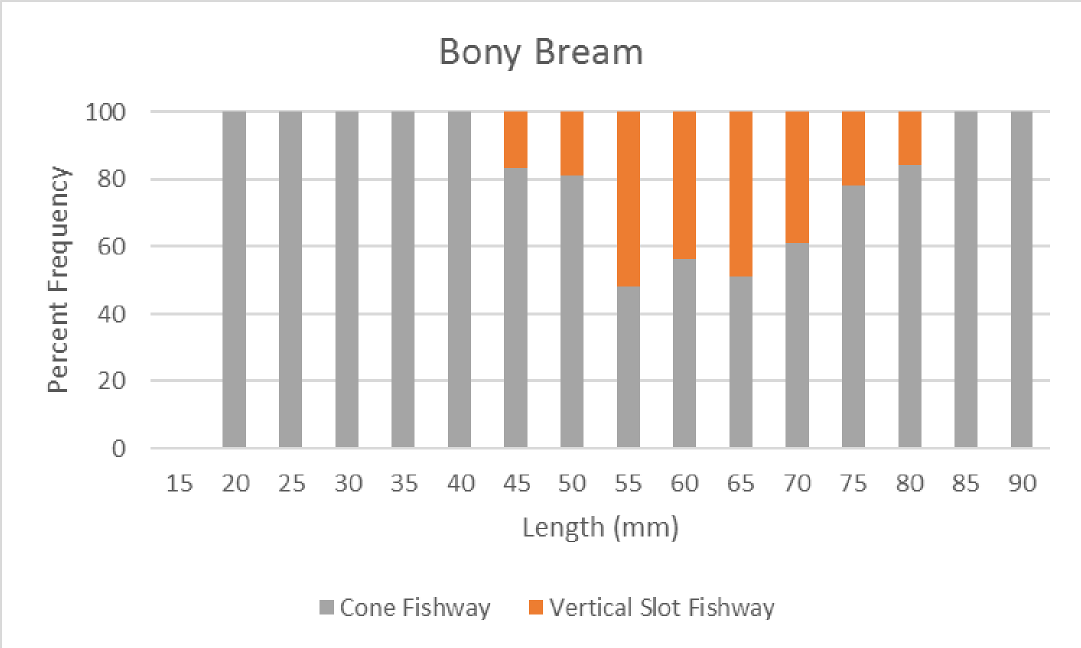

Figure 22. Length frequency of bony bream captured in the March 2016 exit trap samples.

Agassiz's Glassfish

Data from the length frequency graph for small-bodied Agassiz's glassfish indicated that most fish passed through the cone fishway and that the cone fishway passed much smaller fish than the vertical slot fishway. In the vertical slot fishway fish needed to be larger than 40mm to pass in any great numbers, while the cone fishway passed fish as small as 9mm (Figure 23). No fish were captured from the dip net samples and numbers for this species were generally low.

Figure 23. Length frequency of Agassiz's glassfish captured in the March 2016 exit trap samples.

October

The data from the October 2016 sampling of the vertical slot and cone fishways were compared to determine differences in size classes for abundant species entering and exiting the two fishways (empire gudgeon and bony bream) and between the vertical slot and cone fishway exits (mullet).

Empire Gudgeon

Data from the length frequency graph for small-bodied empire gudgeons indicates a distinct variation between the size classes at the entrance, the exit of the cone fishway and the exit of the vertical slot fishway (Figure 24). Smaller fish were found at the entrance of the two fishways, with fish between 10 and 14mm common. The cone fishway successfully passed fish as small as 16mm, but in low numbers, while by 18mm most fish successfully passed the cone fishway. The vertical slot fishway passed fish as small as 20mm in low numbers, but fish needed to be greater than 24mm before ascending in any great numbers. This indicates that the new cone fishway is passing smaller fish than the cone fishway, however some very small fish still cannot ascend.

