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Assessment of passage efficiency at Sawmill Creek and The Splash fishways, Katarapko, South Australia

J. Fredberg, C. M. Bice and L. A. Thwaites

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Author(s): J. Fredberg, C. M. Bice and L. A. Thwaites

Reviewer(s): K. Frahn (SARDI) and B. Ibbotson (DEW)

Approved by: Q. Ye
Science Leader – Inland Waters and Catchment Ecology

Signed:

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South Australian Research and Development Institute - SARDI Aquatic Sciences
2 Hamra Avenue West Beach SA 5024
PO Box 120 Henley Beach SA 5022
P: (08) 8207 5400 **F:** (08) 8207 5415 **E:** pirsa.sardiaquatics@sa.gov.au
W: http://www.pir.sa.gov.au/research

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EXECUTIVE SUMMARY

The Katarapko Anabranch system bypasses Lock and Weir no. 4 on the lower River Murray. The *South Australia Riverland Floodplains Integrated Infrastructure Program* (SARFIIP), completed in 2021, involved a series of on-ground works that aimed to promote a hydrological regime at the Katarapko Anabranch that includes: 1) improved connectivity and extension of flowing water ('lotic') habitats under normal operating conditions; and 2) increased frequency of floodplain inundation due to managed inundation events. The program included construction of substantial blocking banks, and flow regulating structures and associated vertical-slot fishways on Sawmill Creek and The Splash.

The Sawmill Creek and Splash fishways aim to provide passage for a wide size range of fish (30–800 mm in length) and are designed to provide maximum pool turbulence of ≤35 $W.m^{-3}$ across a range of head differentials. As such, both incorporate key-hole slots (250 and 140 mm) to promote benign internal hydraulics yet have capacity for large-bodied fish passage, and have multiple exits to cater for varying headwater levels and head differentials. The Splash fishway, is the longer of the two, comprising 30 pools (primarily 3 x 2 m) in comparison to 21 at Sawmill Creek, and thus has a greater operational range.

In the current study, we sampled the entrances and exits of the Sawmill Creek and Splash vertical-slot fishways, as well as the exit of the adjacent Lock 4 vertical-slot fishway, and aimed to: 1) evaluate fish passage (species composition, abundance and length) against fishway-specific objectives and design specifications; 2) contrast movement among the fishways with regards to species composition and abundance; and 3) inform on future fishway and regulator operation to maximise fish passage.

During October and September 2021, a total of 14 paired-day trapping events were undertaken across the three fishways. Sampling coincided with elevated flow in the adjacent main channel of the River Murray (discharge at Lock 4 = 24,669–30,591 $ML.d^{-1}$) and a high-level managed inundation (13.31 m AHD) of the Katarapko Floodplain. At the Sawmill Creek fishway, head differential ranged 0.64–1.38 m and pool turbulence was <35 $W.m^{-3}$. At The Splash fishway, head differential ranged 0.85–1.95 m and pool turbulence was <35 $W.m^{-3}$.

At the Sawmill Creek vertical-slot fishway, a total of 2,326 fish from 10 species were sampled from the entrance and 4,083 fish from 10 species from the exit. For the most common species, Australian smelt (*Retropinna semoni*), unspecked hardyhead (*Craterocephalus fulvus*), bony

herring (*Nematalosa erebi*) and carp gudgeon (*Hypseleotris* spp.), abundances were similar between entrance and exit trapping events. Alternatively, common carp (*Cyprinus carpio*) were significantly more abundant at the fishway exit. Fish sampled at the entrance of the fishway ranged 12–669 mm in length, whilst those sampled at the exit ranged 12–690 mm in length. Species-specific length-frequency distributions were generally similar between entrance and exit trapping, except for Australian smelt, which exhibited a greater proportion of individuals <50 mm FL at the entrance, and common carp, which exhibited a greater proportion of individuals <50 mm FL at the exit. In the case of Australian smelt, this may indicate a level of size-related obstruction of passage. For common carp, this length discrepancy likely reflects the incidental downstream passage and entrapment of very small juveniles (typically <20 mm FL) from upstream. For the conditions experienced (head differential range = 0.64–1.38 m), the Sawmill Creek fishway was considered to be meeting its design objectives.

At The Splash vertical-slot fishway, a total of 3,573 fish from nine species were sampled from the entrance, and 4,414 fish from seven species from the exit. For the most abundant species sampled, Australian smelt, unspecked hardyhead and Bony herring, abundances were not statistically different between entrance and exit trapping events. Alternatively, for golden perch and common carp, abundances were significantly greater at the exit than at the entrance. Fish sampled at the entrance ranged 23–626 mm in length, whilst those sampled at the exit ranged 18–704 mm in length. For most species, length frequency distributions were similar between entrance and exit samples. For bony herring and Australian smelt, however, greater proportions of individuals 40–79 mm FL and 45–49 mm FL, respectively, were sampled at the entrance. Nonetheless, size related restriction of passage was minor. For the conditions experienced (head differential range = 0.85–1.95 m), The Splash fishway was considered to be meeting its design objectives.

At the Lock 4 vertical-slot fishway exit, a total of 3,240 fish were sampled from six species and ranged in length from 163–1030 mm. Golden perch and common carp were the most abundant species sampled.

In an effort to understand differences in upstream movement via different pathways (i.e. via the River Murray main channel or via the Katarapko Anabranch), particularly for the large-bodied species, we compared abundances from exit trap samples across all fishways. Exit trap catches were significantly different among fishways, with this difference primarily driven by greater relative abundance of golden perch at Lock 4. The results of the current study suggest that in the vicinity

of Lock 4, the bulk of upstream movement was occurring via the main river channel rather than via the Katarapko Anabranch; this result is not unexpected given the much greater discharge, and putatively greater stimulus for upstream movement occurring in the river channel relative to the Katarapko Anabranch. Nonetheless, for common carp, silver perch and bony herring, relative abundance was similar among fishways.

This study suggests that the Sawmill Creek and Splash vertical-slot fishways facilitated the passage of the majority of species likely to undertake movements between the River Murray and the Katarapko Anabranch during elevated main channel flows and a high-level managed inundation. As such, no specific changes to the fishway or operation are suggested. Future operation of the fishways should adhere to fishway performance tables in the SARFIIP Katarapko final design report to ensure attraction and passage are maximised.

Keywords: Vertical-slot fishway, regulator, passage efficiency, anabranch systems, River Murray.

1. INTRODUCTION

1.1. Background

The Katarapko Anabranch and Floodplain system (hereafter 'Katarapko') is one of three large (>9,000 ha) anabranch systems that bypass Lock and Weir structures on the lower River Murray, South Australia (together with Chowilla and Pike). Katarapko bypasses Lock and Weir No. 4 generating a head differential of ~3.5 m between the main inlet through Eckert Creek (Bank J) and the confluence of Katarapko Creek and the River Murray. As such, Katarapko comprises hydraulically diverse aquatic habitats including permanent fast-flowing and slow-flowing creeks, as well as wetlands and backwaters. Permanent lotic (flowing water) habitats are now largely absent under regulated conditions in the lower River Murray main channel (Bice et al. 2017). Subsequently, Katarapko supports a diversity of native aquatic biota including fishes of conservation concern (e.g. Murray cod (*Maccullochella peelii*), freshwater catfish (*Tandanus tandanus*), silver perch (*Bidyanus bidyanus*)) (Bice et al. 2015). The associated floodplains of the system also support ecologically significant vegetation communities that include river red gum (*Eucalyptus camaldulensis*) and black box (*Eucalyptus largiflorens*) woodlands, lignum (*Duma florulenta*) and chenopod shrubland\herblands (incl. flood responsive ephemeral communities). Nonetheless, the Katarapko ecosystem is considered to be in a degraded state due to the impacts of river regulation and water abstraction, 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 facilitate engineered (managed) floodplain inundation at Katarapko with the aim of restoring floodplain health. The program involved a range of on-ground works including the upgrade, installation and replacement of banks and flow regulating structures, construction of fishways, floodplain groundwater and salinity management, and a range of complementary measures. SARFIIP works at Katarapko were completed in 2021 and followed the Murray Futures Riverine Recovery Program (RRP), which included various in-channel remediation works in this system (e.g. upgrade to regulators and fishway construction at Bank J and The Log Crossing). Together, this infrastructure will be used to promote a hydrological regime at Katarapko that includes: 1) improved connectivity and extension of lotic habitats under normal operating conditions; and 2) more frequent floodplain inundation than would occur naturally under current conditions owing to managed inundation events.

Flow regulating structures (e.g. 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 in the Murray-Darling Basin. At Katarapko under SARFIIP, key new regulating structures were constructed on Sawmill Creek and The Splash in 2021 and both incorporated 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 Sawmill Creek and The Splash fishways with comparison to concurrent catches from the existing vertical-slot fishway on Lock 4 in the adjacent River Murray. These data are fundamental in determining if the newly constructed fishways are performing to biological passage objectives and design specifications and inform future regulator and fishway operation.

1.2. Objectives

The objective of the current study was to assess passage efficiency at the Sawmill Creek and Splash fishways, and the Lock 4 fishway. Specifically, the project aimed to:

1) evaluate fish passage (species composition, abundance and length) against fishway-specific objectives and design specifications;

2) contrast movement among the fishways with regards to species-specific abundance of medium- and large-bodied fishes (i.e. adult length >150 mm); and

3) inform on future fishway and regulator operation to maximise fish passage.

