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Assessment of fishway passage efficiency in the Katarapko and Pike Anabranch systems 2017

J. Fredberg and C. Bice

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EXECUTIVE SUMMARY

The restoration of biological connectivity and facilitation of fish passage in the Katarapko and Pike anabranch systems are key objectives under the *South Australia Riverland Floodplains Integrated Infrastructure Program* (SARFIIP) and *Riverine Recovery Program* (RRP). These programs have included the replacement of flow regulating structures on Margaret-Dowling Creek (Pike anabranch) and Eckerts Creek (Katarapko anabranch), namely at Bank J and Log Crossing, to improve capacity to vary flow volumes into, and within, these systems. To enhance connectivity and facilitate fish passage, each of the new structures have incorporated vertical-slot fishways. The current study aimed to sample the entrances and exits of the fishways and evaluate passage efficiency against biological design objectives, with regard to the species and size classes able to successfully ascend. In addition, passage efficiency trials were conducted at each fishway (n = 1–3 per fishway) with bony herring (*Nematalosa erebi*), where a known number of marked individuals were released into the fishways, and the number of marked individuals recaptured used to calculate a proportion of passage success. Ultimately, the results of this study will inform on the success of the construction program, and future regulator and fishway operation.

From 30 November to 15 December 2017, over 16 paired-day samples of the entrances and exits of the three fishways, a total of 10,704 fish were captured from ten species, comprising the majority of fishes expected to move regularly between the Pike and Katarapko Anabranches, and the lower River Murray. The overall catch was dominated by the small-bodied Australian smelt (*Retropinna semoni*; ~77.6% of the total catch) and medium-bodied bony herring (~10% of the total catch), with smaller contributions from the small-bodied species carp gudgeon (*Hypseleotris spp.*, 7.5%) and unspecked hardyhead (*Craterocephalus fulvus*, 3%). The remaining six species collectively comprised ~1.7% of the total catch.

At the Margaret-Dowling vertical-slot fishway, a total of 4,158 fish from six species was sampled from the entrance, and 378 fish from six species from the exit. Fish assemblages (species composition and abundance), and the relative abundance of Australian smelt, differed significantly between entrance and exit samples. Australian smelt were sampled in greater abundance from the entrance, whilst individuals <35 mm (Total Length) also formed a greater proportion of the sampled population at the entrance, suggesting limited passage efficiency for this species, and particularly smaller individuals. A similar pattern was evident for carp gudgeon, albeit without statistical significance. In contrast, the relative abundance of bony herring was similar between the entrance and exit, and whilst species-specific efficiency trials were limited to one event (80% success), results suggest overall passage efficiency at Margaret-Dowling fishway is high for this

species. The Margaret-Dowling fishway was considered to be partially meeting passage objectives under the conditions assessed. Head loss across the fishway was just above the desired design range (900 mm), and thus minor changes to operation (increasing discharge to raise tailwater levels and reduce head loss) would likely improve passage, especially for Australian smelt and carp gudgeon.

At the Bank J vertical-slot fishway, a total of 2,129 fish from seven species was sampled from the entrance, and 552 fish from seven species from the exit. There were significant differences in fish assemblages, and species-specific relative abundance for Australian smelt, carp gudgeon and common carp (*Cyprinus carpio*), between entrance and exit samples. For carp gudgeon and Australian smelt, relative abundances were higher at the entrance than the exit, suggesting limited passage efficiency, and fish <35 mm, in particular, were impeded. In contrast, common carp were significantly more abundant at the exit than the entrance of the fishway, suggesting passage efficiency is high for this species, with the difference in abundance likely attributable to trap 'shyness' at the entrance of the fishway. Bony herring and unspecked hardyhead (*Craterocephalu fulvus*) exhibited similar relative abundance and length-frequency distributions between entrance and exit sampling, suggesting high passage efficiency for these species. The two passage efficiency trails conducted with bony herring, however, suggested limited success (17 and 21%). Nonetheless, these trials may have been effected by other factors, such as escapement, and with consideration of the results of the 'entrance and exit' trapping, passage efficiency for bony herring at this fishway is likely high. Overall, the Bank J fishway, like the Margaret-Dowling fishway, was considered to be partially meeting passage objectives under conditions assessed. Head loss across the fishway was in the upper end on the desired design range (>500 mm), and thus minor changes to structure operation (i.e. increasing discharge to raise tailwater levels and reduce head loss) will likely see greater levels of passage through this fishway.

At the Log Crossing vertical-slot fishway, a total of 2,225 fish from six species was sampled from the entrance, and 1,262 fish from eight species from the exit. There was no significant difference in fish assemblages between entrance and exit sampling of the Log Crossing fishway, suggesting that passage efficiency for the majority of species ascending this fishway was high. Carp gudgeon was the only species that was found to have significantly different relative abundances between entrance and exit sampling, with more fish being caught at the entrance than the exit, thus indicating that passage efficiency was limited for this species. In contrast, abundances were similar for Australian smelt, bony herring and unspecked hardyhead, suggesting high passage efficiency for these species. In addition, three passage trials were conducted with bony herring, yielding passage success of 50–75%, confirming that passage efficiency is high for this species. Length-frequency distributions were generally similar between the entrance and exit, with little evidence of size-related passage obstruction, with the exception of Australian smelt, for which a greater proportion of individuals <35 mm (Fork Length) were sampled from the entrance. Nonetheless, this obstruction was relatively minor and subsequently the Log Crossing fishway could be considered to be meeting design objectives.

Overall, the current study indicated varying passage efficiency among fishways under the scenarios assessed. The Log Crossing vertical-slot appeared to be facilitating the passage of a range of species, but at the Margaret-Dowling fishway, and to a lesser degree at the Bank J fishway, passage efficiency for small fishes (<35 mm), primarily Australian smelt and carp gudgeon, was limited. This was likely the result of a combination of poor swimming ability and fishway internal hydraulics. Actions to reduce internal velocities and turbulence at these fishways, primarily by increasing regulator discharge to increase tailwater levels and reduce overall head loss, will likely see improvements to passage efficiency.

Key recommendations for future operation of these structures, including actions to improve fish passage at the Margaret-Dowling, Bank J and Log Crossing fishways are:

- At the Margaret-Dowling regulator under normal upstream pool levels, increase discharge to 300–400 $ML.day^{-1}$.
    - This will raise the tailwater level, reducing head loss across the fishway to 450–600 mm, and maximum internal water velocity (~0.36–0.52 $m.s^{-1}$) and turbulence (~10–20 $W.m^{3}$).
- At the Bank J regulator under normal upstream pool levels, increase discharge to 400 $ML.day^{-1}$.
    - This will raise the tailwater level, reducing head loss across the fishway to ~420 mm, and maximum internal water velocity (~0.66 $m.s^{-1}$) and turbulence (~19 $W.m^{3}$).
- At all fishways, careful consideration must be given to the distribution of discharge across regulating gates when any change in discharge occurs. This includes consideration of recommendations in detailed design reports and visual inspection to ensure integrity of fishway entrance discharge is maintained, and water recirculation below the structure is minimised.

KEYWORDS: Fish Passage, River Murray, Connectivity, Vertical-slot.

1. INTRODUCTION

1.1. Background

The Katarapko (9,000 ha) and Pike (6,700 ha) anabranches, and associated floodplains, are two of three large anabranch systems (Chowilla is the other) in the Riverland region of the South Australian Murray-Darling Basin (MDB). The Pike anabranch bypasses Lock and Weir no. 5 (hereafter 'Lock'), and the Katarapko anabranch bypasses Lock 4, generating head differentials of 3.0–3.5 m between the inlets to the systems and downstream confluences with the River Murray. As such, these systems comprise a mosaic of aquatic habitats, including permanent fast-flowing and slow-flowing creeks; these flowing habitats are now rare in the main channel of the River Murray (Mallen-Cooper and Zampatti 2018). Subsequently, both systems support a diversity of native aquatic biota including fishes of conservation concern (i.e. Murray cod *Maccullochella peelii*, freshwater catfish *Tandanus tandanus* and silver perch *Bidyanus bidyanus*) (Bice *et al.* 2015, 2016). Nonetheless, both systems are considered to be in a degraded state due to the impacts of river regulation and water abstraction, perhaps most notably fragmentation and obstruction of fish passage by flow regulating structures and reduced flooding frequencies and duration.

Due to the declining state of long-lived floodplain vegetation and need to meet environmental objectives with limited water, the South Australia Riverland Floodplains Integrated Infrastructure Program (SARFIIP) was initiated to increase the frequency of floodplain inundation at both Katarapko and Pike Anabranch floodplain systems, with the aim of restoring floodplain health. The program includes a commitment of up to $155 million for environmental infrastructure including: the upgrade, installation and replacement of banks and flow regulating structures within the floodplain; floodplain groundwater and salinity management; and a range of complementary measures. SARFIIP is complementary to the Murray Futures Riverine Recovery Program (RRP), which included various in-channel remediation works in these systems (DEWNR 2011).

Dams, weirs and levees disrupt the lateral and longitudinal integrity of river systems, representing barriers to fish movement that may lead to declines in populations by preventing dispersal and recolonisation, and restricting access to preferred habitats and spawning grounds (Gehrke *et al.* 1995). Fishways are commonly used to mitigate the impacts of barriers to fish movement in regulated rivers (Clay 1995), including the MDB. Eckerts Creek and Margaret-Dowling Creek are primary influent creeks to the Katarapko and Pike systems, respectively, and flows to these creeks from the River Murray were originally regulated with crude earthen banks and pipe culverts, whilst Eckerts Creek was further regulated by a structure downstream at the Log Crossing. All three structures represented complete barriers to the upstream movement of fishes. Nonetheless, the Bank J inlet and Log Crossing regulators on Eckerts Creek, and Margaret-Dowling Creek inlet regulator have recently been upgraded, including the incorporation of vertical-slot fishways. Critical to any fishway construction program, is the assessment of passage efficiency against biological design objectives.

This project comprised the assessment of passage efficiency at the newly constructed Bank J, Log Crossing, and Margaret-Dowling Regulator fishways. These data are fundamental in determining if the newly constructed fishways are performing to biological passage objectives and design specifications, and will ultimately inform on the success of the construction program, and inform future regulator and fishway operation.

1.2. Objectives

The objective of the current study was to assess passage efficiency at each of the newly constructed fishways on the Bank J and Log Crossing regulators at Katarapko, and the Margaret-Dowling inlet regulator at Pike. Specifically, the project aimed to:

1. Design and construct traps for sampling the entrances and exits of the three fishways;

2. Undertake ‘entrance and exit trapping’ of each fishway and compare data on fish species composition, abundance and length between entrance and exit samples to determine passage efficiency against fishway-specific objectives and design specifications; and

3. Provide advice on future regulator operation in light of results of the current project and previous fishway assessments.

2. METHODS

2.1. Study site

The Pike anabranch system is situated between the townships of Paringa and Lyrup, and bypasses Lock 5 (Figure 1b). Margaret-Dowling Creek, is a major influent creek, together with Deep Creek, that discharges into the Pike anabranch, with flow regulated by a structure located in close proximity to the junction of Margaret-Dowling Creek and the River Murray (Figure 1b). A vertical-slot fishway was incorporated in this regulating structure when upgraded in 2016.