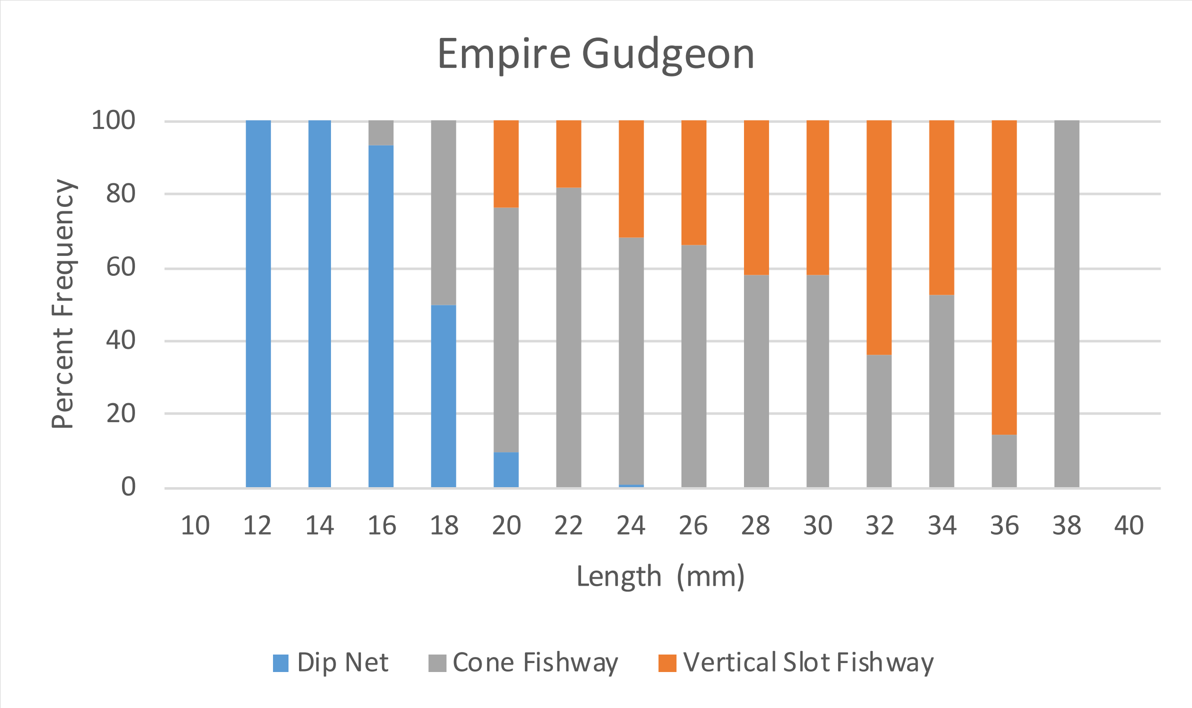

Figure 24. Length frequency of empire gudgeon captured in the March 2016 entrance and exit trap samples.

Striped Mullet

Data from the length frequency graph for juvenile striped mullet indicated that most fish passed through the cone fishway and that the cone fishway passed slightly smaller fish than the vertical slot fishway. In the vertical slot fishway mullet needed to be larger than 32mm to pass in any great numbers, while the cone fishway passed fish as small as 20mm (Figure 25). An absence of fish larger than 74mm from the vertical slot fishway is an indicative of the small numbers of fish of this size encountered during sampling.

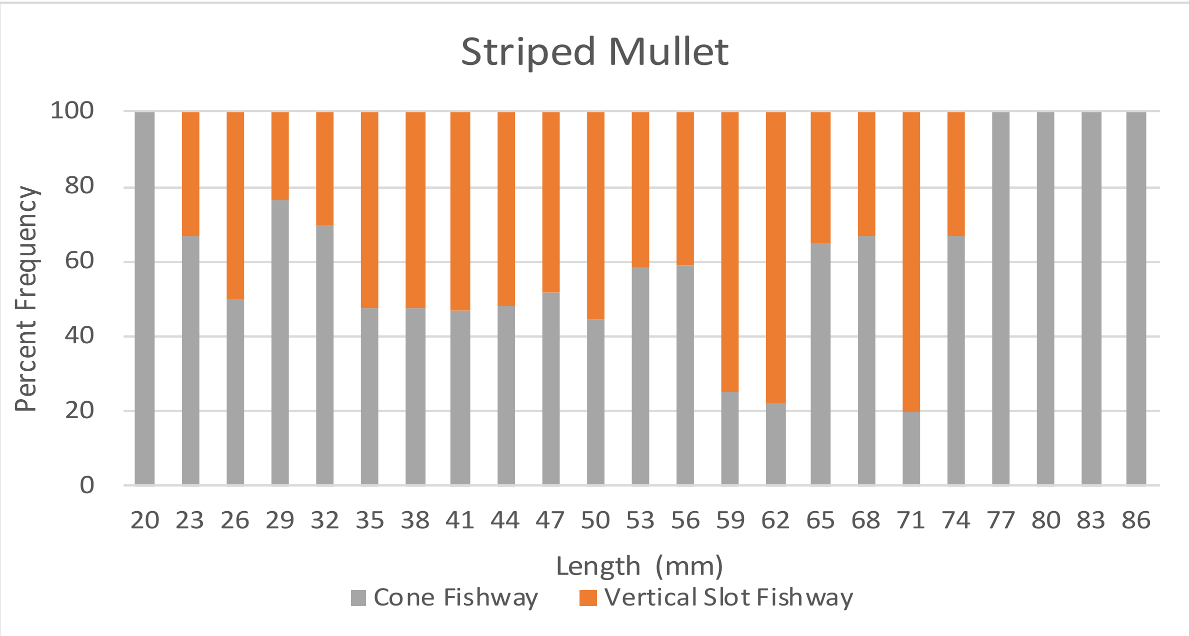

Figure 25. Length frequency of striped mullet captured in the March 2016 entrance and exit trap samples.

Bony Bream

Data from the length frequency graph for juvenile bony bream indicated that most fish passed through the cone fishway and that the cone fishway passed much smaller fish than the vertical slot fishway. In the vertical slot fishway bony bream needed to be larger than 50mm to pass in any great numbers, while the cone fishway passed fish as small as 22mm (Figure 26).