2. METHODS

2.1. Study site and fish fauna

Katarapko is situated in the Riverland region of South Australia between the townships of Loxton and Berri, and bypasses Lock 4 on the River Murray (Figure 1). Water enters the system via multiple influent creeks (primarily through Bank J) and flows through Eckerts Creek before reaching the junction with Sawmill Creek and the Log Crossing Regulator. Under low regulated flows in the River Murray, a small volume of water typically flows from Sawmill Creek into Katarapko Creek, but under higher River Murray flows, flow direction switches. Water that discharges through the Log Crossing Regulator continues to flow through The Splash until it reaches Katarapko Creek. In 2021, two major flow regulating structures were completed on Sawmill creek and The Splash (Figure 1). During normal conditions, these structures are open, but during managed inundations are operated (closed) to inundate the Katarapko Floodplain. Fishways incorporated on these structures represent primary pathways for movement of fish into upper Katarapko during managed inundations.

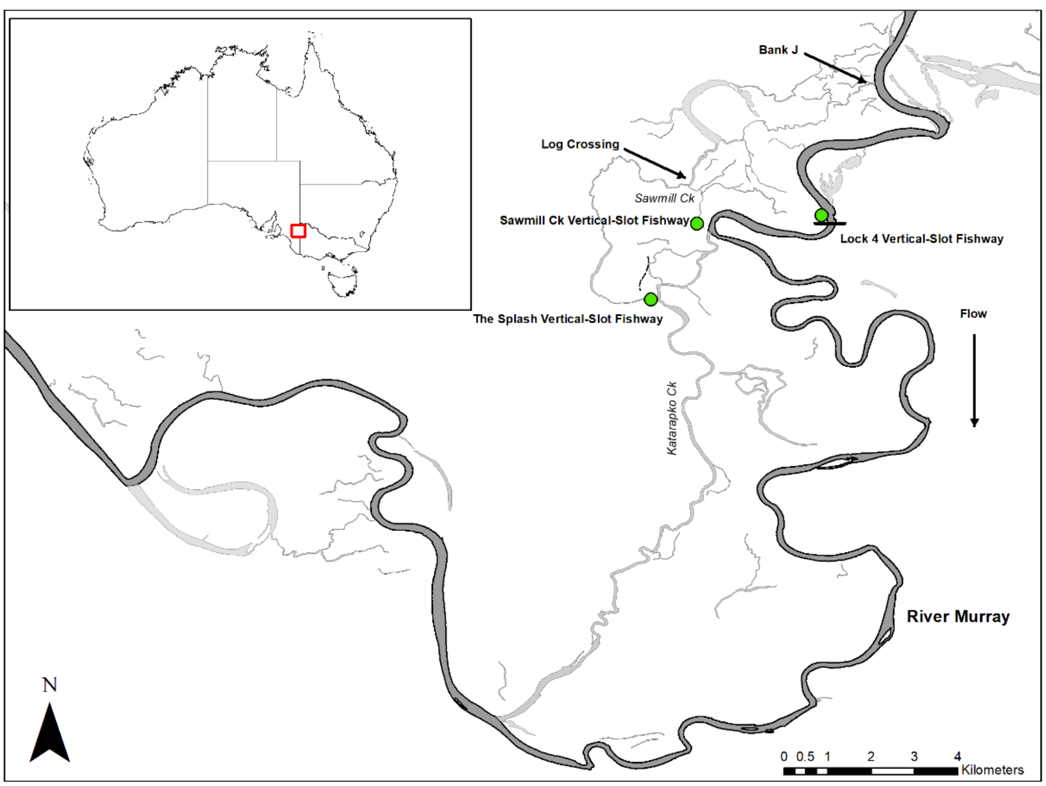


Figure 1. Map of the Katarapko Anabranch and adjacent River Murray. Green circles indicate Lock 4, The Splash and Sawmill Creek regulators and associated vertical-slot fishways that were assessed as part of this study in 2021.

A total of 18 species of fish have been recorded from Katarapko (Fredberg and Bice 2021). In the context of the lower River Murray, this represents a diverse assemblage and includes species of conservation concern, namely Murray cod (*Maccullochella peelii*; *vulnerable* under the EPBC Act 1999), silver perch (*Bidyanus bidyanus*; *critically endangered* under the EPBC Act 1999) and freshwater catfish (*Tandanus tandanus*; *protected* under the Fisheries Management Act 2007). Several species, including Murray cod and golden perch (*Macquaria ambigua*) are known to undertake long-distance riverine migrations and regular movements between anabranch and riverine habitats (Leigh and Zampatti 2013, Zampatti et al. 2018). Movements of many other species, particularly small-bodied fishes (adult length <100 mm), are less well understood, but are commonly observed undertaking longitudinal and lateral movements in the lower River Murray, including at existing fishways at Katarapko (i.e. Bank J and The Log Crossing (Fredberg and Bice 2018). A large proportion of the species present in the lower River Murray are likely to attempt movements between the River Murray and Katarapko, via regulators on Sawmill Creek and The Splash, which will comprise of species with a range of different sizes, morphologies and swimming abilities.

2.2. Fishways

Sawmill Creek and The Splash

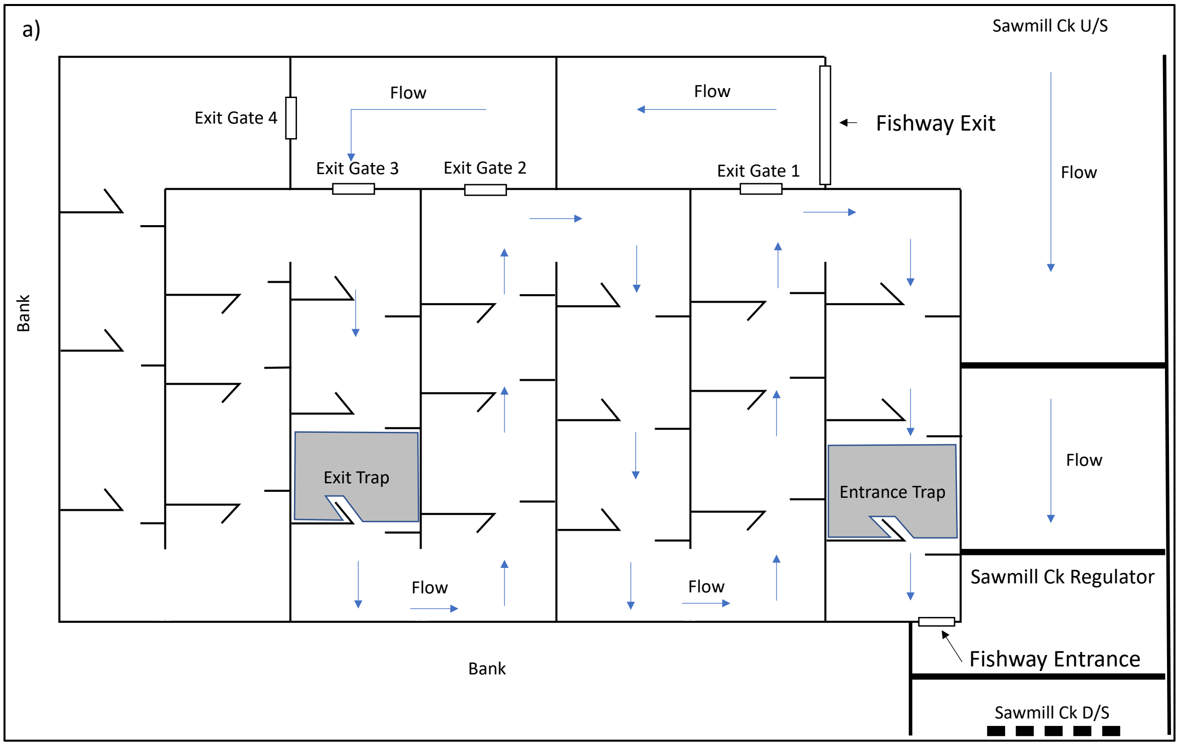
The Sawmill Creek regulator is comprised of one bay with a 2.5 m split leaf regulator gate that is designed to discharge up to 150 $ML.day^{-1}$ (modelled flood flows) (GHD 2018). The Splash regulator is comprised of three 5.3 m wide stop-log bays that are designed to have a maximum discharge of 3,200 $ML.day^{-1}$ when Lock 4 is at maximum water level (GHD 2018). The Sawmill Creek and The Splash regulators can maintain a maximum upstream water level of 13.6 m and 13.5 m AHD, respectively, during managed inundations.

The vertical-slot fishways incorporated on the Sawmill Creek and The Splash regulators were both designed with the objective of providing passage for small-bodied (30–100 mm), medium-bodied (100–300 mm) and large-bodied (300–800 mm) fish. As such, both fishways are designed to maintain, as far as practicable, maximum pool turbulence (energy dissipation factor, EDF) of 35 $W.m^{-3}$, which is in accordance with the current best-practice design for passing Australian small-bodied fishes at vertical-slot fishways (O'Connor et al. 2015).

The Sawmill Creek fishway is incorporated on the western abutment of the regulator and consists of 22 baffles and 21 pools (3 m x 2 m, with larger ‘turning pools’) (Figure 2). The fishway has a flat concrete floor with fishway hydraulics controlled by the invert of the baffle slots and designed to operate at headwater levels from 11.00–13.6 m AHD with a maximum head differential of 2.6 m. The Sawmill fishway has single entrance and exit baffles, but the length of the fishway is governed by four internal gates that can be operated under different head differentials and headwater levels. As such, maximum pool turbulence of ≤35 $W.m^{-3}$ can be maintained throughout the range of head differentials likely to be experienced. Aluminium inserts provide a 'key-hole' baffle, a wide lower slot of 250 mm wide and a narrow higher slot of 140 mm wide high are separated by a block-out section of 100 mm. These key-hole slots are provided to produce internal hydraulics favourable for small-bodied fish (i.e. 140 mm slot), but also have capacity for large-bodied fish to pass (i.e. 250 mm slot).