The Katarapko anabranch system is located between the townships of Loxton and Berri, and bypasses Lock 4 (Figure 1c). Eckerts Creek is the main influent creek to the system, with flow to the creek regulated by the structure at Bank J, which is situated at the junction of Eckerts Creek and the River Murray (Figure 1c). In the mid-reaches of Eckerts Creek (~5.3km downstream of Bank J), the Log Crossing structure regulates discharge to the lower reach of Eckerts Creek and down Sawmill Creek (Figure 1c). Both of these regulating structures have vertical-slot fishways incorporated into their designs.

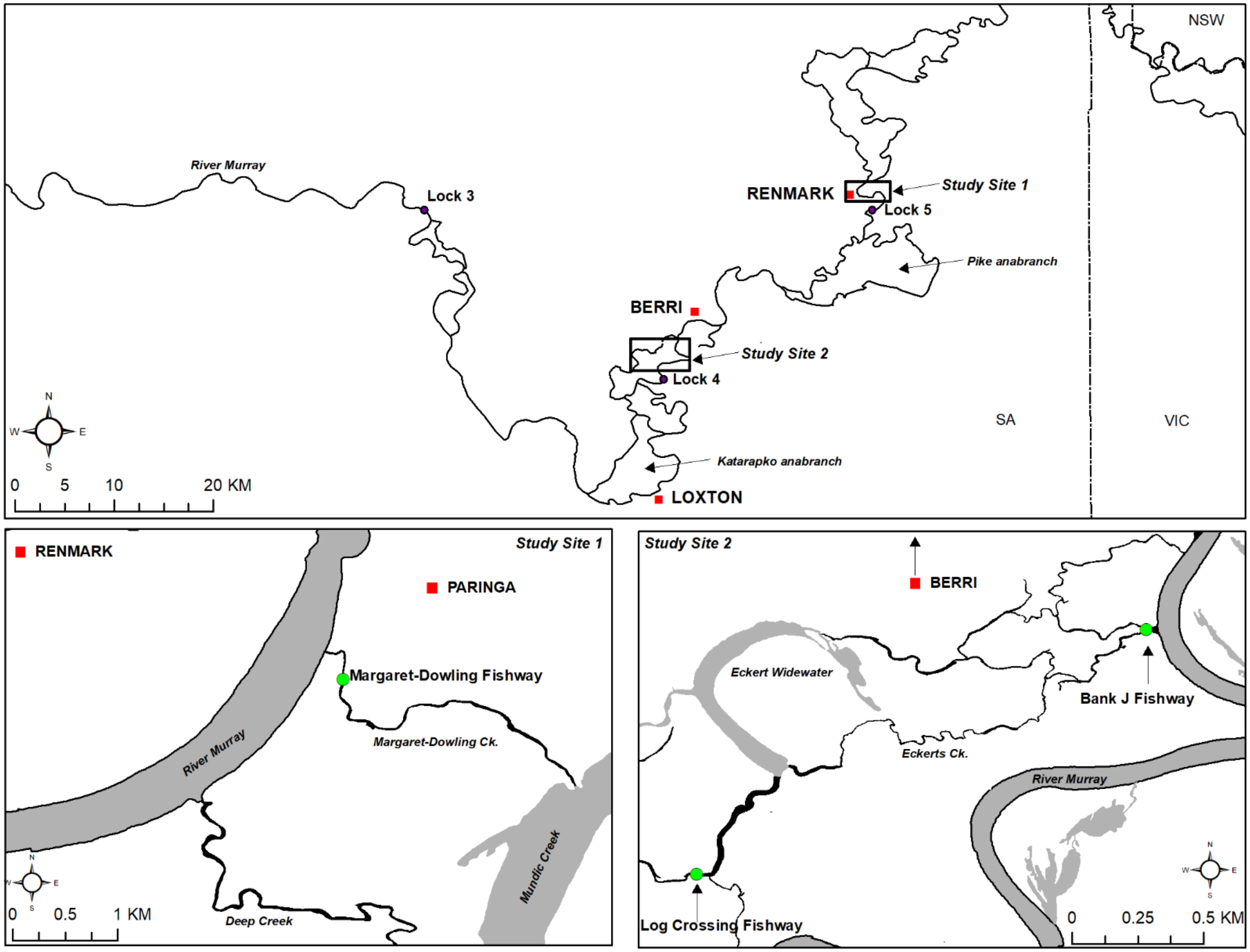

Figure 1. a) Map of the Riverland region of South Australia indicating the location of the Pike and Katarapko Anabranch systems. Inset maps indicate the location of the Margaret-Dowling, Bank J, and Log Crossing regulators and fishways (*green circles*) within the Pike (b) and Katarapko (c) systems, respectively.

2.2. Fishways

Margaret-Dowling

The Margaret-Dowling regulator is comprised of a concrete channel with two ‘lay flat’ overshot gates, capable of regulating discharge from 0 to 600 $ML.d^{-1}$ under normal Lock 5 pool level (16.3 m AHD, Australian Height Datum), and up to ~1,200 $ML.d^{-1}$ when the Lock 5 level is raised (GHD 2015). The associated vertical-slot fishway was designed with the objective of providing passage for a range of fish species and size classes from 50 to 700 mm in length, with the design informed by physical modelling (GHD 2015). The fishway is incorporated on the western side of the regulator, with the entrance positioned at a 45-degree angle directly parallel to the regulator outflows (Figure 2). The fishway consists of six pools (2.0 m wide x 3.0 m long, with 90-degree turning pools having double the standard pool volume) and seven baffles/head drops (Figure 2), consisting of ‘key-hole’ vertical-slots with widths of 150 and 250 mm. Key-hole slots are provided to produce hydraulics favourable for small-bodied fish (150 mm slot), but also capacity for large-bodied fish to pass (250 mm). The fishway has a flat concrete floor and the hydraulic gradient (1:30) is provided by decreasing height of vertical-slot baffles moving in a downstream direction. The fishway has been designed to operate at a range of headwater levels from 15.7 to 16.8 m AHD, comprising ‘normal’ conditions, through to maximum managed inundations using yet to be constructed SARFIIP infrastructure. The greatest total head differential across the fishway is 0.8 m and as such, results in maximum water velocity of 1.61 $m.s^{-1}$ and maximum turbulence of 28–33 $W.m^{-3}$ (Coefficient of Discharge [Cd] = 0.7).

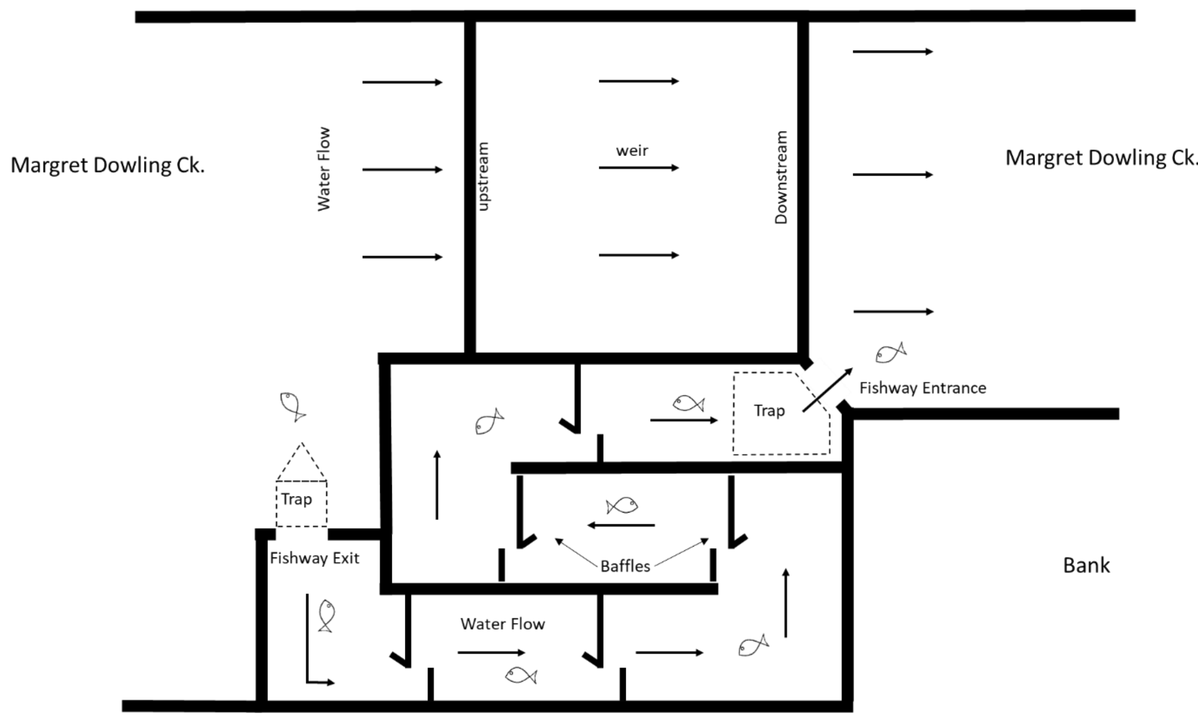

Figure 2. Schematic of the Margaret-Dowling regulator and vertical-slot fishway. The location of fishway traps for both entrance and exit trapping events are indicated.

Bank J

The Bank J regulator is comprised of a concrete channel with three bays, and ‘stoplogs’, are used to regulate discharge (Figure 3). The associated vertical-slot fishway was designed with the objective of providing passage for a range of fish species and size classes from 20 to 500 mm in length, with the design informed by physical modelling (URS 2014). The fishway is incorporated on the eastern side of the regulator, with the entrance positioned at a 90-degree angle, but adjacent to outflow from bay 3 (Figure 3). A free-standing wall (0.4 m wide x 2.4 m long) is positioned in front and downstream of the fishway entrance to limit water recirculation and maintain the integrity of the fishway attraction flow (Figure 3). The fishway consists of five pools (pool sizes vary between 3.2 m long by 2.0 m wide at the upstream end of the fishway, to 5.71 m long by 2.0 m wide at the downstream end) and six baffles/head drops. Each baffle comprises a ‘key-hole’ vertical-slot with widths of 150 and 300 mm (Figure 4). The fishway has a flat concrete floor and the hydraulic gradient (1:25) is provided by decreasing height of vertical-slot baffles moving in a downstream direction. The fishway has been designed to operate at a range of headwater levels from 13.2 m AHD (Lock 4 normal pool level) to 13.8 m AHD and discharge from

200 to 633 $ML.d^{-1}$ under normal pool level, and up to 1,324 $ML.d^{-1}$ under managed inundation scenarios. During high unregulated flows or managed inundations, an additional high flow panel/gate located at the fishway exit can be removed (figure 3), thus allowing the entrance slot attraction flow to be significantly increased. The greatest total head differential across the fishway is 0.75 m and as such, results in a maximum internal water velocity of 1.14 $m.s^{-1}$ and turbulence of 35 $W.m^{-3}$ (Coefficient of Discharge [Cd] = 0.7).