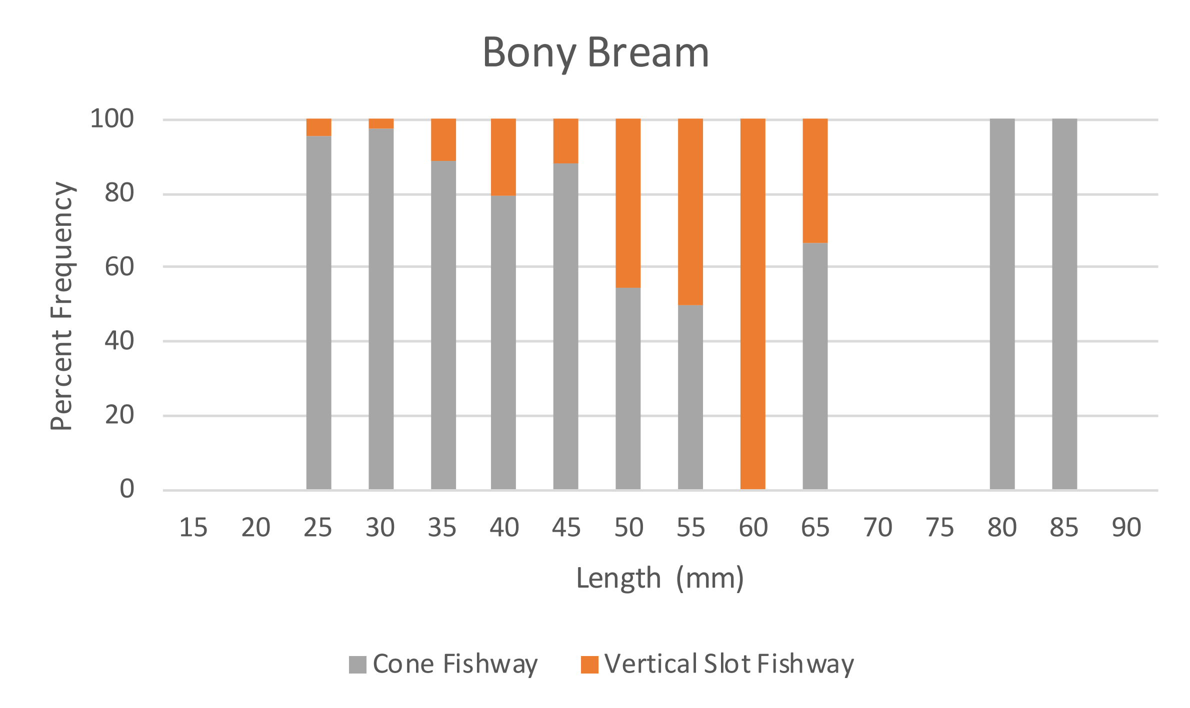

Figure 26. Length frequency of bony bream captured in the March 2016 exit trap samples.

4.4. Discussion

Success of the cone fishway

At the Fitzroy Barrage, a new cone fishway was constructed to assist the passage of small-bodied fish (<100 mm long) past the barrage. The new cone fishway successfully met its original design objectives, with large numbers of small fish ascending. In general, the cone fishway passed seven time more fish than the vertical slot fishway, with many of these fish being of a small size class that could not successfully pass the barrage previously.

In terms of the vertical slot fishway, restricted passage of the smallest size classes of fish is a well-known phenomenon at the Fitzroy Barrage (Marsden et. al. 2015) and at other vertical slot fishway sites in both tropical and temperate rivers (Stuart and Mallen-Cooper 1999; Stuart and Berghuis 2002; Barrett and Mallen-Cooper 2006; Stuart et al. 2007; Baumgartner et al. 2014). Passage of fish within the previous incarnation of the vertical slot fishway was limited to fish >45 mm long, which in a tropical biodiverse river can exclude millions of individuals per year.

Moving forward for the vertical-slot

The mechanism of the failure of small fish to ascend fishways has been experimentally shown as turbulence levels that exceed 35 W/m^3, a hydraulic criterion which expresses energy dissipation within a pool, which is a function of headloss, slot area and pool volume (Mallen-

Cooper et al. 2008). The Fitzroy Barrage vertical-slot has a minimum turbulence level of 42 W/m^3. Conversely, where vertical-slot or cone fishways integrate hydraulic criteria with turbulence of <35 W/m^3 then passage of small fish is maximised, such as the Fitzroy Barrage cone fishway (17 W/m^3), the Barwon breakwater vertical-slot fishway (Vic), and Dight's Falls vertical-slot (Vic). The Fitzroy Barrage cone fishway hydraulics signal a new role for the vertical-slot whereby turbulence could be decreased (e.g. to 31 W/m^3), with baffle inserts, and functionality maximised for small-bodied fish. A major recommendation from the present report is to progress this minor-capital upgrade to the Fitzroy Barrage vertical-slot baffles.

Tailwater stabilisation pool: a new direction for tidal fishways

The new design also incorporated an innovative tailwater stabilisation pool (Figure 27), which allowed the vertical slot fishway to maintain design hydraulics for a much longer period, increasing from approximately 3 hrs per tide to 24 hrs per day. The sampling conducted in this study did not specifically attempt to disentangle the hydraulic mechanism that enabled more fish to successfully migrate however, compared to 1997 data striped mullet, appeared to be ascending the vertical slot fishway at a much smaller size than when the fishway was unmodified. In 1997 the smallest size successfully ascending the fishway was 40 mm whereas in the latest sampling after the stabilisation of the tailwater fish as small as 23 mm successfully ascended. It is anticipated for other species that the modifications may have had a positive effect, as fish were observed in the fishway long after they would have been ejected from the fishway under the previous conditions.

Figure 27. Newly constructed tailwater pool for the two fishways has stabilised tailwater for the vertical slot and cone fishways and prevents fish being ejected.

A number of species appeared to preferentially use the cone fishway instead of the vertical slot fishway, with significantly larger numbers of bony bream, empire gudgeon, fly-specked hardyhead and Agassiz's glassfish ascending the cone fishway, though this may be a result of the gentler hydraulics of the cone fishway. Generally, fish that used the cone fishway were smaller than those that used the vertical slot fishway, highlighting the limitations that an older vertical slot fishway with high turbulence has at passing small fish.