The Splash fishway is incorporated on the western abutment of the regulator and consists of 30 baffles and 29 pools (3 m x 2 m with larger 'turning pools') (Figure 2). Like Sawmill Creek, The Splash fishway has a flat concrete floor with internal hydraulics controlled by the invert of the baffle slots and was designed to operate at headwater levels from 10.18–13.5 m AHD and a maximum head differential of ~3.32 m. The Splash fishway consists of single entrance and exit baffles, but the length of the fishway is governed by four internal gates that can be operated under different headwater levels to maintain a maximum pool turbulence of ≤35 $W.m^{-3}$. The Splash fishway incorporates the same aluminium inserts and keyhole vertical-slot design as the Sawmill Creek fishway.

To optimize entrance conditions for fish approaching the Sawmill and Splash fishways, additional infrastructure measures were taken informed by CFD Modelling (GHD 2018). At both fishways, this included: a raised rock approach to the fishway entrance and vertical baffles on the regulator wing-wall; separation walls adjacent the entrance; and stilling blocks at the regulator outfall. In addition, the Sawmill Creek regulator incorporated a two-stage drop structure (i.e. headloss is dissipated across two sequential weir/gate structures). Collectively, these actions aimed to distribute flow across the channel, limit recirculation and maintain uniform and relatively benign velocity and turbulence on the approach to the fishway entrance. (GHD 2018).



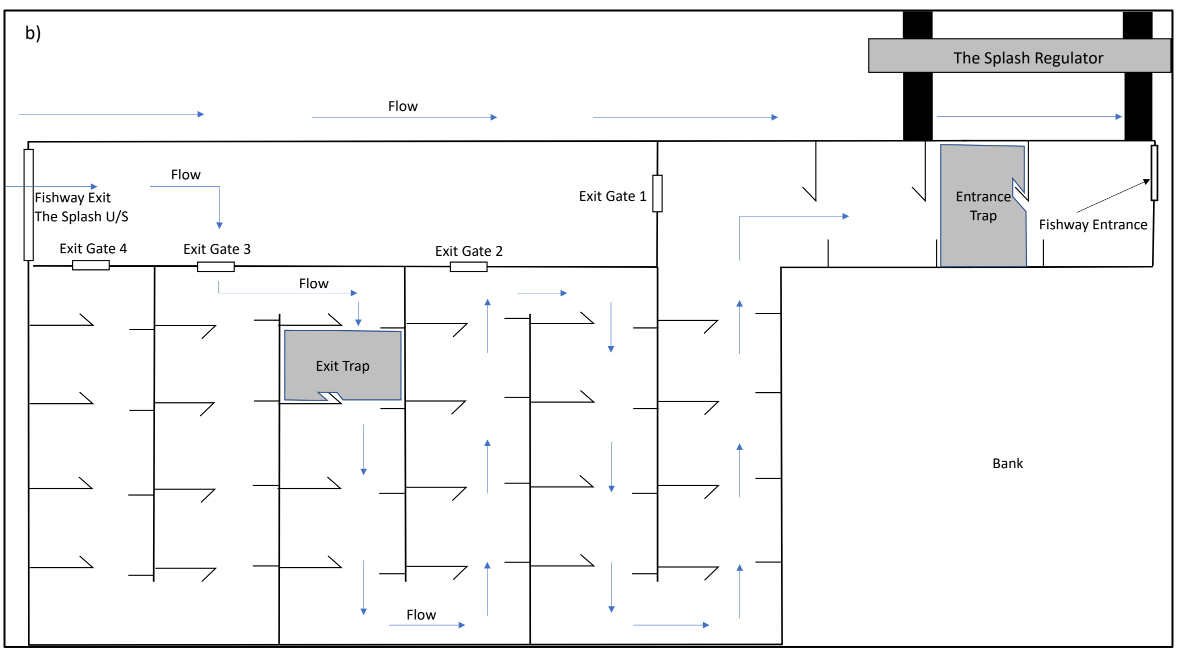


Figure 2. Schematic of the a) Sawmill Creek and b) The Splash vertical-slot fishways. The location of fishway traps for both entrance and exit trapping events are indicated on both fishways.

Lock 4

The weir component of Lock and Weir No. 4 on the River Murray comprises of 17 bays and 'stoplogs' are used to regulate discharge. A vertical-slot fishway (Figure 2) and fish-lock are incorporated on the western bank of the weir. The vertical-slot fishway was designed to pass fish ranging from ~100-1000 mm in length, while the adjacent fish lock aims to provide passage for fish <100 mm in length (Baumgartner et al. 2014). The entrance of the vertical-slot fishway is positioned at a 45-degree angle, adjacent to outflow from bay 17, and consists of 23 baffles and 22 pools with the majority of pools being 3 m long x 2 m wide, and a number of larger resting pools measuring 3 m long x 4.4 m wide. Five exit gates, only one of which is operated at any one time, provide functionality under a range of different water level scenarios. Internal concrete baffles/vertical-slots have slot widths of 300 mm. The fishway has a flat concrete floor with the hydraulic gradient of (1:23) (Baumgartner et al. 2014). The greatest operational head differential is 3.2 m, whilst the maximum slot water velocity is 1.7 $m.s^{-1}$ with maximum pool turbulence of 95 $W.m^{-3}$ (co-efficient of discharge = 0.7).

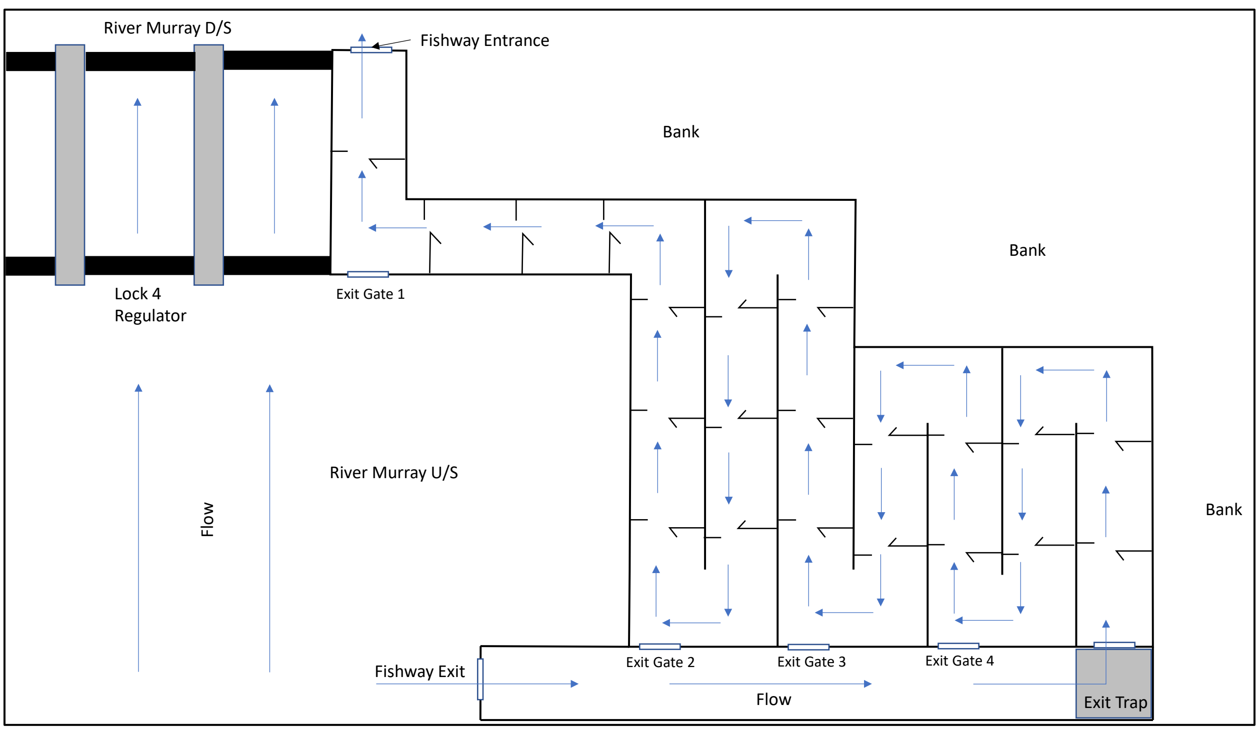


Figure 3. Schematic of the Lock 4 vertical-slot fishway. The location of the exit fishway trap for exit trapping events is indicated on the fishway.

2.3. Fishway sampling

Fish were sampled from both the entrances and exits of Sawmill Creek and The Splash vertical-slot fishways. Only the exit of the Lock 4 fishway was sampled as high water levels associated with high discharge through the weir resulted in fishway depth in the entrance cell (>3.5 m) precluding trapping. Sampling was undertaken over 14 nights from 27 September–22 October 2021 during a high-level (13.31 m AHD) managed inundation of the Katarapko floodplain. Entrance and exit trapping allow comparison of species, abundance and size range of fish attempting to ascend (entrance) with those that successfully ascend (exit) the fishway. The number of sampling events varied among fishways, with Sawmill Creek sampled for a total of 7 entrance and 7 exit sampling events, The Splash sampled for 5 entrance and 9 exit events, and Lock 4 sampled for a total of 13 exit events. All traps were set overnight (~24 hours) during each event.