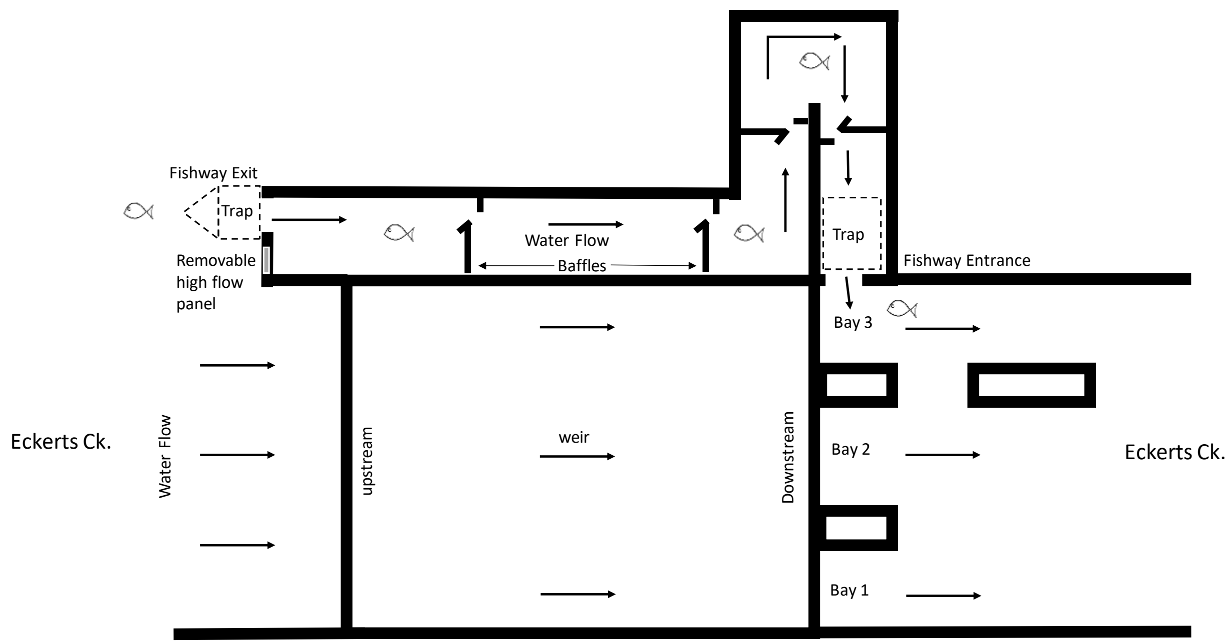

Figure 3. Schematic of the Bank J regulator and vertical-slot fishway. The location of fishway traps for both entrance and exit trapping events are indicated.

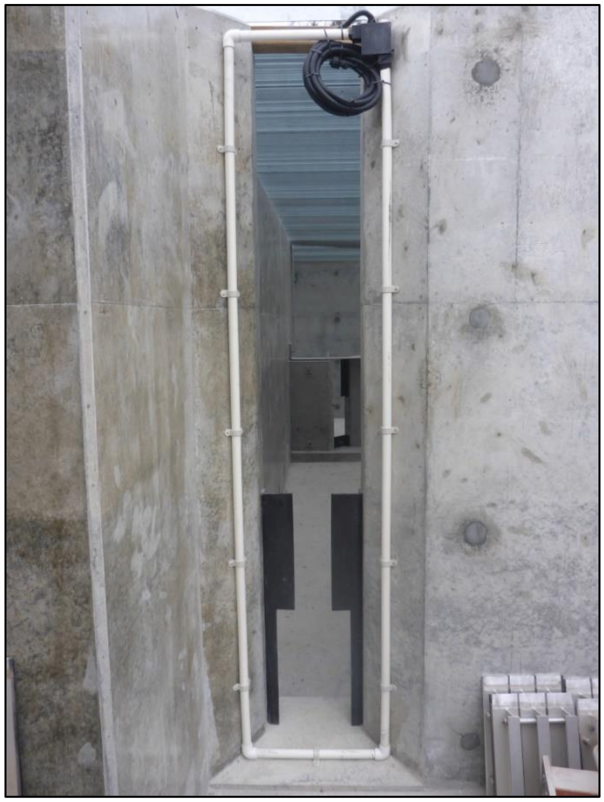

Figure 4. The key-hole vertical-slot design found on each baffle of the Bank J fishway. Similar key-hole slots are incorporated in the Log Crossing and Margaret-Dowling fishways.

Log Crossing

The Log Crossing regulator is comprised of a concrete channel with four bays and ‘stoplogs’, collectively capable of regulating flow from 150 to 500 ML.d^{-1} under normal conditions, and up to 1,400 ML.d^{-1} under unregulated flows and managed inundations (Figure 5). The associated vertical-slot fishway was designed with the objective of providing passage for a range of fish species and size classes from 20 to 500 mm in length, with the design informed by physical modelling (URS 2014). The fishway is incorporated on the western side of the regulator, with the entrance positioned at a 90-degree angle, but adjacent to outflows from bay 4 (Figure 5). A free standing wall (0.4 m wide x 2.4 m long) is positioned in front and downstream of the fishway entrance to limit water recirculation and maintain the integrity of the fishway attraction flow (Figure 5). The fishway consists of three pools (pool sizes vary between 3.2 m long by 2.0 m wide at the upstream end of the fishway, to 5.71 m long by 2.0 m wide at the downstream end) and four baffles/head drops. Each baffle comprises a ‘key-hole’ vertical-slot with widths of 150 and 300 mm (Figure 4). The fishway has a flat concrete floor and the hydraulic gradient (1:25) is provided by decreasing height of vertical-slot baffles moving in a downstream direction. The fishway has been designed to operate at a range of headwater levels from 13.2 m AHD (Australian Height Datum) to 13.8 m AHD (Lock 4 normal pool level = 13.2 m AHD) and discharge from 200 to 718 $ML.d^{-1}$. Additionally, removable high flow panels/gates are located on each of the four baffles, thus allowing entrance slot attraction flow to be significantly increased when flow and water levels are increased (e.g. during managed inundations) (Figure 5). The greatest total head differential across the fishway is 0.81 m and as such, results in maximum internal water velocity of 1.14 $m.s^{-1}$ and turbulence of 35 $W.m^{-3}$ (Coefficient of Discharge [Cd] = 0.7).

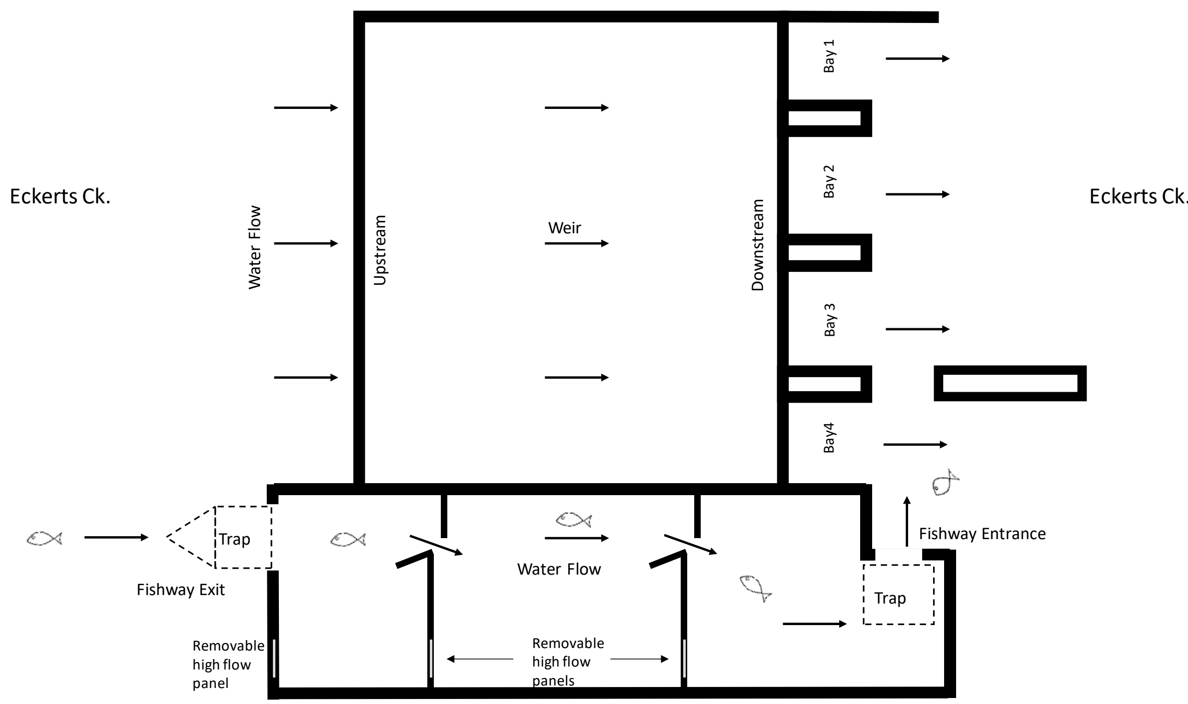

Figure 5. Schematic of the Log Crossing vertical-slot fishway. The location of fishway traps for both entrance and exit trapping events are indicated.

2.3. Fishway sampling

Fish were sampled from Margaret-Dowling, Bank J and Log Crossing fishways over 16 days, from 30 November to 15 December 2017. On consecutive days, the entrance and the exit of the fishways were sampled overnight (~24 hours) for a total of 7–8 sampling events for the entrance and exit of each fishway.

The entrances of the fishways were sampled using specifically designed cage traps. The Bank J and Log Crossing traps were constructed from 'Qubelok' aluminium square tube (25 x 25 mm), whilst the Margaret-Dowling trap was constructed from 50 mm aluminium square tube. All entrance traps were clad with a combination of 3 mm perforated aluminium sheet and 6 mm knotless mesh. These traps were designed to fit within the first cells of the fishways, and configured to sample all fish entering the fishway (Figure 6a), with nylon brushes used to ensure fish could not bypass the trap. Entrance traps incorporated single 'cone-shaped' entrances (Margaret-Dowling: 150 mm wide x 1320 mm high; Bank J: 150 mm wide x 1350 mm high; Log Crossing: 150 mm wide x 1280 mm high). The exit traps incorporated an aluminium frame and single 'cone-shaped' entrances (Margaret-Dowling: 150 mm wide x 980 mm high; Bank J: 150 mm wide x 1160 mm high; Log Crossing: 150 mm wide x 920 mm high), and collapsible 'net-bag' (6 mm mesh) to increase holding room for sampled fish and ease with lifting. These traps were mounted against the upstream side of the fishway exits, using guides for the fishway 'de-watering gates' and oriented to catch all fish exiting the fishways (Figure 6b).

Figure 6. a) View of the entrance vertical-slot of the Bank J fishway with entrance trap deployed, and b) exit trap/net in place at the Margaret-Dowling fishway.

All fish collected were removed from traps and transferred to aerated 200 L holding tubs. Fish were identified to species and enumerated, and length measurements (fork length (FL) or total length (TL) depending on tail morphology) were taken for a sub-sample of up to 50 individuals per species per trapping event. Following processing, all sampled fish were released upstream of the fishways (except bony herring used in passage efficiency trials, see below). Water physico-chemical parameters (dissolved oxygen, pH, Conductivity and temperature) and upstream and downstream water levels (m AHD Australian Height Datum) were measured daily during sampling. Total head loss (the difference between the upstream and downstream water surface level) across the fishway, and head loss across the first baffle, were measured daily.