Only one species, longtom, were recorded from the vertical slot fishway in greater numbers than the cone fishway. However, it was noted that a number of longtom occurred in the cone fishway, but could not enter the trap due to the smaller mesh on the trap entrance. A number of species were captured in very low numbers from only one of the fishways. Barramundi, bullrout, mouth almighty, western carp gudgeon, spangled perch, Hyrtl's tandan, sleepy cod and tilapia numbers were too low to establish if they had a preference for either of the fishways. With adequate design attention, we note that either cone or vertical slot fishways can pass these species.

A number of fish were captured in large enough numbers to enable comparison of their length frequencies between the two fishways. The analysis of length frequency data established the minimum size of each species that can successfully pass each fishway and is a useful comparison for likely success. The cone fishway was able to successfully pass smaller fish than the vertical slot fishway with bony bream (Figure 28) as small as 20mm, less than half the size required to be successful in the vertical slot fishway. Agassiz's glassfish, striped mullet (Figure 28), empire gudgeon (Figure 28) and bullrout (Figure 29) also had similar results, with fish as small as 9mm, 20mm, 12mm and 23mm respectively ascending the cone fishway. The minimum size successful through the vertical slot fishway for Agassiz's glassfish was 25mm, striped mullet, 23mm, empire gudgeon, 16mm and bullrout, 170mm.

Figure 28. Juvenile empire gudgeon (top), Mullet (2nd top), Bony Bream (3rd top) and adult rainbowfish (bottom) that ascend the cone fishway in Oct 2016.

Figure 29. Juvenile Bullrout that ascended the fishway in Oct 2016

Increasing passage of these smaller fish is critical to the long-term population health in the lower Fitzroy system. The lack of passage for these small fish was identified as early as 1997 (Figure 30) during sampling of the vertical slot fishway (Stuart 1999). Delaying their successful passage and forcing these fish to congregate below the barrage is likely to have disastrous consequences on their survival. The area below the barrage is intensively fished by predators such as birds (Figure 31), barramundi and bull sharks. These predators can quickly deplete the stocks of juvenile fish trying to pass the barrage, negatively affecting the production of the whole river system. Successfully passing these fish through the cone fishway, day and weeks earlier than when they could pass through the present vertical slot fishway will increase survival rates and increase the productivity of fisheries above the barrage. Upgrading the hydraulics of the vertical slot to current best-practice would complement the functionality of the cone fishway.