The entrance and exit traps at both the Sawmill Creek and The Splash fishways were constructed from aluminum square tube (50 x 50 mm) and were clad with a combination of 3 mm perforated aluminum sheet and 6 mm knotless mesh. Traps were designed to fit within the concrete channel of the entrance and exit of the fishways and had dimensions of ~1800 x 2150 x 2200 mm (L x W x H). All traps incorporated double 'cone' entrance funnels (top funnel: 140 x 1100 mm, bottom funnel: 200 x 400 mm, W x H). Due to elevated flows in the River Murray main channel at the time of sampling, tailwater at both fishways were significantly elevated causing water to flow (50–1500 mm depth) over both fishways entrance traps. At Sawmill Creek a stop grill constructed from 3 mm perforated mesh was used to block any fish attempting to move over the trap, as the trap was typically <100 mm under the surface. At The Splash entrance, however, the trap was up to 1.5 m under the water surface and a second trap (500 x 350 x 1600 mm, L x W x H), consisting of a single 'cone' entrance funnel (150 x 1000 mm, W x H) was placed on top of the existing trap to sample any fish moving in this part of the water column. The Lock 4 exit trap (~1700 x 1800 x 1500 mm, L x W x H) was constructed from stainless steel and covered in 25 mm square mesh and had 3-mm square mesh covering the floor of the cage. These mesh dimensions mean that small-bodied fish <100 mm in length are not effectively sampled at this 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 (mm, fork length (FL) or total length (TL) depending on tail morphology) taken for a sub-sample of up to 50 individuals per species per trapping event. Large-bodied fish were tagged with external and PIT (passive integrated transponder) tags. Following processing, all native species and tagged fish were released upstream of the fishways. Total head loss (the difference between the upstream and downstream water surface level) across the fishway, and head loss across the entrance and exit baffles were measured daily.

2.4. Data Analysis

Passage efficiency

Passage efficiency at the Sawmill Creek and The Splash fishways was assessed by comparing assemblage structure, species-specific abundance and length-frequency distributions between entrance and exit trapping events. Similarity in fish assemblages, with regards to species identity and abundance (fish.hour^{-1}.trap event^{-1}), among entrance and exit samples was assessed using multidimensional scaling (MDS) ordination and single-factor (trap position) PERMANOVA (Permutational Multivariate Analysis of Variance) ($\alpha = 0.05$). These analyses were performed on Bray-Curtis similarity matrices in the software package PRIMER v. 6.12 and PERMANOVA+ (Anderson et al. 2008). When difference occurred, Similarity of Percentages (SIMPER) analysis was used to determine species contributing to differences in assemblages (a 50% cumulative contribution cut-off was applied). Species-specific passage efficiency was assessed for the most abundant species (> 40 individuals) at each fishway 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. Due to low numbers of permutations in some instances *p* values were calculated using the Monte Carlo technique, where the real data is compared against 5000 runs of randomised data (Dufrene and Legendre 1997). Fish relative abundance data were fourth-root transformed prior to all analyses.

The length-frequency distributions of the most common species (i.e. >25 individuals sampled at both the entrance and exit) were compared between entrance and exit trapping events to determine if any size-related obstruction of passage had occurred. A two-tailed Kolmogorov-Smirnov 'goodness-of-fit' test was used to determine statistical differences ($\alpha = 0.05$) in length-frequency distributions between entrance and exit samples (pooled over the study period).

Comparison of medium- and large-bodied fish migration among fishways

The relative abundances of medium- and large-bodied species (typical adult length >150 mm) successfully passing each fishway (i.e. exit samples) was compared to assess differences in migration pathways. Species-specific relative abundance (fish.hour-^{1}.trap event^{-1}) from exit trapping events were compared between fishways using uni-variate PERMANOVA, performed on Euclidean Distance similarity matrices.

3. RESULTS

3.1. Environmental conditions

In July 2021, flow at Lock 4 on the lower River Murray was generally <7000 $ML.d^{-1}$, but increased to ~20,000 $ML.d^{-1}$ in mid-August and throughout much of September (Figure 4a). Discharge increased to ~30,000 $ML.d^{-1}$ in late September and remained at this volume for the remainder of the study. Managed inundation of Katarapko occurred from 26 July to 10 November 2021. The upstream pool level of Lock 4 was raised by approximately 0.3 m, while operation of the Sawmill and Splash regulators saw increases in upstream water levels of ~2.4 and 3.3 m, respectively, at these structures, and an inundation height at Katarapko of ~13.3 m AHD (Figure 4b).

During fishway sampling from 27 September–22 October 2021, flow at Lock 4 ranged from 24,669–30,591 $ML.d^{-1}$ and headloss across the structure was 1.21–1.62 m (Figure 4). At the Sawmill Creek and Splash regulators, discharge and headloss were more variable due to planned recession from peak managed inundation. Discharge and headloss at Sawmill Creek ranged 97–223 $ML.d^{-1}$ and 0.64–1.38 m, and at The Splash ranged 789–1239 $ML.d^{-1}$ with head loss ranging from 0.85–1.95 m. At both the Sawmill Creek and Splash fishways, during sampling, exit gate 3 was in operation, this meant that pool turbulence at both fishways ranged between 30–35 $W.m^{-3}$ during peak inundation, but lowered to <30 $W.m^{-3}$ when inundation levels were dropped.

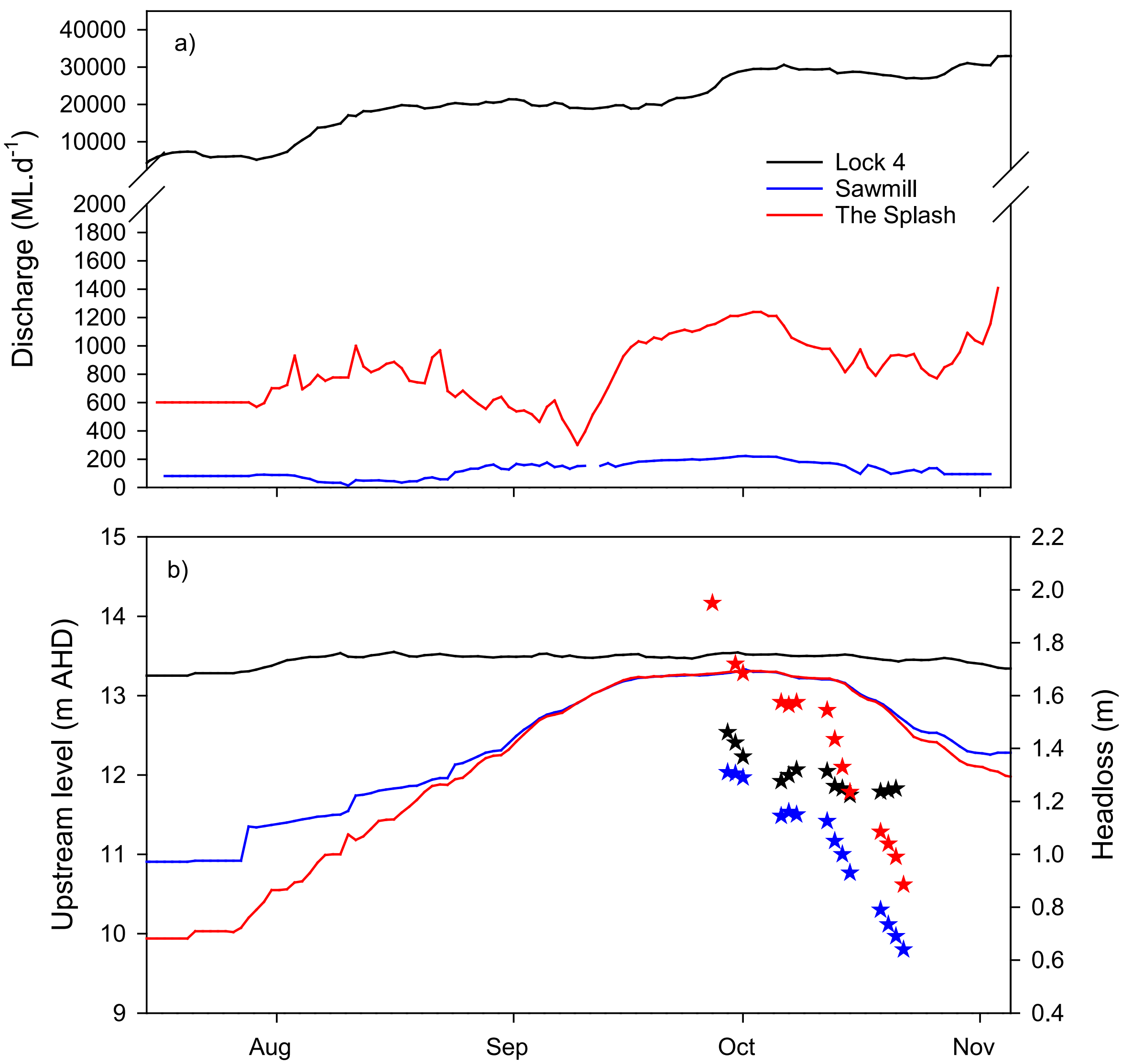


Figure 4. a) Discharge ($ML.d^{-1}$) and b) upstream water level (m AHD) at Lock 4 (*black*), Sawmill Creek (*blue*) and The Splash (*red*) from mid-July to early-November 2021. Headloss (m) during each trapping event is also presented in plot b (*stars*).