2.4. Passage efficiency trials

In addition to entrance and exit trapping, passage efficiency trials were conducted for bony herring (*Nematalosa erebi*). When bony herring were captured in entrance trapping events, a sub-sample was tagged with visual implant elastomer (VIE, Northwest Marine Technology, Shaw Island, WA, USA) on the dorsal surface of the head (Figure 7), and released into holding pens. During subsequent entrance trapping events, the exit trap was deployed and tagged bony herring (*n* = 4–15 individual fish) released back into the fishways upstream of the entrance trap. The exit trap was subsequently lifted the following day, and tagged bony herring that successfully ascended the fishway were counted and passage success expressed as a proportion of the number of fish tagged and released into the fishways. Varying numbers of passage efficiency trials were conducted at the Log Crossing (*n* = 3), Bank J (*n* = 2) and Margaret-Dowling (*n* = 1) fishways.

Figure 7. Bony herring tagged with fluorescent green visual implant elastomer (VIE) prior to use in a passage efficiency trial.

2.5. Data analysis

Similarity in fish assemblages, with regards to species identity and abundance (fish.hour^{-1}.trap event^{-1}), among the entrance and exit of each fishway was assessed using multidimensional scaling (MDS) ordination and PERMANOVA (Permutational Multivariate Analysis of Variance) (α = 0.05). These analyses were performed on Bray-Curtis similarity matrices of fourth-root transformed abundance data in the software package PRIMER v. 6.12 and PERMANOVA+ (Anderson *et al.* 2008). Individual species passage efficiency was assessed for the most abundant species (i.e. >20 individuals) that were sampled over the study period at each fishway. This was completed by comparing relative abundance (fish.hour^{-1}.trap event^{-1}) between entrance and exit samples using uni-variate PERMANOVA, performed on Euclidean Distance similarity matrices. Fish relative abundance data were fourth-root transformed prior to all analyses.

The size distribution of the most common species (i.e. >20 individuals sampled at both the entrance and exit) were compared between entrance and exit trapping events to determine if smaller fish, with correspondingly poorer swimming abilities, were unable to ascend the fishways. A two-tailed Kolmogorov-Smirnov ‘goodness-of-fit’ test was used to determine statistical differences in length frequency distributions between entrance and exit samples (pooled over the study period) at each fishway.

3. RESULTS

3.1. Environmental conditions

During fishway sampling in November/December 2017, flow at the South Australian border (QSA) ranged 12,912 to 17,642 ML.d^{-1}, whilst the upstream mean pool level at Lock 5 was 16.32m AHD, and 13.26 m AHD at Lock 4. Discharge at Margaret-Dowling, Bank J and Log Crossing regulators was approximately ~200, ~290, and ~240 ML.d^{-1}, respectively. Total head loss across the Margaret-Dowling regulator was 0.9 m throughout sampling, and ranged 0.5–0.54 m across the Bank J regulator, and ranged 0.23–0.25 across the Log Crossing regulator.

3.2. Catch summary

A total of 10,704 fish from 10 species were sampled from the Margaret-Dowling, Bank J and Log Crossing regulators (Table 1). The overall catch was dominated by the native small-bodied Australian smelt (*Retropinna semoni,* ~77.6%) and medium-bodied bony herring (*Nematalosa erebi,* ~10%), with smaller contributions from the native small-bodied species carp gudgeon (*Hypseleotris spp.*, 7.5%) and unspecked hardyhead (*Craterocephalus fulvus*, 3%). The remaining six species collectively comprised ~1.7% of the total catch (Table 1).

Table 1. Species, total number and length range of fish sampled from the entrance and exit of the vertical-slot fishways at Margaret-Dowling, Bank J and Log Crossing during assessment in November/December 2017.

		Margaret - Dowling Vertical-Slot			Bank J Vertical Slot			Log Crossing Vertical-Slot			Total
Common name	**Scientific name**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	
	Sampling events	7	7		7	8		7	8		
	No. of species	6	6		7	7		6	8		
Native Species											
Golden perch	*Macquaria ambigua*	0	0	-	3	5	243-274	0	0	-	**8**
Silver perch	*Bidyanus bidyanus*	0	1	245	0	0	-	0	2	75-90	**3**
Bony herring	*Nematalosa erebi*	16	7	109-322	90	103	36-334	541	312	38-365	**1,069**
Unspecked hardyhead	*Craterocephalus fulvus*	4	3	33-48	40	29	30-55	185	71	30-54	**332**
Australian smelt	*Retropinna semoni*	4,062	358	29-60	1,664	280	26-70	1,101	846	24-60	**8,312**
Carp gudgeon	*Hypseleotris spp.*	60	4	27-48	309	24	27-45	391	19	24-47	**807**
Invasive species											
Common carp	*Cyprinus carpio*	7	5	153-577	22	109	162-530	5	6	131-427	**154**
Goldfish	*Carassius auratus*	0	0	-	0	2	170-210	2	5	90-176	**9**
Eastern gambusia	*Gambusia holbrooki*	0	0	-	0	0	-	0	1	24	**1**
Redfin perch	*Perca fluviatilis*	8	0	60-81	1	0	72	0	0	-	**9**
	Total	**4,158**	**378**		**2,129**	**552**		**2,225**	**1,262**		**10,704**

3.3. Passage efficiency

Margaret-Dowling

At the Margaret-Dowling vertical-slot fishway, a total of 4,158 fish from six species were sampled from entrance trapping, and 378 fish from six species from exit trapping (Table 1). Silver perch and redfin perch were only detected from the exit and entrance of the fishway, respectively, whilst the remaining five species sampled were captured from both the entrance and exit. The MDS ordination of the fish assemblage data displayed a strong grouping of samples by entrance and exit events (Figure 8), supported by PERMANOVA, which indicated assemblages were significantly different between entrance and exit trapping ($Pseudo\text{-}F_{1,\ 13} = 6.23$, $p < 0.003$).

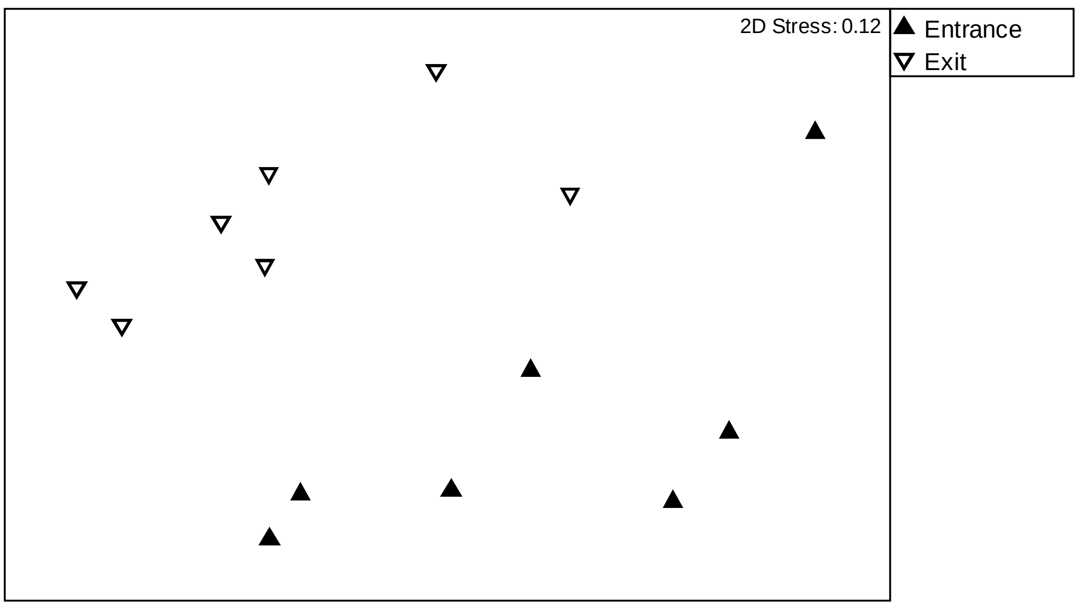

Figure 8. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at Margaret-Dowling Creek.

Of the common species, relative abundance was similar between entrance and exit trapping events for bony herring ($Pseudo\text{-}F_{1,\ 13} = 0.14$, $p = 0.745$), but relative abundance of Australian smelt was significantly greater at the entrance than the exit ($Pseudo\text{-}F_{1,\ 13} = 7.68$, $p < 0.003$) (Figure 9). Additionally, greater numbers of carp gudgeon were observed at the entrance ($n = 60$) than the exit ($n = 6$), but relative abundance did not differ significantly ($Pseudo\text{-}F_{1,\ 13} = 1.63$, $p = 0.32$), most likely due to high within group variability in relative abundance.

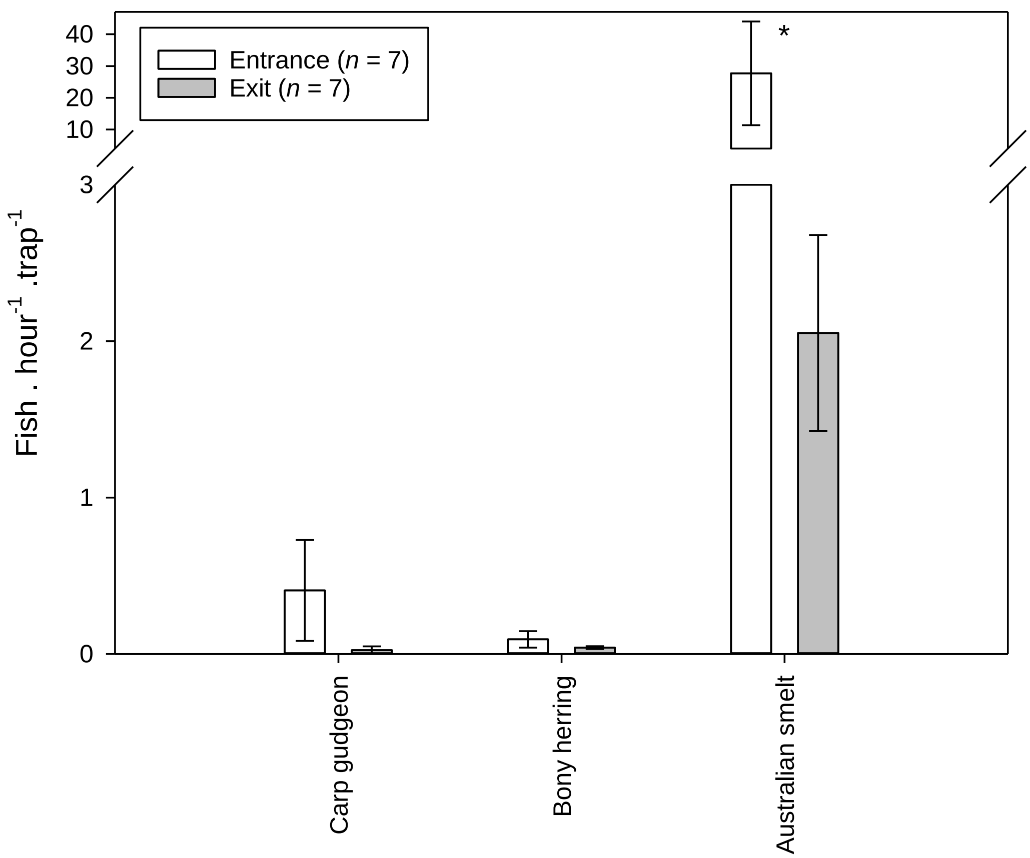

Figure 9. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Margaret-Dowling vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 27–577 mm in length, whilst those that successfully ascended the fishway ranged 27–440 mm in length (Figure 10). Carp gudgeon (entrance range: 27–48 mm TL, exit range: 27–43 mm TL) and bony herring (entrance range: 109–322 mm FL, exit range: 118–302 mm FL) appeared to have similar length distributions from the entrance and exit, but statistical comparison was not possible due to low sample sizes (Figure 10). Length distributions of common carp (entrance range: 153–577 mm FL, exit range: 186–440 mm FL) appeared different, with greater proportions of fish <200 mm sampled from the entrance, and a greater proportion of fish >400 mm sampled from the exit, albeit without statistical significance. Australian smelt were sampled from similar length ranges at the entrance (29–60 mm FL) and exit (31–60 mm FL), but length-frequency distributions were significantly different ($D_{367, 271}$ = 0.278, p < 0.001) with a higher proportion of fish <35 mm caught at the entrance (33%) than the exit (10%) (Figure 10).