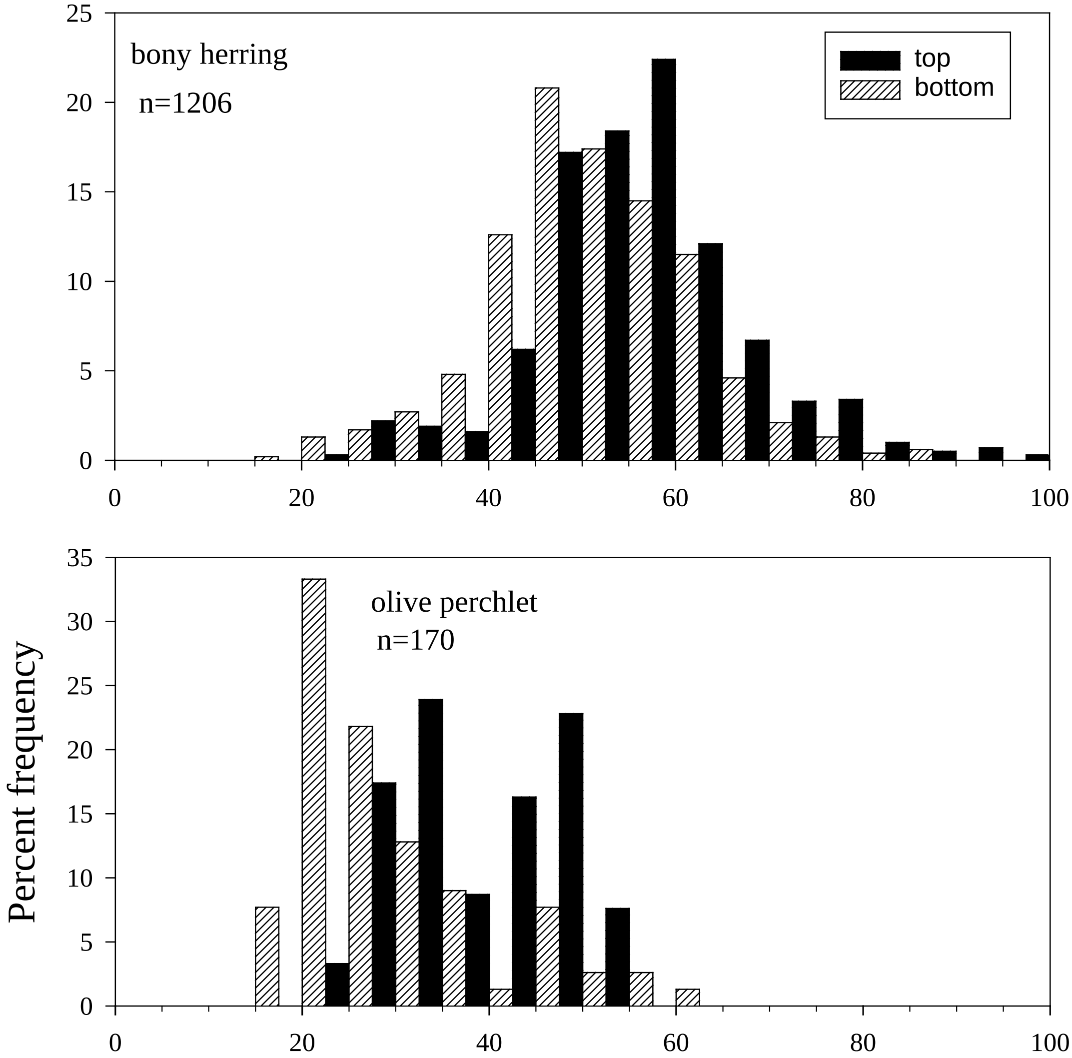

Figure 30. Length frequency of bony herring and Agassiz's glassfish (olive perchlet) at the top and bottom of the barrage fishway in 1995-97 (Stuart 1999)

Figure 31. Birds feeding on fish ejected from the vertical slot fishway prior to modification.

The passage of large fish through either of the fishways was not specifically studied during this sampling as our objective was to determine the success of the new cone fishway for small fish. The methods used excluded large fish from the traps through the use of screens, hence the low numbers recorded by the sampling. Barramundi, longtom, catfish and large bony bream were observed in the exit of the cone fishway against the exclusion screen on several occasions during the sampling, so it is anticipated that they can successfully ascend this fishway type. Previous sampling has established that larger fish were successfully using the vertical slot fishway. Further sampling of large fish in both fishways would be useful in the future to determine if the new cone design provides adequate passage conditions for these larger fish.

Two issues occurred during sampling that may have affected the results. The escape of small fish from the traps and the variability of catches over the sampling period. The main issue was the escape of juvenile eels from the traps. Despite being observed exiting the cone fishway and entering the cone fishway trap in high numbers, by the time traps were raised very few eels remained in the traps. Eels are a very thin species and when around 50-70mm long they are only a few millimetres round and have a fantastic ability to escape through the mesh of the trap despite the small size of the mesh. While no comparison data could be obtained, it was obvious through observation that juvenile eels were successfully ascending the cone fishway in large numbers as they were often seen on the wet margins of the cone fishway (Figure 32) all the way to the top of the fishway.

Figure 32. Juvenile long-finned eels ascending the cone fishway.

Another species that may have escaped from traps were juvenile empire gudgeons, which were found at the base of the fishway as small as 10mm long, however, only low numbers of fish as small as 12mm were found at the top of the cone fishway and 16mm at the top of the vertical slot fishway. As the traps must pass sufficient water to run each of the fishways the minimum size of the mesh cannot be smaller than that used for the experiments (1.5mm). However, at 10-14mm long juvenile empire gudgeons are very thin and there may have been some escapement of these smaller size ranges through the mesh of the fishway traps. The two fishway may therefore have performed better than is recorded through trapping for these very small fish. Observation of millions of these very small fish (Figure 33) was made throughout the cone fishway, however in the vertical slot fishway very few smaller fish could be detected past the sixth cell from the bottom of the fishway. It is therefore likely that the cone fishway is the more successful fishway for these very small fish.

Figure 33. Very small empire gudgeons accumulating in the calm area of the cone fishway. Observing the smaller fish was difficult.

5. Synthesis and Conclusions

5.1. Improvements to the Fitzroy Barrage Fishways

The improvements that have been made to the Fitzroy barrage fishways over the last 47 years have reflected the development of knowledge in fish passage throughout Australia, particularly suitable fishway design and the relationship between pool turbulence levels and passage success of small-bodied fish (Table 3).

Table 3. The configuration of fishways constructed on the Fitzroy Barrage over the last 45 years

Fishway Type	Build Date	Head Loss (mm)	Max velocity ($m.s^{-1}$)	Turbu-lence (W/m^3)	Water use (Ml/day)	Fish/ Day
Pool and weir	1970	150	0.87	215	52	-
Hybrid pool and weir fishway	1987	150	2.50	250	52	45
Vertical-slot	1994	97	1.40	42	18	302
Cone Fishway	2015	80	1.20	<17	8	3182

The earliest versions of the fishway at the Fitzroy barrage were based on northern hemisphere salmonid designs and were determined many years later to be ineffective for native fish (Stuart 1999). Modification to the configuration of the baffles was made in 1987, however these failed to improve passage (Stuart 1999). The 1994 modifications were based on fish passage research undertaken for Australian tropical and temperate fish species (Mallen-Cooper 1992). It changed the fishway to a vertical slot design and was much more successful than the previous designs. Stuart (1999) estimated that this version of the fishway passed at least 110,000 fish per year.

In the ensuing 20 years, there have been many fish passage learnings and the latest modifications to the Fitzroy Barrage fishway have included prioritising hydraulics that pass the super abundant small juvenile fish (<100 mm long) that enter freshwater from the estuary. Providing improved passage for these small size-classes is critically important and has required a reduction in water velocity (head loss per pool) and most of all a reduction in turbulence within the fishway.

This study has demonstrated that the hydraulic changes have been very successful, with passage rates through the combined cone and vertical slot fishway in the order 1,160,000 fish per year, a tenfold increase in fish numbers from the previous design. Considering the current sampling excluded all large fish and especially blue catfish that made up the bulk of these samples our estimate of annual fish passage rates is likely to be conservative. We also note that upgrading the hydraulics of the vertical slot would also further improve annual passage rates.