3.2. Catch summary

A total of 17,639 fish from 12 species were sampled collectively from the Sawmill Creek, Splash and Lock 4 fishways (Table 1). The overall catch was dominated by the native small-bodied Australian smelt (*Retropinna semoni,* ~73%) and the native large-bodied species golden perch (*Macquaria ambigua*, 17%). Non-native common carp (*Cyprinus carpio*, 7%) and the native medium-bodied bony herring (*Nematalosa erebi,* ~1.3%) were the next most numerous species, while the remaining eight species collectively comprised ~1.8% of the total catch (Table 1).

Table 1. Species and total fish abundance sampled at The Splash, Sawmill Creek and Lock 4 fishways during the Katarapko vertical-slot fishway assessment in 2021.

		The Splash Vertical-Slot			Sawmill Ck Vertical Slot			Lock 4 Vertical-Slot		Total
Common name	**Scientific name**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	**Exit**	**Length range (mm)**	
	Sampling events	5	9		7	7		13		
	No. of species	9	7		9	10		6		
Native Species										
Golden perch	*Macquaria ambigua*	13	79	224-546	12	5	277-490	2,833	291-560	**2,942**
Silver perch	*Bidyanus bidyanus*	0	5	167-205	3	2	124-239	11	173-440	**21**
Murray cod	*Maccullochella peelii*	0	0	-	0	0	-	5	693-1030	**5**
Bony herring	*Nematalosa erebi*	34	142	22-363	56	10	94-308	4	163-269	**246**
Unspecked hardyhead	*Craterocephalus fulvus*	8	37	37-55	52	1	30-54	0	-	**98**
Australian smelt	*Retropinna semoni*	3,468	3,758	33-68	2,077	3,633	37-67	0	-	**12,936**
Carp gudgeon	*Hypseleotris spp.*	22	0	26-45	37	21	30-57	0	-	**80**
Murray rainbowfish	*Melanotaenia fluviatilis*	4	0	58-62	3	4	61-68	0	-	**11**
Pouched lamprey	*Geotria australis*	1	0	470	0	0	-	0	-	**1**
Invasive species										
Common carp	*Cyprinus carpio*	21	386	18-704	78	402	12-690	389	195-760	**1,276**
Goldfish	*Carassius auratus*	2	7	143-205	8	4	170-300	1	164	**22**
Redfin perch	*Perca fluviatilis*	0	0	-	0	1	280	0	-	**1**
	Total	**3,573**	**4,414**		**2,326**	**4,083**		**3,243**		**17,639**

3.3. Passage efficiency

Sawmill Creek

At the Sawmill Creek vertical-slot fishway, a total of 2,326 fish from nine species were sampled from entrance trapping, and 4,083 fish from ten species from exit trapping (Table 1). Redfin perch (*Perca fluviatilis*) (n = 1) was the only species to be sampled exclusively at the exit, whilst the remaining nine species were sampled at both the entrance and exit. PERMANOVA indicated that fish assemblages among entrance and exit trap samples were not significantly different (*Pseudo-*$F_{1,\ 13}$ = 1.3079, p = 0.276). MDS ordination supported this result with fish assemblage data exhibiting interspersion of samples based on trap type (Figure 4).

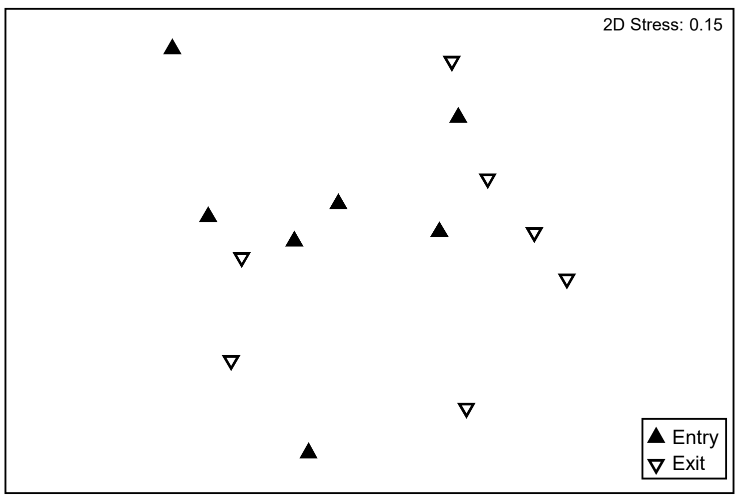


Figure 5. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at the Sawmill Creek Regulator.

For the most common species, relative abundances of carp gudgeon (*Hypseleotris* spp.; *Pseudo-*$F_{1,\ 13}$ = 1.2812, p = 0.287), unspecked hardyhead (*Pseudo-*$F_{1,\ 13}$ = 0.3511, p = 0.568), bony herring (*Pseudo-*$F_{1,\ 13}$ = 2.1114, p = 0.176) and Australian smelt (*Pseudo-*$F_{1,\ 13}$ = 1.2493, p = 0.298) were not significantly different between the fishway entrance and exit (Figure 5). Common carp, however, were significantly more abundant at the fishway exit than the fishway entrance (*Pseudo-*$F_{1,\ 13}$ = 5.5906, p = 0.031; Figure 5).

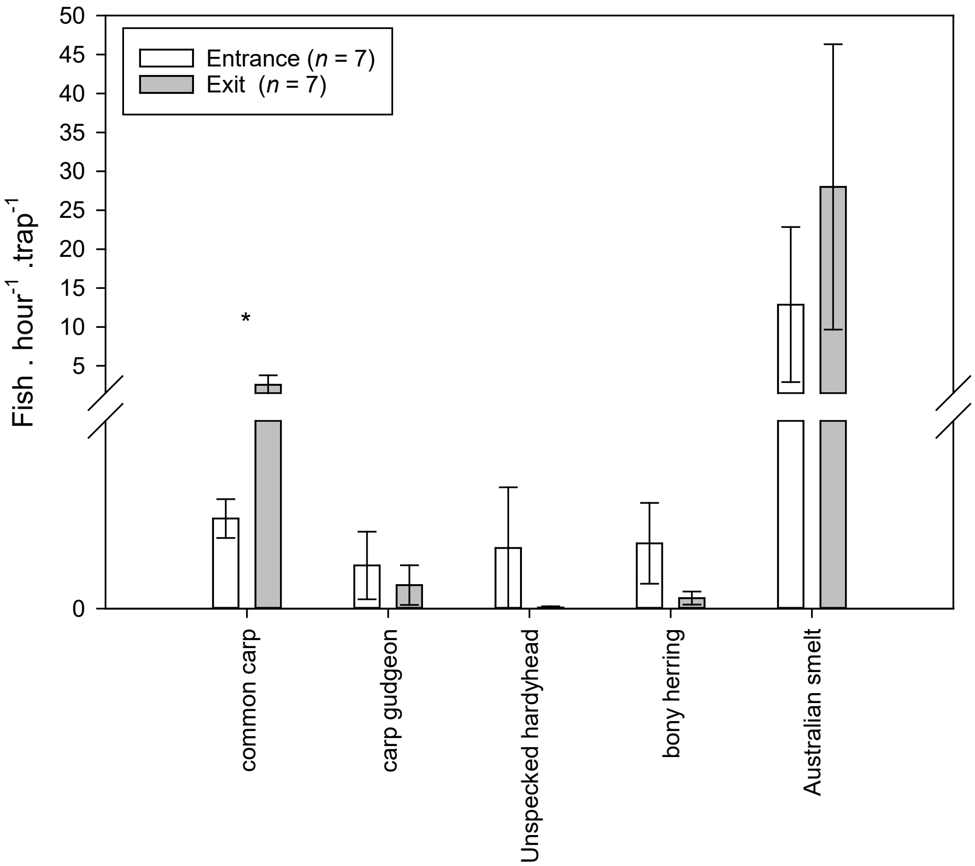


Figure 6. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Sawmill Creek Regulator vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 12–669 mm in length, whilst those sampled from the exit ranged 12–690 mm in length (Figure 7). Length frequency distributions for common carp ($D_{73,\ 217}$ = 0.264, p < 0.001) and Australian smelt ($D_{318,\ 344}$ = 0.117, p = 0.022) were significantly different between the fishway entrance and exit. The most notable difference in length-frequency distributions for common carp between entrance and exit samples was the greater proportion of individuals <50 mm FL sampled at the exit (>40%) compared to the entrance (~15%; Figure 7d). For Australian smelt, length-frequency distributions appeared similar among entrance and exit samples with the exception of slightly greater proportions of individuals 40–44 mm FL at the entrance (26 %) than the exit (19%), and slightly greater proportions of individuals

50–54 mm FL at the exit (38%) than the entrance (25%). For the remaining species, statistical analysis could not be performed due to limited sample sizes, but most species were sampled from similar length ranges across the entrance and exit (Figure 6).