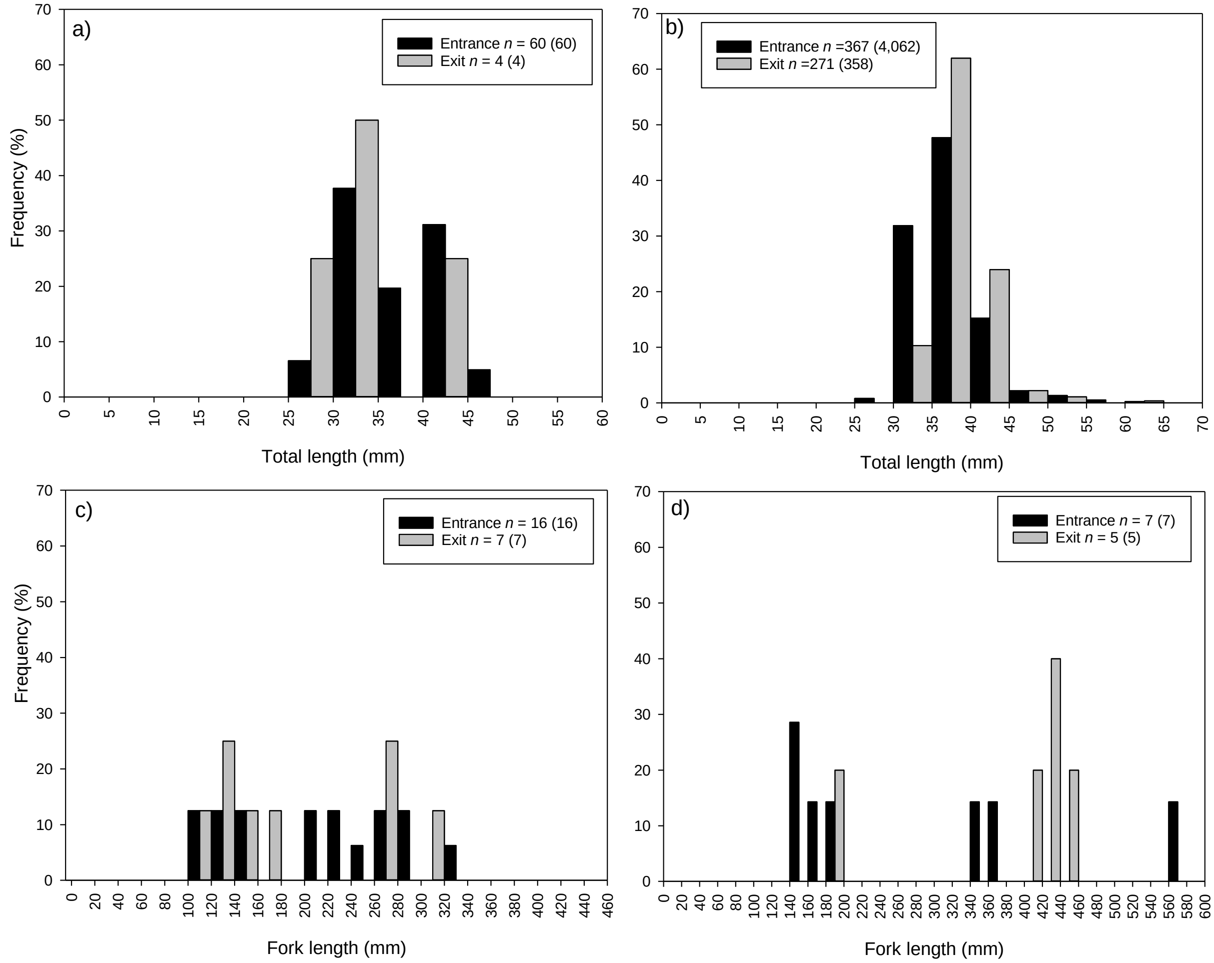

Figure 10. Length-frequency distributions of a) carp gudgeon, b) Australian smelt, c) bony herring and d) common carp captured from the entrance (black bar) and exit (shaded bar) of the vertical-slot fishway at Margaret-Dowling Creek. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

A single passage efficiency trial was conducted for bony herring at Margaret-Dowling vertical-slot, with 80% of released bony herring sampled at the exit of the fishway (Table 2). Tagged and recaptured individuals exhibited similar length ranges and mean lengths.

Table 2. Details of bony herring passage efficiency trials conducted at the Bank J, Log Crossing and Margaret-Dowling vertical-slot fishways, including the number and lengths (range and mean ± standard error) of fish tagged and subsequently recaptured, and passage efficiency (number of fish recaptured as a proportion of those tagged).

	Tagged fish			Recaptured fish			
Trial no.	***n***	**Length range**	**Mean length**	***n***	**Length range**	**Mean length**	**Passage efficiency (%)**
Bank J							
1	12	137–334	199 ± 20	2	168–263	215 ± 48	16.67
2	14	130–248	161 ± 10	3	136–157	145 ± 6	21.43
Log Crossing							
1	4	116–272	174 ± 36	3	116–258	166 ± 47	75
2	5	83–365	181 ± 54	3	85–103	93 ± 5	60
3	10	80–292	157 ± 23	5	126–292	233 ± 34	50
Margaret-Dowling							
1	10	109–286	182 ± 23	8	109–286	186 ± 28	80

Bank J

At the Bank J vertical-slot fishway, a total of 2,129 fish from seven species were sampled from entrance trapping, and 552 fish from seven species were sampled from exit trapping (Table 1). Goldfish (*Carassius auratus*) was only sampled from the exit, and redfin perch only from the entrance, whilst the remaining six species were sampled from both the entrance and exit of the fishway. The MDS ordination of the fish assemblage data displayed groupings of samples by entrance and exit trapping events (Figure 11), and PERMANOVA indicated assemblages were significantly different ($Pseudo\text{-}F_{1,14} = 5.41$, $p < 0.024$).

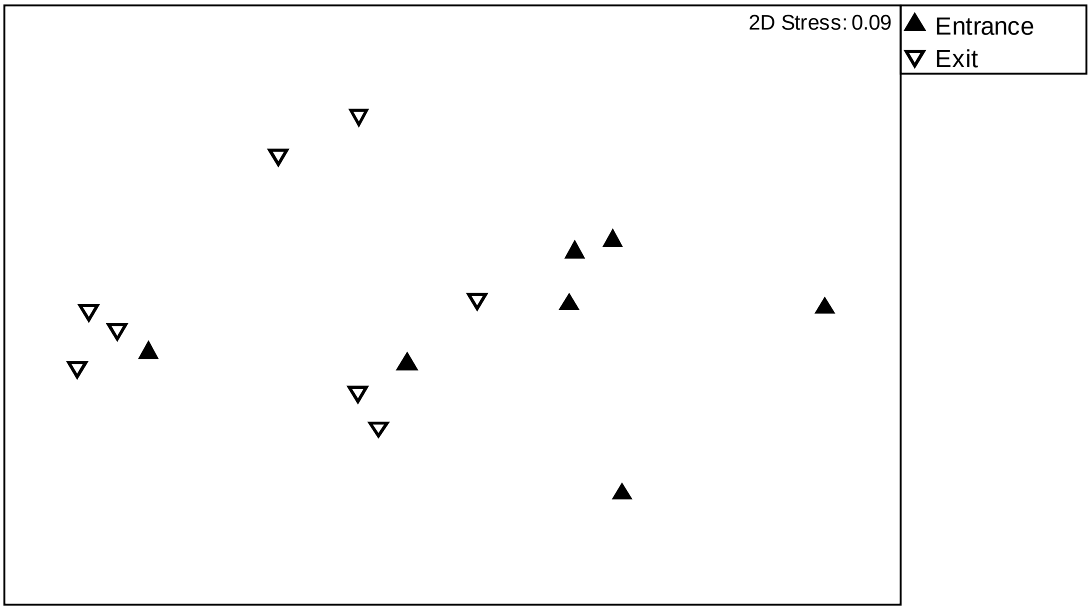

Figure 11. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at Bank J.

For common species, relative abundance was similar between entrance and exit trapping events for unspecked hardyhead (*Pseudo-*$F_{1,\ 14}$ = 1.049, p = 0.339) and bony herring (*Pseudo-*$F_{1,\ 14}$ = 0.828, p = 0.557) (Figure 12). In contrast, relative abundance differed significantly between entrance and exit trapping for common carp (*Pseudo-*$F_{1,\ 14}$ = 8.40, p < 0.008), carp gudgeon (*Pseudo-*$F_{1,\ 14}$ = 8.04, p < 0.016) and Australian smelt (*Pseudo-*$F_{1,\ 14}$ = 6.54, p < 0.026), with common carp more abundant at the exit, and the latter species more abundant at the entrance.