5.2. Success of Passage of Small Fish

Ensuring the passage of juvenile fish is essential to maintaining fish populations in hydraulically diverse tropical rivers. These juvenile fish need free access along the river as well as access to floodplain wetlands. This provides access to nursery and refuge habitats to ensure they can live and grow and survive through subsequent dry seasons. When these juvenile fish are prevented from passing barriers they are subject to elevated levels of predation, such as that witnessed at the Fitzroy Barrage, when large numbers of juvenile fish in and below the old fishway were consumed by catfish and barramundi (Figure 34).

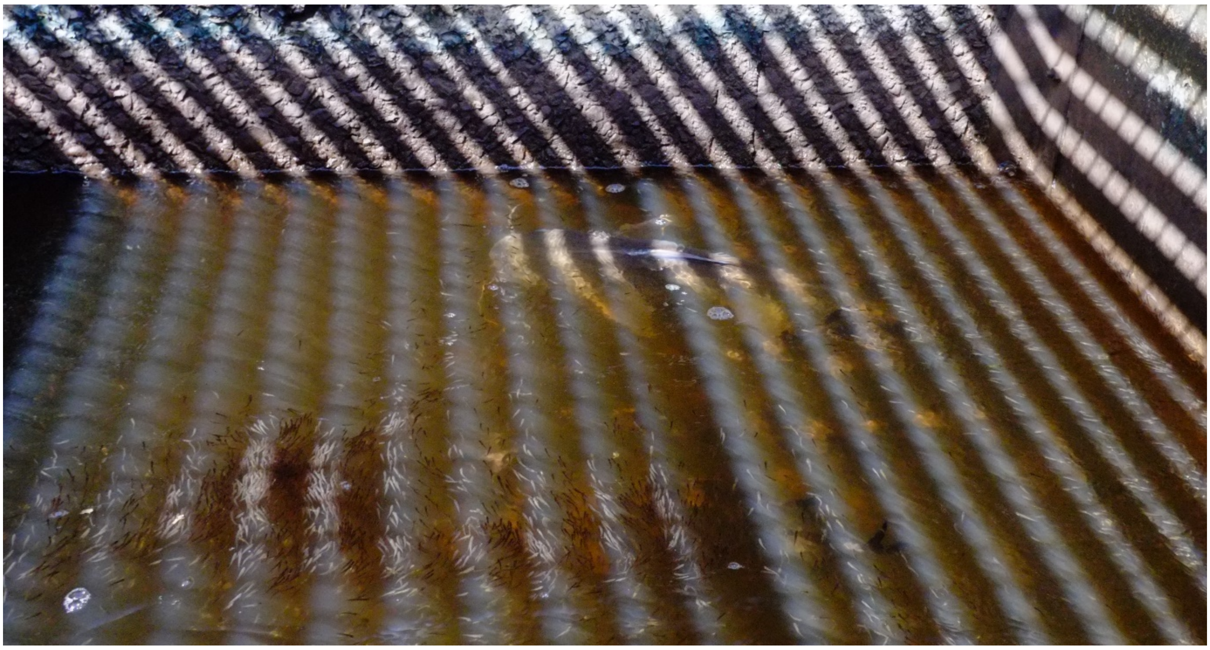

Figure 34. Large and small predators consume large quantities of juvenile fish that are unable to pass migration barriers.

The addition of the cone fishway, which complements the vertical slot fishway, has greatly increased the capacity of the Fitzroy Barrage fishways to pass small fish. Large numbers of juvenile empire gudgeons and striped mullet (Figure 35) successfully ascended the new fishways, demonstrating remarkable success. Fish numbers through each of the fishways was affected by the tidal height and flows in the river, with the maximum number of fish recorded in the previous vertical slot fishway (2000fish/hour) occurring on spring tides on the recession of flows in the wet season. This rate was 100 times greater than the average catch for this fishway.

Even though the cone fishway was sampled on neap tides to ensure maximum ascent distances, it still recorded fish passage rates seven times greater than the old vertical slot fishway. The maximum passage rate of 147 fish/hour is therefore likely to be only a fraction of the highest likely rate of passage. Extrapolating from this sampling data it is therefore likely that the barrage fishways will pass 3.8M juvenile fish annually, contributing to significant restoration of the lower Fitzroy Basin. This increase in juvenile fish numbers is likely to significantly enhance fish communities upstream of the barrage over the coming years and validates installing the new fishway.

Figure 35. A large sample of empire gudgeons and striped mullet from October 2016.

Despite the overwhelming success of the passage of small fish, the sampling highlighted the need for further research into the energetics of small fish as they pass through fishways. While significant numbers of small fish were successful at passing the new fishway, there were still fish at the lowest end of the size scale (e.g. 10-12 mm long) that did not ascend far up the cone fishway. Trapping the smallest fish was difficult, but observation suggested that only a small proportion of these fish could pass all the way through either of the fishways.

Fish were observed on underwater video transitioning across a single slot and it appeared to required a strenuous effort for them to move through the slot. What was observed was that fish could pass through the velocity of a single slot, but having to repeat this process multiple times was energetically beyond most of the cohort. While the fish could undertake one, six or even ten of the short sprints required to move through the slots, undertaking the whole fishway length appeared to be beyond the energy reserves stored in the muscles of these tiny post larval fish. In fact, each fishway pool contained fewer and fewer very small fish (Figure 36), as the fish held station recovering from their last slot ascent and eventually could not progress further having probably depleted their limited energy reserves.