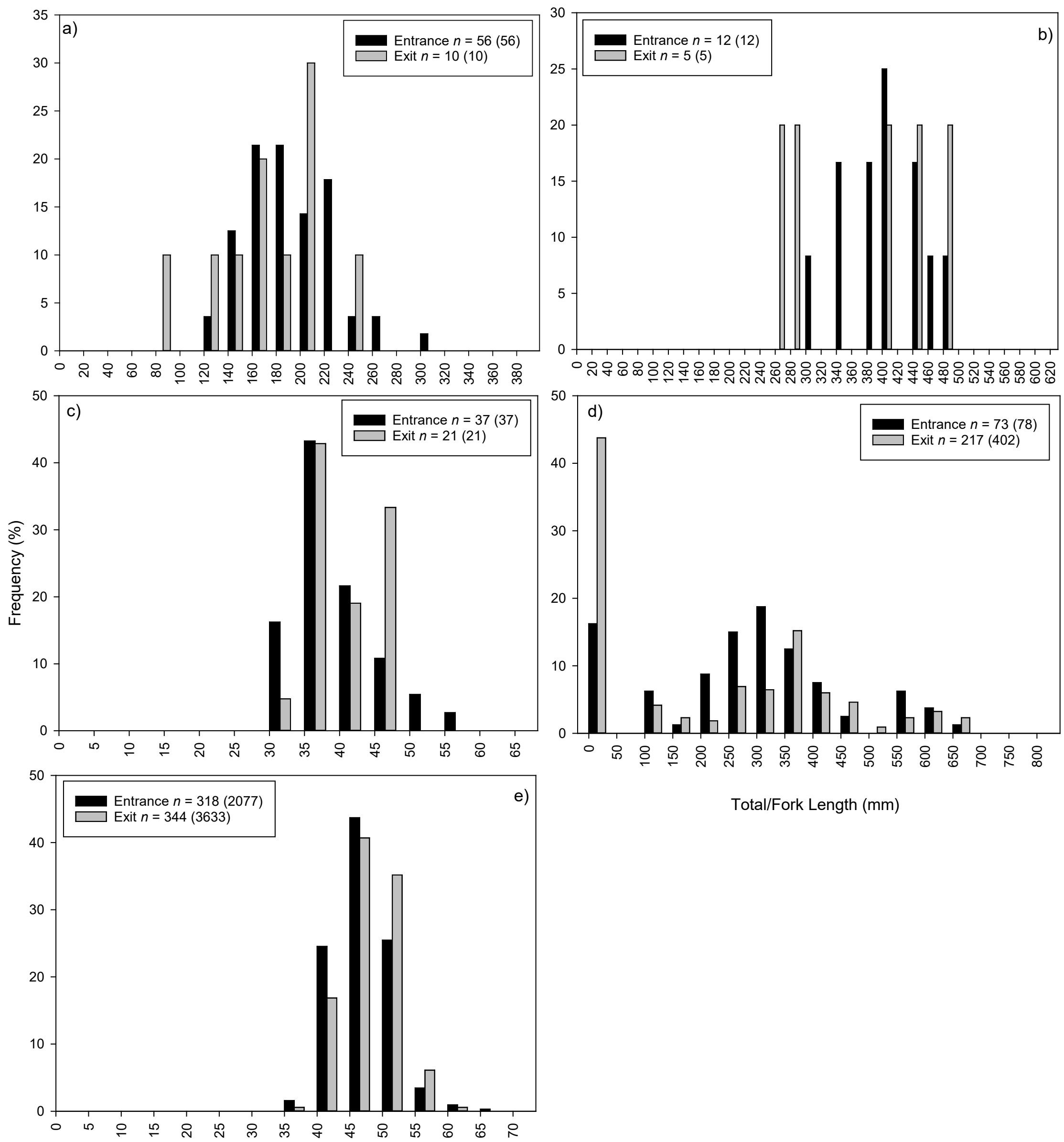


Figure 7. Length-frequency distributions of a) bony herring, b) golden perch, c) carp gudgeon, d) common carp and e) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of the Sawmill Creek Regulator vertical-slot fishway. Sample sizes represent the number of fish measured for length and those in brackets represent the total number of fish sampled for each species. Note: plots have varying axis scaling.

The Splash

At The Splash vertical-slot fishway, a total of 3,573 fish from nine species were sampled from entrance trapping, and 4,414 fish from seven species from exit trapping (Table 1). Carp gudgeon (n = 22), Murray rainbowfish (n = 4) and pouched lamprey (*Geotria australis*) (n = 1) were only sampled at the entrance of the fishway, whilst silver perch (n = 5) were exclusively sampled from the exit. PERMANOVA indicated there was a significant difference in fish assemblages among entrance and exit trap samples (*Pseudo*-$F_{1,\ 13}$ = 3.3767, p = 0.016). This was supported by MDS ordinations of fish assemblage data, which exhibited a strong dispersion of samples by trap type (Figure 7). SIMPER suggested that the fish assemblages differed between entrance and exit sampling primarily due to high abundances of Australian smelt sampled at the entrance, and common carp at the exit.

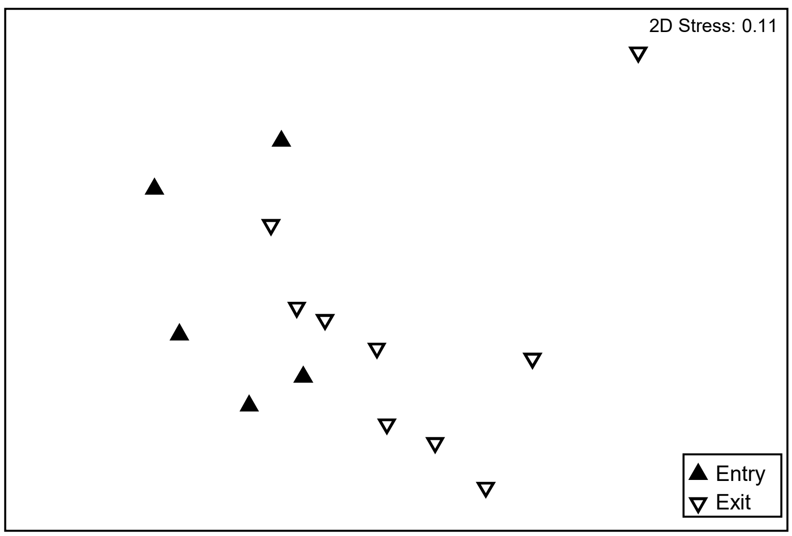


Figure 8. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at The Splash Regulator.

Relative abundances of common carp (*Pseudo*-$F_{1,\ 13}$ = 5.3135, p = 0.045) and golden perch (*Pseudo*-$F_{1,\ 13}$ = 10.069, p = 0.007) were statistically different between entrance and exit trapping. Higher abundances of both species were sampled at the exit (Figure 8). The abundances of bony herring (*Pseudo*-$F_{1,\ 13}$ = 0.087, p = 0.772), Australian smelt (*Pseudo*-$F_{1,\ 13}$ = 2.67, p = 0.148) and unspecked hardyhead (*Pseudo*-$F_{1,\ 13}$ = 0.012, p = 0.915) were not significantly different between entrance and exit samples (Figure 8).

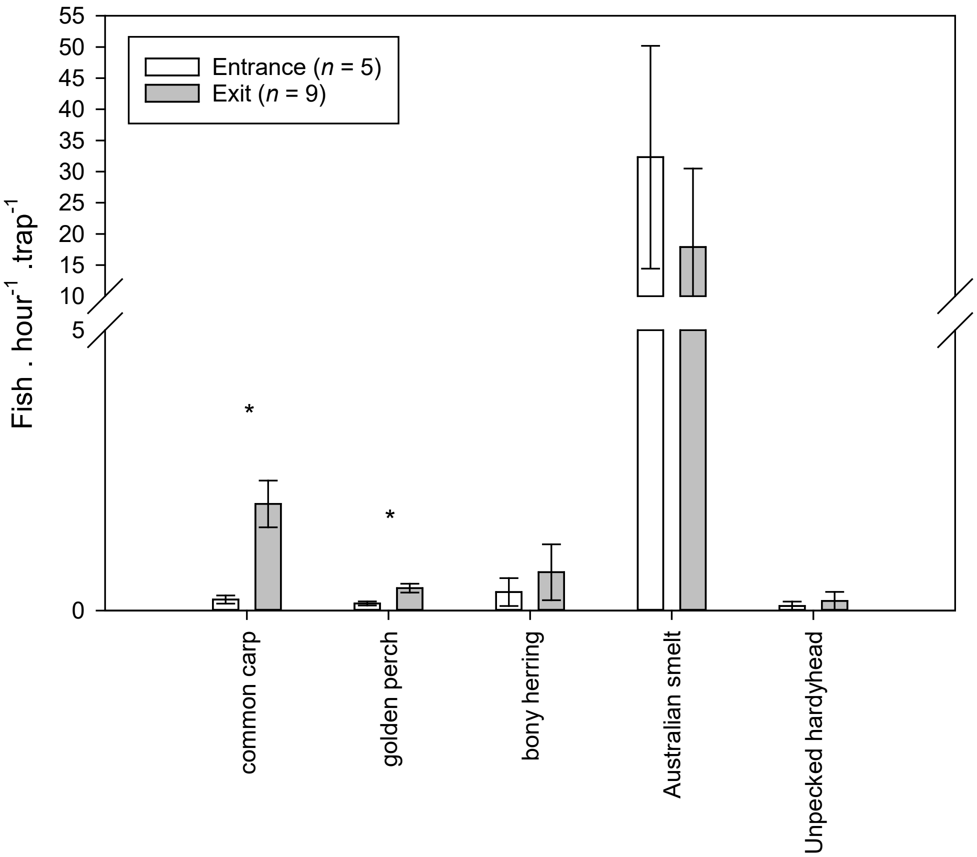


Figure 9. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of The Splash Regulator vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by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

Fish sampled at the entrance of The Splash fishway ranged from 23–626 mm in length, whilst those sampled at the exit ranged from 18–704 mm in length (Figure 9). The length-frequency distributions for bony herring ($D_{34,\ 144} = 0.313$, $p < 0.009$) and Australian smelt ($D_{200,\ 257} = 0.134$, $p = 0.035$) were significantly different between the fishway entrance and exit. For bony herring, a greater proportion of individuals 40–79 mm FL were sampled from the entrance (35%) than the exit (8%), while for Australian smelt, distributions appeared similar, with the exception of slightly greater proportion of individuals 45-49 mm FL at the entrance (45%) than at the exit (32%) (Figure 9). All remaining species were sampled in too fewer numbers to enable statistical comparison. Nonetheless, as per the Sawmill Creek fishway, common carp <50 mm FL were more numerous at the fishway exit (Figure 9).