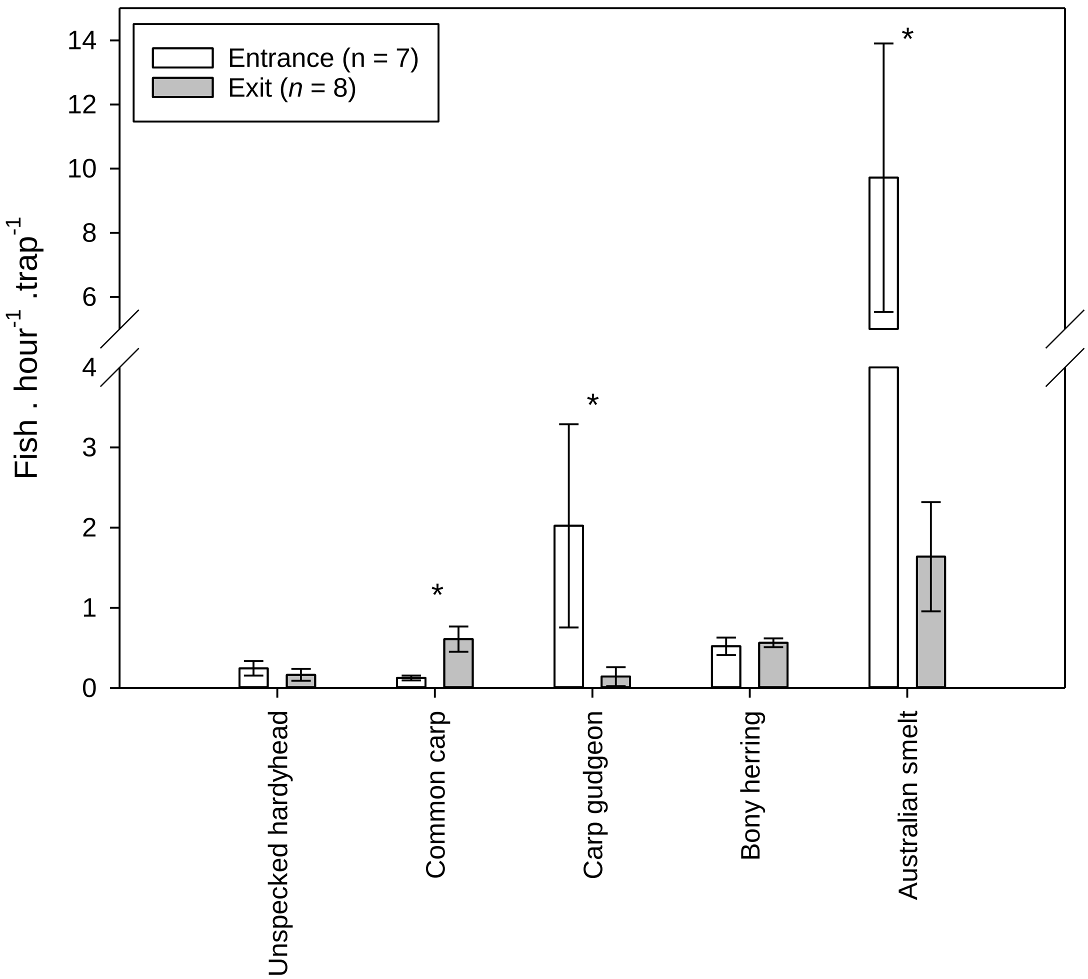

Figure 12. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Bank J vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 26–530 mm in length, whilst those that successfully ascended the fishway ranged 30–470 mm in length (Figure 13). Unspecked hardyhead ($D_{40, 29}$ = 0.307, p = 0.066), bony herring ($D_{90, 104}$ = 0.121, p = 0.449) and common carp ($D_{22, 109}$ = 0.135, p = 0.862) exhibited similar length distributions between the entrance and exit of the fishway (Figure 13a, d and e). Alternatively, length-frequency distributions were significantly different between entrance and exit samples for Australian smelt ($D_{287, 175}$ = 0.363, p < 0.001) and carp gudgeon ($D_{187, 24}$ = 0.361, p = 0.005), in both cases due to greater proportions of individuals <35 mm in length at the entrance than at the exit (Figure 13b and c).

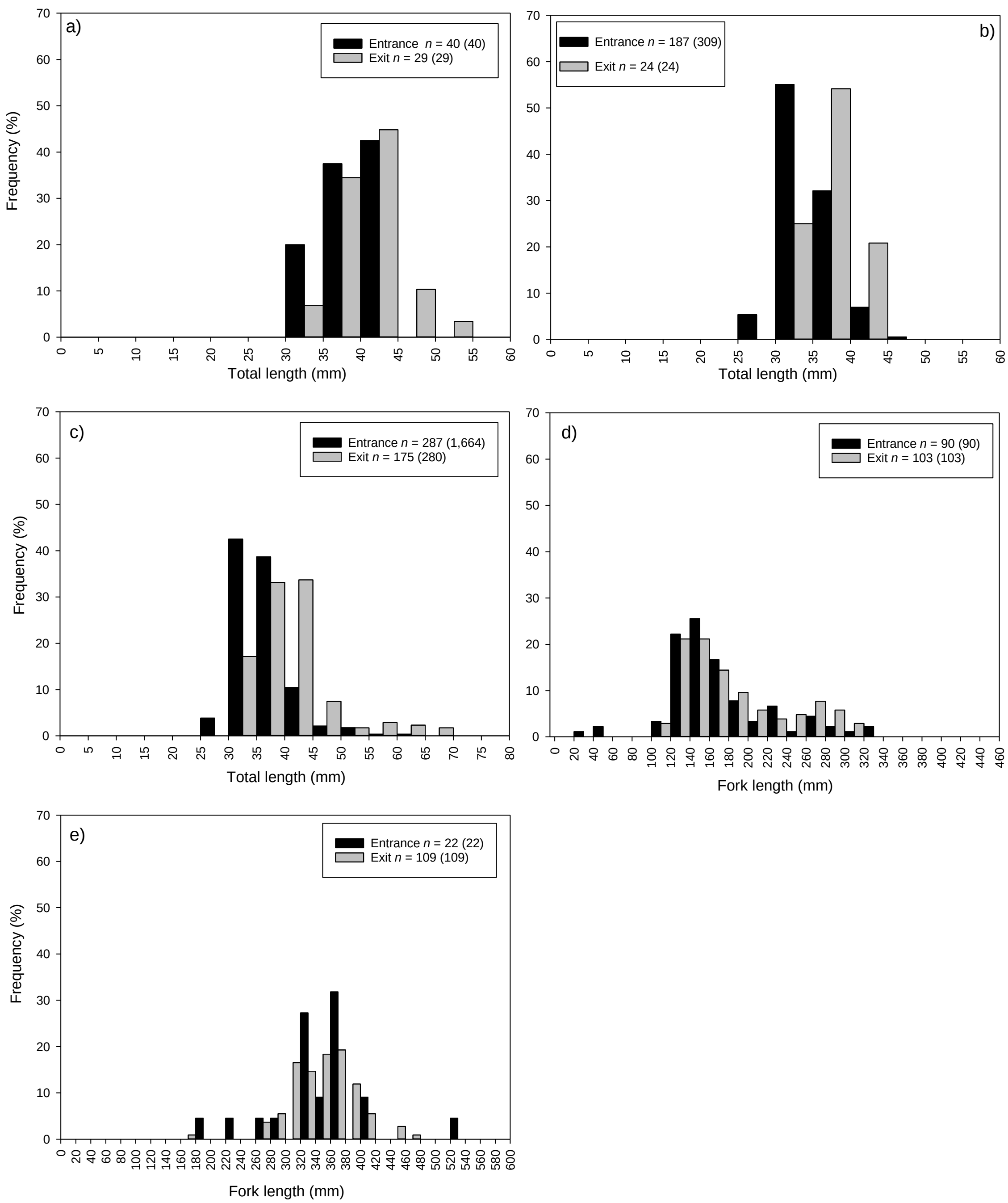

Figure 13. Length-frequency distributions of a) unspecked hardyhead, b) carp gudgeon, c) Australian smelt, d) bony herring and e) common carp captured from the entrance (black bar) and exit (shaded bar) of the vertical-slot fishway at Bank J. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

Over two passage efficiency trials conducted with bony herring, efficiency ranged 16.7–21.4% (Table 2). The length ranges of tagged and recaptured individuals was similar for the first trial, but in the second trial, the mean length of fish recaptured was smaller than that of the initially tagged fish, albeit without statistical significance.

Log Crossing

At the Log Crossing vertical-slot fishway, a total of 2,225 fish from six species were sampled from the entrance, and 1,262 fish from eight species were sampled from the exit (Table 1). Both silver perch and eastern gambusia (*Gambusia holbrooki*) were only sampled from the exit of the fishway, whilst all other species were sampled from both the entrance and exit of the fishway. The MDS ordination of the fish assemblage data displayed interspersion of samples from entrance and exit trapping events (Figure 14), and PERMANOVA indicated assemblages were not significantly different ($Pseudo\text{-}F_{1,\,14} = 1.23$, $p = 0.326$).

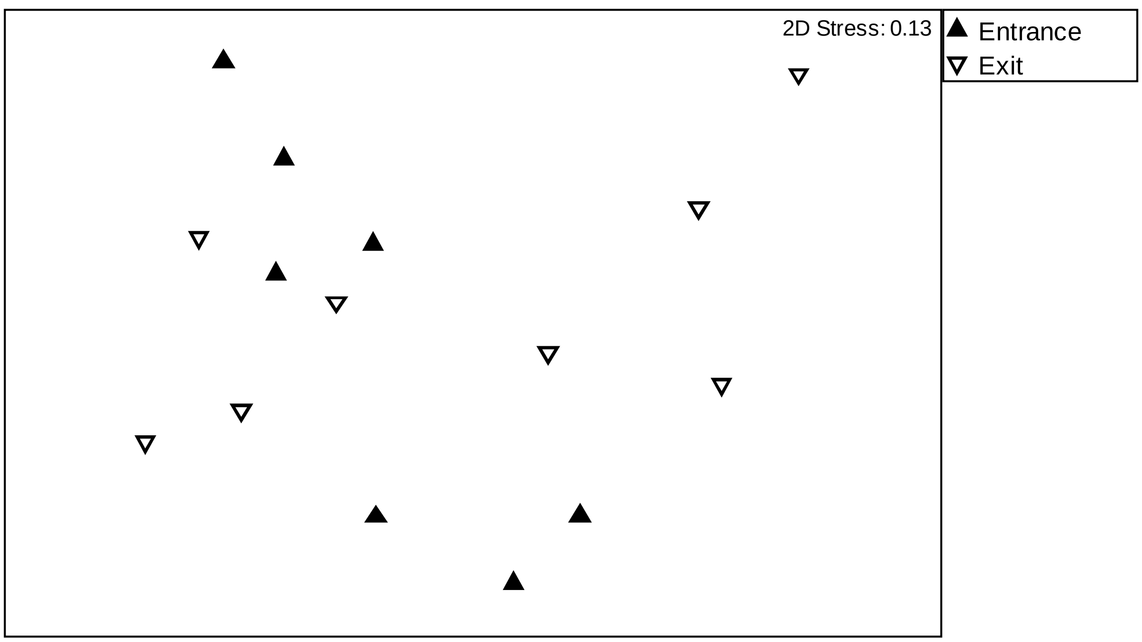

Figure 14. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at Log Crossing.

For the most common species, comparison between entrance and exit trapping events indicated no significant difference in the relative abundances of unspecked hardyhead (*Pseudo*-$F_{1,\,14}$ = 0.302, p = 0.559), bony herring (*Pseudo*-$F_{1,\,14}$ = 0.39, p = 0.804) and Australian smelt (*Pseudo*-$F_{1,\,14}$ = 0.128, p = 0.725) (Figure 15). Alternatively, the relative abundance of carp gudgeon was significantly different between entrance and exit trapping (*Pseudo*-$F_{1,\,14}$ = 14.03, p < 0.004) (Figure 15).