Figure 36. Small fish accumulate in the corner of pools as they ascend, numbers drop off in subsequent pools as these smallest fish apparently run out of energy stores.

Consideration to how the smallest fish (<12 mm long) could be assisted to replenish energy reserves within the fishway would be a useful avenue of research as the fishway hydraulics have already been taken to the lowest level practical level for the current technology.

5.3. Increased Fishway Operating Time

The inclusion of a stabilised tailwater pool for the vertical slot fishway in the design of the new cone fishway (Figure 37) addressed one of the major concerns with the old fishway, the ejection of fish from the fishway as tides recede. The flushing of fish out of the fishway was a recognised event that attracted numerous predators to the fishway each day. As the tide began to recede many birds would congregate at the foot of the fishway in anticipation of a daily feed. Once tide levels fell below the ideal operation level, fish began to be ejected from the fishway where they were predated on by birds (Figure 31) and other fish.

Figure 37. Stabilised tailwater pool for the vertical slot fishway.

The construction of the new cone fishway rectified the fish ejection issue, with the tailwater for the vertical slot fishway being stabilised to maintain design hydraulics through the fishway at all times. This has had a number of impacts on the vertical slot fishway, including

a) Lengthening the time fish have suitable hydraulic conditions in which to ascend the vertical slot fishway from around 6hrs per day to 24hrs per day.

b) Increased depth of water at the entrance to the fishway to reduce access for birds to the ascending fish.

c) stabilising hydraulic conditions for moderate size fish within the fishway so that there is a likely increase in the number of fish ascending the fishway

d) increased the number of juvenile mullet that can ascend the fishway.

This reduction of predation and increase in available passage time will have a positive impact on the number of fish that can successfully ascend the vertical slot fishway, as well as through the cone fishway.

Another aspect that has increased the operating range of the fishway was the inclusion of a cone fishway leg that operates to a lower tidal level than the vertical slot fishway and the upper leg of the cone fishway (Figure 38). This lower leg extends from the stabilising pool at the base of the vertical slot fishway to the edge of the apron closest to gate 1 and provides 1.2m of additional height range to the fishway. The result of this is additional access time for fish to enter the fishway system. Previously fish had access to the fishway for approximately 8% of time per day and on 39% of high tides (i.e. 61% of high tides did not reach the fishway and there was no access). The new configuration has increased the operating range of the fishway system so that fish can now access the fishways for approximately 33% of the time per day and on 95% of high tides throughout the year. This has significantly increased the potential access to the fishways for fish.

Figure 38. The lower leg of the cone fishway (top right) provides access into the fishway on lower tide levels.

5.4. Ecological Value of Fishway Investment

The Fitzroy Barrage has long been recognised as a barrier to fish movement on the Fitzroy River, with a number studies identifying that fish communities upstream have been affected by the change in habitat and inhibition of movement to the estuary (Kowarsky and Ross 1981; Stuart and Mallen-Cooper 1999). The first barrage fishways proved ineffective as they only ever passed a very small proportion of the fish community attempting to migrate past the barrage and as for many other early Australian fishways, they largely failed to mitigate the impact of barriers on fish passage (Harris 1984). The latest iteration of fishway on the barrage, the combined vertical slot and cone fishway, enables a vast increase in the number of fish moving past the barrage. The ecological benefits that these extra fish will provide the river system upstream will be significant.

There is no data nor ecological modelling to inform managers timeframes regarding long-term recovery of fish communities upstream of the barrage. A key question is whether the current improved level of fish passage is sufficient to lead to the recovery of populations upstream. Certainly, improved access for an estimated 3.8 M/fish per year would appear to be ecologically significant. However, to support long-term fish population processes in a large tropical river with high biomass there is likely to be a very high requirement for fish passage transparency among habitats. Hence, we suggest monitoring fish communities upstream to inform for the future need of a fishway on the northern bank of the barrage. This would provide a potential doubling of the capacity of fish passage at the site and would reduce large accumulations of fish that still occur on the north bank.

The ecological value of any fishway investment made to date is difficult to quantitatively measure, however we provide a preliminary analysis below. Firstly, the improvement in fish passage at the barrage has greatly increased the number of fish passing and this seemingly provides great ecological value for the investment. This investment success can be clarified by a brief comparison to fish stocking investment; the only other viable way of providing fish to the river upstream.

Commercial fish production provides three species for stocking at the following costs (GAWB 2014):

- barramundi - 50mm fish @$1.20 each
- striped mullet - 50mm fish @$0.65 each
- mangrove jack - 50mm fish @$10 each

By comparison, the new cone fishway cost in the order of $350,000 to construct and has a design life of 25 years. At a passage rate through the cone fishway of approximately 3.8M fish per year as determined by the recent sampling, the cost of providing passage for each fish over the life of the structure would be in the order of $0.004 per fish (i.e. for every dollar of investment 40 fish successfully migrate past the barrage), around 200 times cheaper than the cost for stocking a similar number of fish. In addition, the barrage fishways are passing a much greater diversity of species, not just recreationally important fish species, clearly demonstrating the value of including fish passage on the barrage for whole fish community recovery.

5.5. Economic Benefits of Fishway Investment

The economic benefit to the Fitzroy River and the Rockhampton Region of the new fishway will be difficult to measure without extensive before and after studies of the fisheries. However, the addition of 3.8M fish annually to the river upstream will likely have a positive impact on fisheries in the region. In November 2015, a commercial net free zone was created in the lower Fitzroy River below the Fitzroy Barrage, with many of the previous commercial target species using the barrage fishway as juveniles to access freshwater nursery habitats upstream (e.g. striped mullet). Hence, providing improved access for these species through the barrage fishways will help to boost populations and in the long-term provide major benefits to the lower Fitzroy recreational fishery.