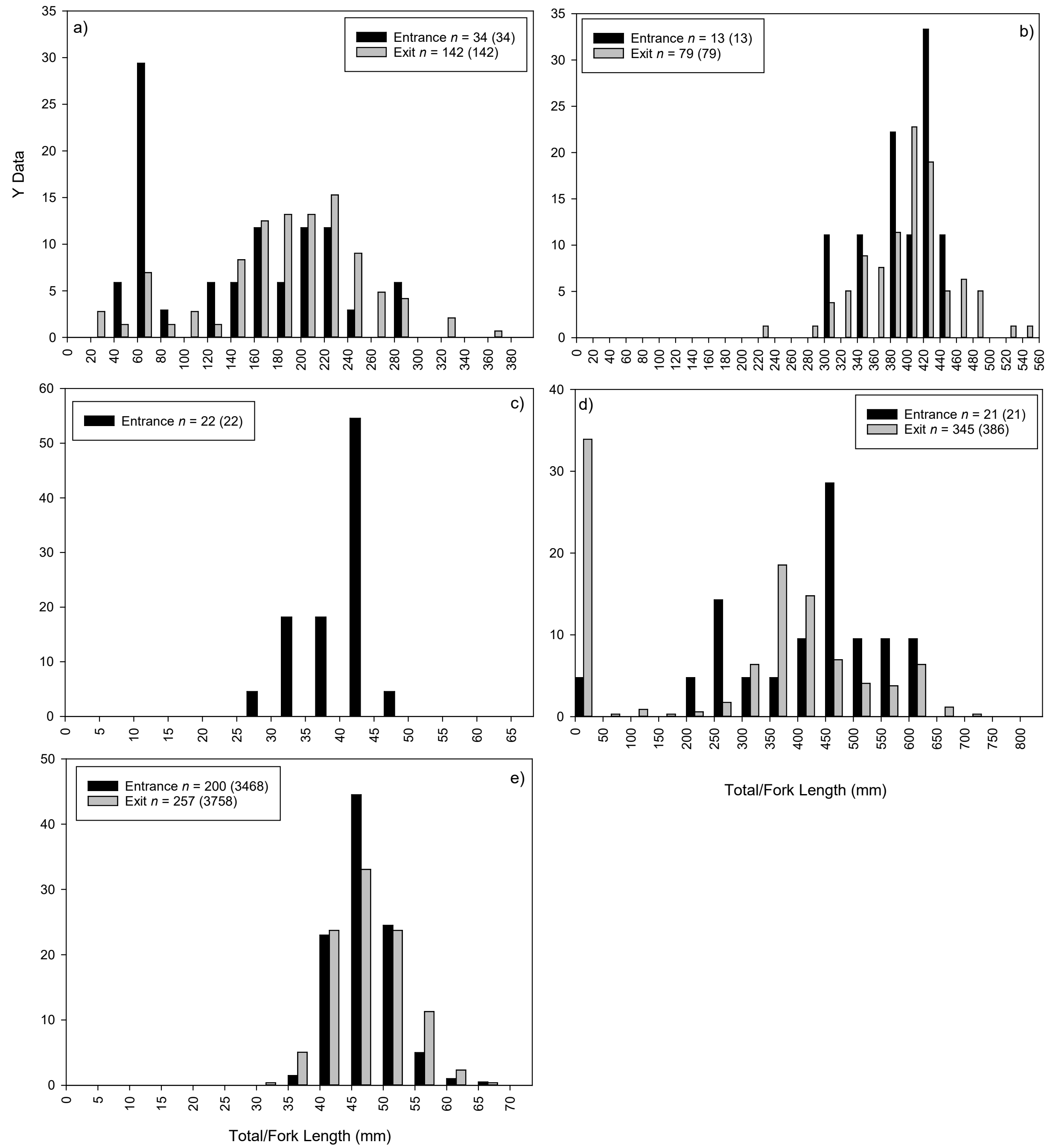


Figure 10. Length-frequency distributions of a) bony herring, b) golden perch, c) carp gudgeon, d) common carp and e) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of The Splash Regulator vertical-slot fishway. Sample sizes represent the number of fish measured for length,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

Comparison of medium- and large-bodied fish migration among fishways

At the Lock 4 vertical-slot fishway, a total of 3,243 fish from six medium- and large-bodied species (length range 163–1030 mm) were sampled from exit trapping (Table 1). This compared to 424 individuals from six species at the Sawmill Creek exit and 619 individuals from five species at the Splash exit (Table 1). Golden perch, silver perch, bony herring, common carp and goldfish (*Carassius auratus*) were collected at all fishway exits, while Murray cod (*Maccullochella peelii*) were only sampled at Lock 4 and redfin perch only at Sawmill Creek. (Table 1).

Relative abundance of golden perch ($Pseudo\text{-}F_{2,\,28}$ = 96.859, p = 0.001) was significantly greater at Lock 4 than at Sawmill and The Splash, while abundances of common carp ($Pseudo\text{-}F_{2,\,28}$ = 0.294, p = 0.754), bony herring ($Pseudo\text{-}F_{2,\,28}$ = 2.308, p = 0.097) and silver perch ($Pseudo\text{-}F_{2,\,28}$ = 0.783, p = 0.456) were not significantly different among fishways (Figure 11).

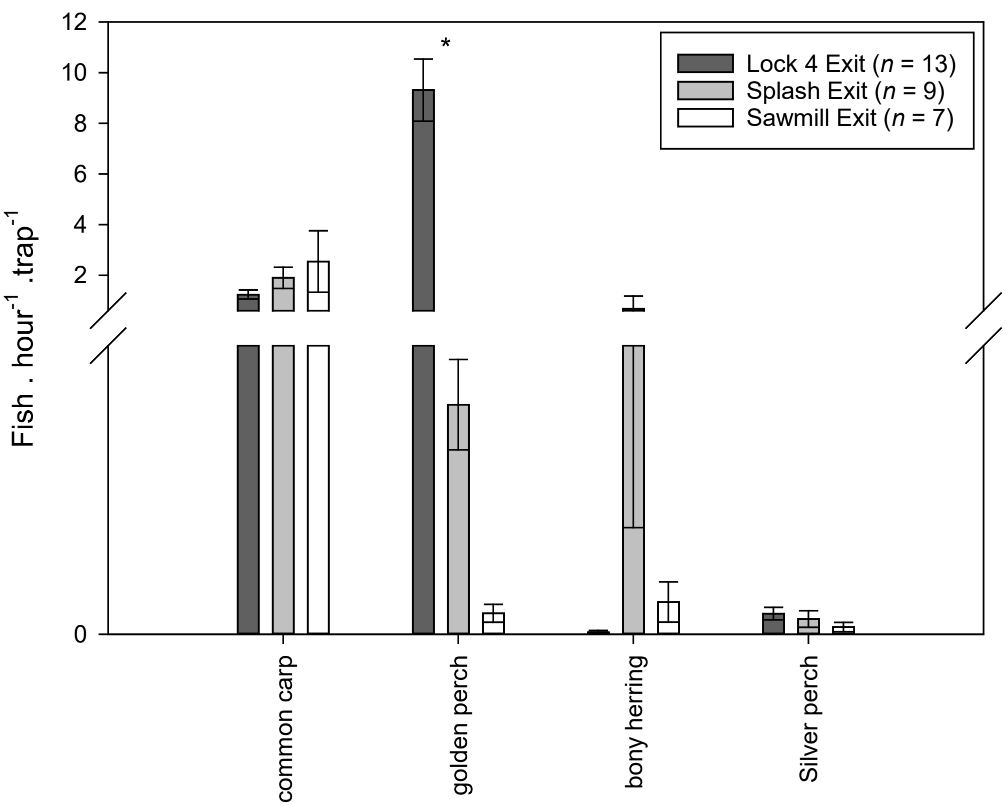


Figure 11. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the medium- and large-bodied species sampled at the exits of the Sawmill Creek (open bar), The Splash (light shaded bar) and Lock 4 (dark shaded bar) vertical-slot fishways. Significant differences between exit abundance are indicated by asterisks.

4. DISCUSSION

The restoration of hydrological and biological connectivity through the removal of barriers to movement and construction of fishways was a central focus of management interventions at Katarapko under RRP and SARFIIP. This included the construction of four vertical-slot fishways within the system; firstly on Eckert's Creek at Bank J and Log Crossing, and secondly on large flow regulating structures at Sawmill Creek and The Splash. Fundamental to fishway construction programs is assessment of passage efficiency against design criteria. The specific objective of the current study was to sample the entrances and exits of Sawmill Creek and The Splash Regulator fishways to evaluate passage efficiency, regarding the abundance and size classes of fish species able to successfully ascend. Additionally, we aimed to compare the movement of medium- and large-bodied species through these fishways to that through the Lock 4 vertical-slot fishway on the adjacent main channel of the River Murray.