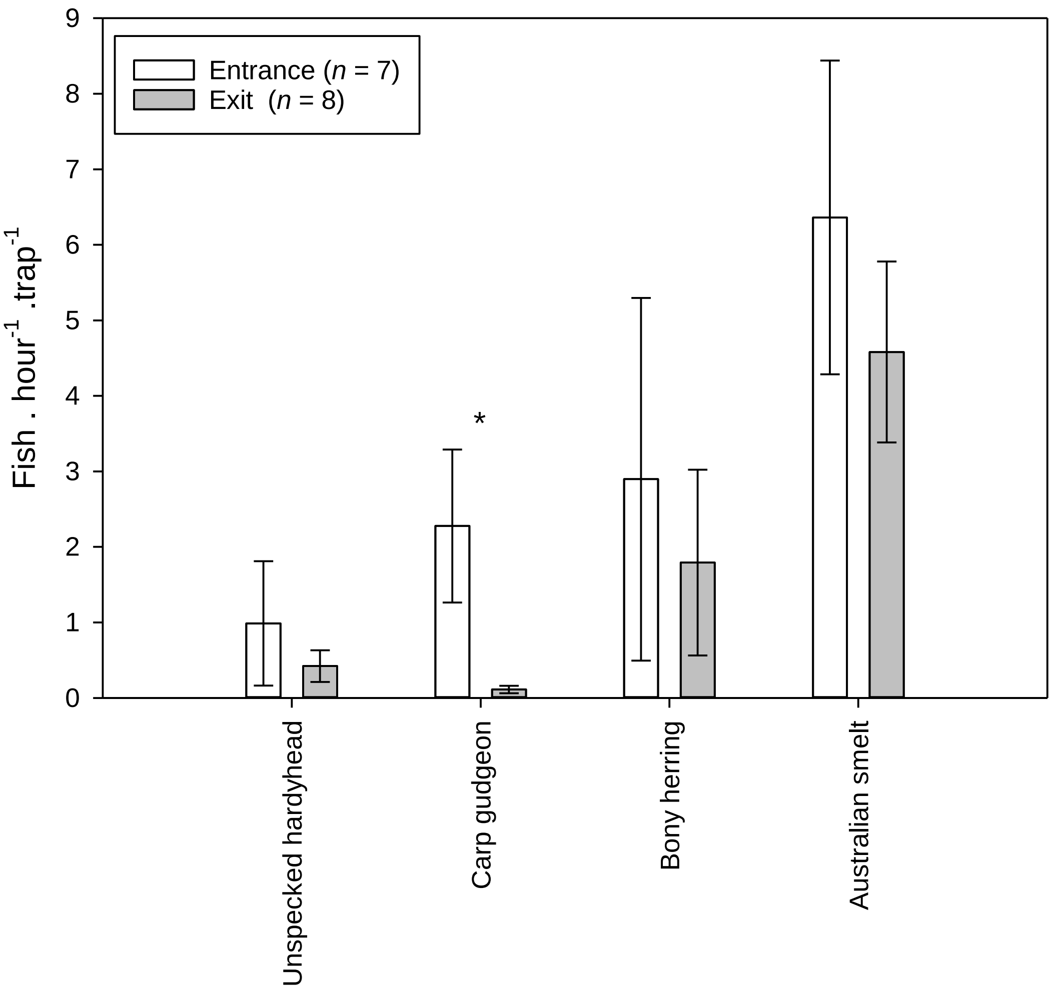

Figure 15. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Log Crossing vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 24–420 mm in length, whilst those that successfully ascended the fishway ranged 24–427 mm in length (Figure 16). Length-frequency distributions of unspecked hardyhead ($D_{72,\ 73}$ = 0.113, p = 0.714) and carp gudgeon ($D_{202,\ 19}$ = 0.121, p = 0.449) were statistically similar between entrance and exit trapping events (Figure 16a and b). Common carp also appeared to be sampled from similar length distributions at the entrance (range: 150–420 mm FL) and exit (131–427 mm FL) (Figure 16e), but low sample sizes precluded statistical comparison. Length distributions of Australian smelt differed significantly between the entrance and exit ($D_{258,\ 341}$ = 0.262, p = 0.001), likely due to a greater proportion of fish <35 mm FL at the entrance (~55%) than at the exit (~28%) (Figure 16c). Bony herring also exhibited a significant difference in length distributions between the entrance and exit ($D_{117,\ 141}$ = 0.196, p = 0.013), but in contrast to Australian smelt, this difference was likely due to a greater proportion of small individuals (40–59 mm FL) at the exit (78%) than at the entrance (56%) (Figure 16d).

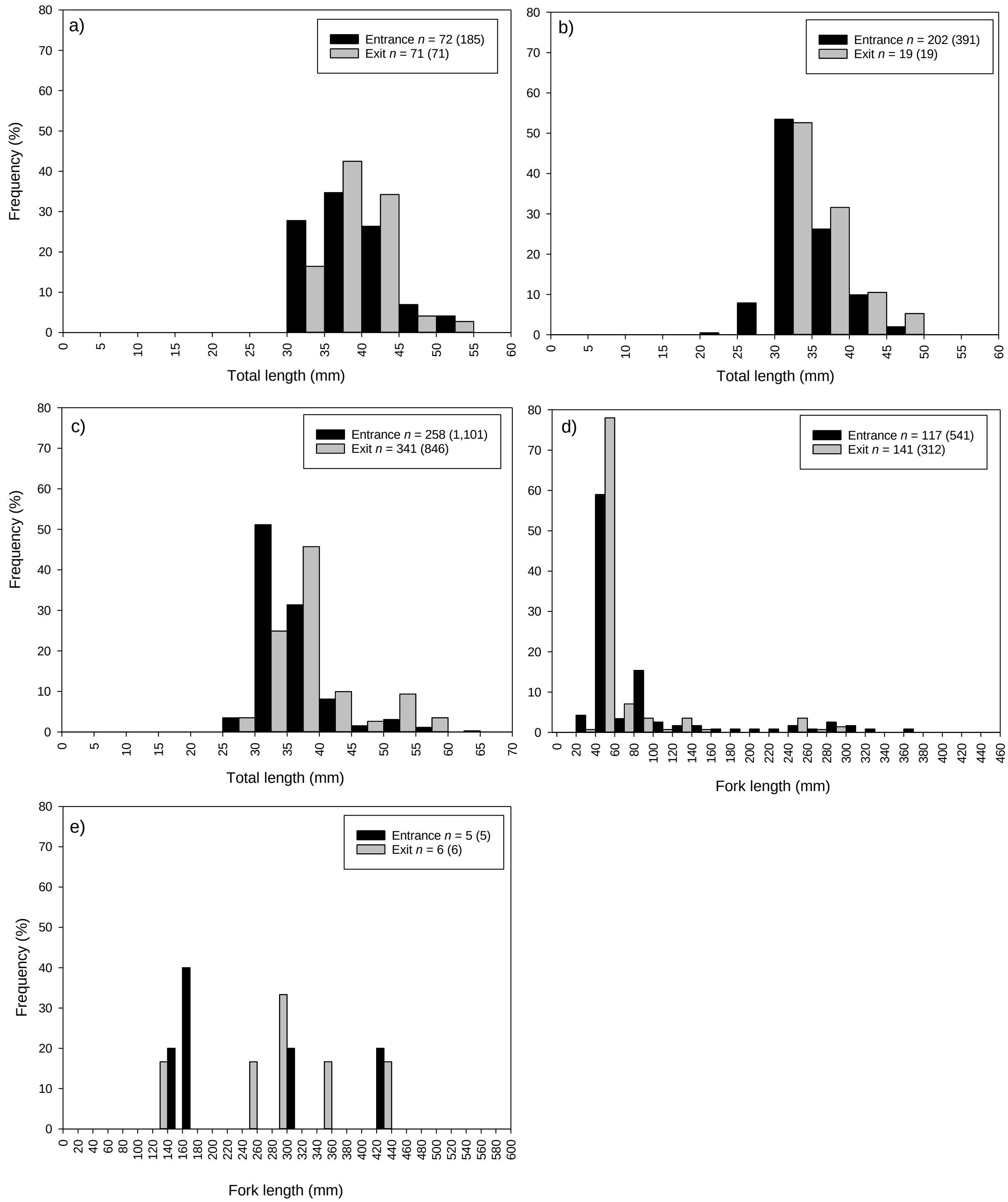

Figure 16. Length-frequency distributions of a) unspecked hardyhead, b) carp gudgeon, c) Australian smelt, d) bony herring and e) common carp captured from the entrance (black bar) and exit (shaded bar) of the vertical-slot fishway at Log Crossing. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

Over three trials at the Log Crossing vertical-slot fishway, passage efficiency for bony herring ranged 50–75% (Table 2). In most instances, length ranges and means were similar between tagged and recaptured fish, with the exception of trial 2, when the mean length of recaptured fish was smaller than tagged fish.

4. DISCUSSION

The restoration of hydrological and biological connectivity, through the removal of barriers to movement or construction of fishways, is a central focus of management interventions in the Pike and Katarapko Anabranches under RRP and SARFIIP. Fundamental to effective fishway construction programs, is assessment of passage efficiency against design criteria. The primary objective of the current study was to sample the entrances and exits of the Margaret-Dowling, Bank J and Log Crossing fishways to evaluate passage efficiency, in regards to the abundance and size classes of species able to successfully ascend. Secondly, the project aimed to provide advice on future operation of these regulators and associated fishways.

4.1. Fishway use

Totals of six, seven and eight species were sampled from the Margaret-Dowling, Bank J, and Log Crossing fishways, respectively, representing the species most commonly sampled at sites in the vicinity of these structures during previous monitoring (e.g. Bice *et al.* 2015, 2016), and expected to use these fishways. Species that were not detected at one or all of these fishways, but have been detected via standardised monitoring (i.e. electrofishing) include Murray cod (Margaret-Dowling Creek), freshwater catfish (*Tandanus tandanus*, Margaret-Dowling and Eckerts creeks) and dwarf flat-headed gudgeon (*Philypnodon macrostomus*, Margaret-Dowling and Eckerts creeks). Nonetheless, Murray cod are likely not abundant in both Margaret-Dowling and Eckerts creeks, whilst freshwater catfish and dwarf flat-headed gudgeon are thought to be largely sedentary, and not commonly encountered using fishways in the lower River Murray (Baumgartner *et al.* 2008, Stuart *et al.* 2008).

Australian smelt was the most abundant species sampled at all fishways, followed by bony herring. These species are typically among the most abundant fishes in the Pike (Bice *et al.* 2016) and Katarapko anabranches (Bice *et al.* 2015), and more broadly in the lower River Murray (Wilson *et al.* 2012, Bice *et al.* 2014, 2015). Despite no targeted studies on the movements of Australian smelt and bony herring, they are commonly sampled in substantial numbers undertaking longitudinal riverine migrations at fishways on main channel weirs of the lower River Murray (Baumgartner *et al.* 2008, Stuart *et al.* 2008) and lateral movements between riverine and off-channel habitats (Connallin *et al.* 2011), suggesting both types of movement are important components of these species' life histories. The construction of fishways at Katarapko and Pike, and appropriate operation of these structures, will see greater levels of population connectivity within the Riverland region for these species.