5.6. Benefits to other Fishway Sites

The 45-year fishway history at the Fitzroy Barrage has truly revolutionised fish passage in Australia; this includes a research history with significant numbers, a wide variety of species and structure owners focussed on delivering excellent outcomes for fisheries. Hence the site has provided a great deal of learning in the fish passage field. The most recent iteration, with the cone fishway, has built on past learning and is providing guidance to a broad range of projects throughout Australia and overseas. Since the cone fishway was developed in

Queensland and refined at the Fitzroy Barrage, cone fishways have been constructed using the same design principles in:

- far north Queensland,
- Victoria, and
- Laos (S-E Asia).

5.7. Barramundi Passage

In the lower Fitzroy River, there has always been a strong community focus of barramundi ecology and fishing opportunities.

The conceptual understanding of the life cycle of barramundi in the Fitzroy River can be generally described as:

- The strongest year-classes of barramundi are associated with high discharge of freshwater to the Fitzroy River estuary.
- Adults spawn at the mouth of the river in high salinity environments.
- Larvae stay in the lower river until they are around 20mm long.
- Very small fish (25 – 100mm) enter supra-tidal wetlands, freshwater wetlands (e.g. Yeppen and Woolwash lagoons) and small creek systems (e.g. Nankin, Raglan, 12 Mile, Moore’s creeks) and remain there for 1-2 wet seasons (depending on access conditions). Very small fish are not known to migrate upstream within the main river channel to the Fitzroy barrage.
- Where connection flows allow, sub-Adult fish 200mm-600mm long leave their juvenile habitat and migrate up the main channel of the Fitzroy River and into large freshwater habitats as far upstream as Baralaba, some sub-adult fish also remain in the estuary.
- Sub-Adult fish usually stay in upstream freshwater reaches for 2-5 years but some fish stay for up to 8 years.
- Adult fish leave large freshwater habitats and return downstream at a large size (>600 mm) to the estuary to spawn as males and then remain in the estuary or coastal water, undergoing sex inversion to females and growing to a usual maximum size of 1400 mm (35 kg), They remain in tidal waters for the remainder of their lives (i.e. 20+ years).

Research into the life cycle of barramundi has identified that juvenile barramundi (<100mm) undertake movements into floodplain nursery habitats outside of the main river channel (Hyland 1997, Stuart 1999, Sawynok and Platten 2005). Streams and floodplain lagoons such as 12 Mile Creek, Raglan Creek and Nankin Creek are prime locations for these very small barramundi as they contain the food rich, predator free habitats that these very small fish require. It is the sub-adult fish (200-600 mm long) that are most likely to be moving upstream at the Fitzroy Barrage as they undertake their second-year up river migrations.

As such it is to be expected that only the larger sub-adult barramundi will migrate upstream through the Fitzroy Barrage fishways and sampling has confirmed that these fish used the vertical slot fishway. During the 1997 sampling sub-adult barramundi were recorded many times in the fishway, generally in the 200mm to 400mm size range (Stuart 1999). During the cone fishway trials, a mesh was placed over the traps so that large fish could not enter. Hence, we did not collect barramundi, however they were and we expect them to efficiently use both the vertical slot and cone fishways (Figure 39).

Figure 39. Sub-adult barramundi captured in the cone fishway just outside the fishway trap. Barramundi, along with all medium/large fish, were excluded from the cone fishway trapping objectives as the objective was to demonstrate very small (<100 mm long) fish passage. However, the new modifications to the barrage fishways will certainly improve passage conditions for barramundi.

5.8. Conclusions

The construction of the new cone fishway alongside the vertical slot fishway on the Fitzroy Barrage has vastly increased the passage of small fish which will contribute to recovery of lower basin fish communities. The modest investment in the cone fishway and modifications for the existing vertical slot fishway has increased fish passage rates to an estimated 3.8 M fish per year. This is possibly the highest number of fish migrating through fishways at any site in Australia. Our cost-benefit analysis indicates that for every cent of the latest investment a minimum of 25 fish will migrate upstream past the barrage during its 25-year design-life. The investment in fish passage clearly demonstrates unique value-for-money. For the Fitzroy Basin Association, the barrage fishway modifications have been a significant step forward in restoring the environmental values of the lower Fitzroy Basin and can be summarised as

1. an extension of the operational time of the fishway from the part-time (6 hours/day) to full time (24 hours/day),
2. extension of the operational range from 39% to 95% of high tides,
3. an exponential increase in the number of fish using the fishway to around 3.8 Million fish per annum,
4. extension of successful passage to the multitude of small-bodied fish (<45 mm long) from the current passage rate of 10% up to 80%.

Building on these achievements, with monitoring to demonstrate outcomes and identify new opportunities, will be crucial in recovery of fish communities in the lower Fitzroy Basin.

5.9. Recommendations.

The barrage fishway modifications have exceeded their design objectives but could be further complemented with:

- Minor rectification of the existing vertical slot baffles to bring the hydraulics into line with current best practice and further complement the cone fishway in restoring upstream fish passage.
- Monitoring the recovery of lower Fitzroy Basin fish communities and providing data to support any future decision for the need for interventions such as a fishway for the north bank.

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