4.1. Fishway use and passage efficiency

Sawmill Creek

A total of ten species were sampled from the Sawmill Creek fishway, comprising the majority (56%) of species previously detected in the system and expected to use the fishway during Spring (Fredberg and Bice 2018, Fredberg et al. 2022). Species not recorded were those either typically uncommon at the site (e.g. Murray cod) or not commonly encountered in fishways in the lower River Murray (e.g. freshwater catfish *Tandanus tandanus* and dwarf flat-headed gudgeon *Philypnodon macrostomus*) (Fredberg and Bice 2018, Fredberg et al. 2022).

Fish assemblage structure was similar between the entrance and exit of the Sawmill Creek fishway. Species-specific comparisons of abundance data, however, suggested unspecked hardyhead was more abundant at the fishway entrance. Unspecked hardyhead, a small-bodied native species (adult length typically <60 mm TL), exhibits poor swimming ability when compared to larger species, and low abundance at the exit may indicate obstruction of passage for this species. Significantly greater abundances of common carp were detected at the exit than at the entrance of the Sawmill Creek fishway. Interrogation of length-frequency distributions indicates that this discrepancy was due to greater abundances of individuals <50 mm FL, most of which ranged from just 12–20 mm FL. These individuals are likely to have poor swimming ability and as such, this result is unlikely to be indicative of high passage efficiency for fish <20 mm FL. Rather it is suspected that many of these small individuals may have entered the trap from an upstream direction (e.g. via mesh). Managed and natural floodplain inundation commonly promote recruitment of common carp, and young or year (YOY) were highly abundant in upstream habitats at Katarapko during fishway sampling. Alternatively, for Australian smelt, the most numerous species sampled at the Sawmill Creek fishway, abundance was similar at the entrance and exit. This is also a small-bodied species, albeit one with relatively strong swimming ability (Kilsby and Walker 2010); these results suggest the fishway is effectively passing this species.

For the species that were sampled in adequate numbers to allow comparisons of length distributions between entrance and exit samples, only common carp and Australian smelt exhibited statistically significant differences. As above, differences for common carp appear related to incidental capture of high abundances of YOY <20 mm FL in the exit trap and are unlikely to reflect influence of length on successful passage. For Australian smelt, differences were driven by slightly greater proportions of fish 40–44 mm FL at the entrance (26%) than at the exit (19%). Whilst statistically significant, this difference is unlikely to be ecologically significant or reflective of substantial obstruction of passage.

The vertical-slot fishway on the Sawmill Creek Regulator appears to be functioning to biological design objectives. The fishway is attracting and passing a diversity of species and a large range of sizes under the conditions at which the fishway was assessed. These were characterised by head differential of 0.64–1.38 m, and a pool turbulence of <35 $W.m^{-3}$. This pool turbulence is common with other fishways in the MDB that have sought to pass 'fish assemblages' (Stuart et al. 2008, Baumgartner et al. 2014). The passage of most small-bodied fishes, and notably the most abundant species present, Australian smelt, was facilitated. The exception was the unspecked hardyhead; passage efficiency for this species is commonly poor, even at structures when small-bodied fish passage is a priority (e.g. Fredberg and Bice 2018). This result and other studies suggest that effectively passing high proportions of small-bodied species such as unspecked hardyhead and carp gudgeon, at large regulating structures, may be a limitation of the vertical-slot design.

The Splash

A total of nine species were sampled from The Splash fishway, which comprises half (50%) of species previously detected in the system (Fredberg et al. 2022) and expected to use the fishway during spring (Fredberg and Bice 2018). Notably, a pouched lamprey (470 mm TL) was detected within this fishway. This is the first record of this species using a fishway in Katarapko and is an encouraging result given it is not commonly found in the lower River Murray.

Fish assemblages were significantly different between the entrance and exit of The Splash fishway, with this difference driven by high abundances of Australian smelt sampled at the entrance, and common carp at the exit. Nonetheless, species-specific comparison of abundance between entrance and exit samples suggested no significant difference for Australian smelt, unspecked hardyhead and bony herring. For the two most abundant large-bodied species sampled – golden perch and common carp – abundance was significantly greater at the exit than the entrance. Similar to the Sawmill Creek fishway, the disparity for common carp was due to greater abundances of individuals <50 mm FL, most of which ranged from just 18–30 mm FL, at the exit. This was likely due to movement from upstream and incidental entrapment rather than a pattern in passage efficiency. For golden perch, however, greater abundance at the exit may be the result of entrance trap 'shyness' caused by the trap being visible to fish entering the fishway. Similar patterns of greater exit abundance have been observed during trapping of other floodplain regulator fishways in the Riverland region (Bice et al. 2016, Fredberg and Bice 2018, Fredberg et al. 2020).

Fish sampled from the entrance of The Splash vertical-slot fishway ranged 23–626 mm in length, while those from the exit ranged 18–704 mm in length. The length-frequency distributions for bony herring and Australian smelt were significantly different between the fishway entrance and exit with greater proportions of individuals 40–79 mm FL and 45–49 mm TL sampled at the entrance, respectively. Despite differences in length-frequency distributions for bony herring, the species was more abundant from exit trapping, suggesting ecologically significant obstruction of passage based on length is unlikely. Similarly, for Australian smelt, whilst statistically significant, differences in length-distribution were related to mid-sized individuals, while individuals <40 mm FL were sampled in similar proportions. For the remaining species that were sampled from both the entrance and exit, statistical analysis was not performed due to limited sample sizes, yet length-frequency distributions appeared similar. Carp gudgeon, however, were only collected from the entrance of the fishway and not the exit, suggesting passage was likely obstructed. Laboratory trials indicate carp gudgeon exhibit swimming ability among the poorest of all small-bodied fishes native to the MDB (Bice 2004, Kilsby and Walker 2010).

The vertical-slot fishway at The Splash Regulator is likely functioning to biological design criteria. The fishway has attracted and passed a diversity of species and a large range of sizes under high tailwater conditions and a high-level inundation (up to a head differential of ~1.95 m).

4.2. Comparison of movement through Sawmill Creek, The Splash and Lock 4 fishways

Fish passing through fishways at Katarapko or the River Murray (Lock 4) may be undertaking small-scale movements for purposes of feeding and dispersal or may be undertaking larger-scale longitudinal movements that may influence life history processes (e.g. spawning). In an effort to understand differences in absolute movement of medium- and large-bodied species via these different pathways, we compared abundances from exit trap samples across all fishways. Golden perch, silver perch, bony herring, common carp and goldfish were sampled from all three fishways exits, while Murray cod were only sampled from Lock 4 and redfin perch only from Sawmill Creek. Golden perch abundance was significantly greater at Lock 4, while for remaining species sampled in adequate numbers – bony herring, common carp and silver perch – abundances were not significantly different among fishways.

Differences among movement pathways for golden perch and common carp likely relate to differences in life history. The migratory tendencies of golden perch are well known (Koehn et al. 2020), with adult movements in the lower River Murray typically characterised by uni-directional upstream migrations, peaking in frequency in spring, without return (Zampatti et al. 2018, Bice et al. 2021). Additionally, the species is pelagophilic, with spawning occurring mostly in riverine environments. Alternatively, common carp favor inundated floodplains, when available, for spawning and nursery habitats.

The results of the current study suggest that in the vicinity of Lock 4, the bulk of upstream movement in spring 2021 was occurring via the main river channel rather than via Katarapko; this result is not unexpected given the much greater discharge, and putatively attraction, occurring in the river channel relative to Katarapko. For common carp, attraction to water flowing off the Katarapko Floodplain likely resulted in similar numbers of fish being sampled at all three fishways, despite far greater discharge from Lock 4.

5. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to assess fish movement and passage efficiency at the newly constructed Sawmill Creek and The Splash fishways. Our study has shown these fishways facilitated the passage of the majority of species likely to undertake movements between the River Murray and Katarapko. The fishways facilitated effective passage for the most abundant species sampled (i.e. Australian smelt), including small individuals (i.e. 30–50 mm), as well as several medium- to large-bodied species. This suggests that the design of these fishways was appropriate in achieving passage objectives for a range of target species and lengths (30–800 mm) under conditions of elevated river flows and a high-level managed inundation.

Passage efficiency – the ability for fish to ascend a fishway once the entrance was located – was a focus of the current assessment with little consideration of attraction efficiency. Attraction efficiency is the proportion of individuals attempting to migrate that are subsequently able to locate and enter the fishway. Attraction efficiency has commonly not been assessed in Australian fishway studies and typically comprises targeted investigations using telemetry (acoustic or radio) or mark-recapture techniques. This remains a key gap in fishway assessments and could inform future fishway and regulator designs.

Based on the results of this study, no specific changes to the fishway or operation are suggested. Nonetheless, we provide the following recommendations;

- Monitoring of the Sawmill Creek and Splash vertical-slot fishways, at differing inundation heights will provide greater information on fish passage during a range of scenarios;
- Assessment of attraction efficiency at these and other fishways in the lower River Murray would better inform on overall effectiveness of fish passage. This remains a knowledge gap for many fishways in the southern MDB and could inform future structure design and operation; and
- Future operation of these fishways should closely follow guidance in the detailed design report (GHD 2018) to optimise fishway and regulator gate settings to maximise attraction and passage.

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