The fishways were also utilised by low numbers of large-bodied native golden perch and silver perch. These species are highly mobile (Reynolds 1983), and recent evidence suggests the population dynamics of these fishes operate over large spatial-scales (100s to 1000s km), and may include large distance adult migration, riverine spawning and downstream egg/larval drift, as well as substantial juvenile migration (Zampatti *et al.* 2015, 2018). Prior to the construction of the fishways, the volitional movement of these fish between certain sections of the Pike and Katarapko systems, and the River Murray, was only possible during overbank flooding. Contemporary conceptual models of the life history of these species, suggest local spawning within these anabranch systems is unlikely. Subsequently, the construction of fishways will allow access to the River Murray, and thus contribution to broader populations, by individuals that would have otherwise been restricted to given reaches of creek. Furthermore, the Log Crossing fishway now provides connectivity for these species from the downstream end of the system, whilst fishways planned for new regulators in the lower part of the Pike system (e.g. Tanyaca regulator) will likely facilitate the same process.

4.2. Passage efficiency

Margaret-Dowling

There was a significant difference in fish assemblages, and individual species relative abundance, between entrance and exit samples of the Margaret-Dowling vertical-slot fishway, suggesting limited passage efficiency for certain species. This was the case for Australian smelt, which dominated the catch (97% of total catch), and was found in substantially higher number (n= 4,062) at the entrance than the exit (n= 358). Carp gudgeon were also caught in substantially greater numbers from the entrance (n = 60) than the exit (n = 4), albeit without statistical significance. Furthermore, comparison of length-frequency distributions indicated individuals <35 mm TL formed a greater proportion of the sampled population at the entrance, suggesting these smaller individuals, in particularly, were being obstructed. In contrast, the relative abundance of bony herring was similar between the entrance and exit, and whilst species-specific efficiency trials were limited to one event (80% success), results suggest overall passage efficiency is high for this species.

Obstruction of passage of small Australian smelt and carp gudgeon could likely be attributed to the poor swimming ability of these small-bodied fish, and fishway hydraulics at the time of sampling. Throughout sampling, discharge was putatively 200 $ML.day^{-1}$, although there is concern over the accuracy of flow volumes from the operating system (R Bonner SA Water Pers. Comm.). As such, head loss across the fishway during sampling was approximately 900 mm, which is above the preferred operating range for this fishway (800 mm), likely resulting in maximum water velocities (~1.61 $m.s^{-1}$) and turbulence (~33 $W.m^{-3}$) within the fishway. Carp gudgeon typically do not grow >50 mm TL and are known to have poor swimming abilities, with laboratory trials reporting mean burst speeds as low as 0.5 $m.s^{-1}$ (Bice 2004). Alternatively, adult Australian smelt are able to maintain swimming at velocities of 0.5 $m.s^{-1}$ (Kilsby and Walker 2010), and presumably exhibit greater burst swimming velocities, but small individuals (<35 mm TL) likely have poorer swimming abilities. Bony herring, which successfully passed this fishway, likely have greater swimming ability; whilst specific trials of swimming ability have not been undertaken for bony herring, other related species of shad (e.g. American shad, *Alosa sapidissima*) are believed to be strong swimmers (Weaver 1965), and adults (>300 mm FL) commonly traverse fishways with maximum velocities of >3 $m.s^{-1}$ (Lariner and Travade 2002).

During assessment, this fishway was partially meeting passage objectives. The fishway was primarily designed for the passage of fish 50–700 mm in length, and appeared to be meeting this objective, but passage of fish <50 mm appeared to be hindered. During trapping, the fishway was operating beyond its preferred design range of head loss, and thus, minor changes to operation, namely increasing discharge through the regulator, would likely improve passage greatly. With discharge of 400 $ML.day^{-1}$ through the regulator, head loss across the fishway is reduced to <500 mm and turbulence to <20 $W.m^{3}$ (GHD 2015). The nearby Deep Creek fishway was assessed in 2016 (Bice *et al.* 2016), and has a very similar design to Margaret-Dowling. The maximum preferred head differential for Deep Creek is 1000 mm, and during sampling was predominantly 900–1000 mm, with no significant obstruction of Australian smelt observed, although carp gudgeon were likely obstructed. Actions to reduce head loss at the Margaret-Dowling fishway by >100 mm will likely see improvements to passage of Australian smelt, and other similar species.

Bank J

There were significant differences in fish assemblages, and species-specific relative abundance for Australian smelt, carp gudgeon and common carp, between entrance and exit samples of the Bank J fishway. For carp gudgeon (entrance n = 309 and exit n = 24) and Australian smelt (entrance n = 1,664 and exit n = 280), total number and relative abundance were higher at the entrance than the exit, suggesting limited passage efficiency, and fish <35 mm, in particular, were impeded. Nonetheless, passage efficiency of Australian smelt was greater than observed at the Margaret-Dowling fishway. In contrast, common carp were significantly more abundant at the exit than the entrance of the fishway. As such, passage efficiency is likely high for this species, and the difference in abundance is likely attributable to trap 'shyness' at the entrance of the fishway, which has been previously observed for large-bodied fishes in the lower River Murray (Baumgartner and Harris 2007, Fredberg and Zampatti 2018).

Bony herring and unspecked hardyhead exhibited similar relative abundance and length-frequency distributions between entrance and exit sampling, suggesting high passage efficiency for these species at Bank J for a range of different size classes. The two passage efficiency trails conducted with bony herring, however, suggested limited success (17% and 21%). Nonetheless, in the second trial, the fish recaptured at the exit of the fishway had a smaller mean length than those initially tagged and released into the fishway. Small fish have inherently weaker swimming abilities than their larger con-specifics (Beamish 1978), and contrary to our results, if passage efficiency was low, it would be expected fish at the exit would have a greater mean length. As such, these trials may have been affected by other factors, such as escapement, and we suggest, when also considering the results of the 'entrance and exit' trapping, that passage efficiency for bony herring at this fishway is likely high.

During sampling, this fishway could be considered to have been partially meeting biological design objectives, with high passage efficiency for some species, but limited for others. The fishway is designed to operate at regulator discharge of 200–718 $ML.d^{-1}$ when upstream water levels are at normal pool level, and during operation, discharge was ~290 $ML.d^{-1}$ and head loss ~550 mm. Increasing discharge at the Bank J regulator, to raise tailwater levels and reduce head loss, will likely see greater levels of successful fish passage through this fishway.

Log Crossing

There was no significant difference in fish assemblages between entrance and exit sampling of the Log Crossing fishway, suggesting that passage efficiency for the majority of species ascending this fishway was high. Carp gudgeon relative abundances were significantly different relative abundances between entrance (n = 391) and exit (n = 19) sampling, whilst abundances were not significantly different for Australian smelt (entrance n = 1,101 and exit n = 846), bony herring (entrance n = 541 and exit n = 312) and unspecked hardyhead (entrance n = 185 and exit n = 71). In addition, three passage trials were conducted with bony herring, yielding passage success of 50–75%, suggesting passage efficiency is high for this species. Length-frequency distributions were generally similar between the entrance and exit, with little evidence of size-related passage obstruction, with the exception of Australian smelt, for which a greater proportion of individuals <35 mm were sampled from the entrance. Nonetheless, this obstruction was relatively minor. Subsequently, during sampling, this fishway could be considered to have been meeting design objectives.

4.3. Recommendations for structure operation

The results of assessments indicated varying passage efficiency among fishways. The Log Crossing vertical-slot appeared to be facilitating the passage of a range of species, but passage efficiency for small fishes (<35 mm), primarily Australian smelt and carp gudgeon, was limited at the Margaret-Dowling fishway, and to a lesser degree at the Bank J fishway. This was likely the result of a combination of poor swimming ability and fishway internal hydraulics. Actions to reduce internal velocities and turbulence at the Margaret-Dowling and Bank J fishways, primarily through increasing regulator discharge to increase tailwater levels and reduce overall head loss, will likely see improvements to passage efficiency.

Whilst only low numbers of large-bodied native fishes (e.g. golden perch) were sampled from the fishways, and passage efficiency could not be statistically assessed, the successful passage of common carp and bony herring, as well as successful ascents made by individual Australian smelt as small as 30 mm FL at all fishways, suggests passage efficiency should be high for silver perch, golden perch and Murray cod. Additionally, high passage efficiency has been recorded for juvenile and adult silver perch and golden perch from vertical-slot fishways on the lower River Murray that have similar or greater internal water velocities and turbulence to the fishways in the current study (Baumgartner *et al.* 2008, Stuart *et al.* 2008).

Fishway effectiveness is typically viewed as a function of passage efficiency and attraction efficiency, which is defined as the ability of fish attempting to migrate to locate the fishway entrance (Cooke and Hinch 2013). Reliably assessing attraction efficiency typically involves mark-recapture or telemetry studies, which are difficult when regarding small-bodied fishes and species that are not undertaking driven, often obligate migrations (e.g. salmonids). As such, in the absence of empirical data on attraction efficiency, it is suggested that considerable attention is given to maintaining favourable entrance conditions at all fishways. This involves altering the split of discharge across regulator gates/flumes to maintain the integrity of fishway entrance flow and limit recirculation below the regulator and fishway.

Key recommendations for future operation of these structures, including actions to improve fish passage at the Margaret-Dowling, Bank J and Log Crossing fishways are:

- At the Margaret-Dowling regulator under normal upstream pool levels, increase discharge to 300–400 $ML.day^{-1}$.
    - This will raise the tailwater level, reducing head loss across the fishway to 450–600 mm, and maximum internal water velocity (~0.36–0.52 $m.s^{-1}$) and turbulence (~10–20 $W.m^{3}$).
- At the Bank J regulator under normal upstream pool levels, increase discharge to 400 $ML.day^{-1}$.
    - This will raise the tailwater level, reducing head loss across the fishway to ~420 mm, and maximum internal water velocity (~0.66 $m.s^{-1}$) and turbulence (~19 $W.m^{3}$).
- At all fishways, careful consideration must be given to the distribution of discharge across regulating gates when any change in discharge occurs. This includes consideration of recommendations in detailed design reports and visual inspection to ensure integrity of fishway entrance discharge is maintained, and water recirculation below the structure is minimised.

The Pike and Katarapko anabranches are currently the subject of broader management actions under SARFIIP, which includes the construction of further regulating structures and blocking banks to enable managed floodplain inundation. The design of the fishways constructed on the Margaret-Dowling, Bank J and Log Crossing regulators, considered multiple scenarios, including operation at varying flows during no inundation (i.e. ‘normal’ conditions), through to maximum level managed inundations. The current study assessed passage efficiency during ‘normal’ conditions, but the effectiveness of these structures during managed inundations remains unknown, and is a priority for future monitoring.

5. CONCLUSION

Most of the fish species likely to undertake movements between the Pike and Katarapko anabranches, and the lower River Murray, were captured from the Margaret-Dowling, Bank J and Log Crossing fishways, and some individuals of all species, successfully ascended the fishways. The Log Crossing fishway was performing to biological design objectives, whilst the Margaret-Dowling and Bank J fishways were partially meeting objectives. Nonetheless, minor changes to the operation of these structures will likely improve passage efficiency. Ultimately, all three fishways have contributed to improving connectivity at sites that were fragmented and disconnected from the main river channel except during times of flood.

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