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Assessment of passage efficiency at the Tanyaca Creek and Pike River regulator fishways

C. M. Bice and J. Fredberg

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EXECUTIVE SUMMARY

The Pike Anabranch system bypasses Lock and Weir no. 5 on the lower River Murray. The *South Australia Riverland Floodplains Integrated Infrastructure Program* (SARFIIP), completed in 2020, involved a series of on-ground works to ultimately promote a hydrological regime at the Pike Anabranch that includes: 1) improved connectivity and extension of flowing water ('lotic') habitats under normal operating conditions; and 2) increased frequency of floodplain inundation owing to managed inundation events. The program included construction of substantial regulating structures and associated vertical-slot fishways on Tanyaca Creek and the Pike River.

The Tanyaca Creek and the Pike River fishways aim to provide passage for fish with a wide range of lengths (30–800 mm) and are designed to produce maximum pool turbulence of ≤30 $W.m^{-3}$ across a range of head differentials. As such, both incorporate key-hole slots (250 x 500 mm and 140 x 1000 mm) to promote benign internal hydraulics yet capacity for large-bodied fish passage and have multiple exits to cater for varying headwater levels and head differentials. The Tanyaca Creek fishway, however, is longer than the Pike River fishway and incorporates an additional exit gate. As such, it has a greater operational range within which target turbulence can be maintained.

The current study aimed to sample the entrances and exits of the newly constructed Tanyaca and Pike vertical-slot fishways, as well as the existing adjacent Lock 5 vertical-slot fishway 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 December 2020 and February 2021, a total of 16 paired-day trapping events were undertaken at the entrances and exits of the three fishways. December sampling coincided with a low-level managed inundation, resulting in head differentials and maximum pool turbulence of 1.7–1.8 m and 24–25 $W.m^{-3}$ at the Tanyaca Creek fishway and 1.6–1.8 m and 25–38 $W.m^{-3}$ at the Pike River fishway. During February 2021, trapping occurred during 'normal operating conditions' and head differential was ~1.3 m HD at both fishways, with estimated maximum turbulence of ~25 and 21 $W.m^{-3}$ at the Tanyaca and Pike fishways, respectively.

At the Tanyaca Creek vertical-slot fishway, a total of 5,143 fish from 10 species was sampled at the entrance and 5,125 fish from 10 species at the exit. For the most common species, Australian smelt (*Retropinna semoni*, 88% of catch), abundances were similar between entrance and exit

trapping events. Alternatively, common carp (*Cyprinus carpio*), golden perch (*Macquaria ambigua*) and bony herring (*Nematalosa erebi*) were significantly more abundant at the fishway exit and carp gudgeon (*Hypseleotris* spp.) significantly more abundant at the fishway entrance. Fish sampled at the entrance ranged 17–620 mm (fork length (FL) or total length (TL), depending on tail morphology), whilst those that successfully ascended the fishway ranged 24–720 mm in length. Length frequency distributions were generally similar between entrance and exit trapping, excepting that for Australian smelt, which indicated a small but significantly greater proportion of individuals <40 mm FL at the entrance than at the exit. For the conditions experienced (head differential range = 1.3–1.8 m), the Tanyaca Creek fishway was considered to be meeting its design objectives of passing fish 30–800 mm in length.

At the Pike River vertical-slot fishway, a total of 987 fish from nine species was sampled at the entrance and 668 fish from nine species at the exit. For the most abundant species sampled, bony herring (50% of catch) and Australian smelt (35% of catch), no significant difference in abundance was detected between entrance and exit trapping events. Fish sampled at the entrance ranged 17–640 mm in length, whilst those that successfully ascended the fishway ranged 27–710 mm in length. For most species, length distributions were statistically similar between the entrance and exit. The one exception was bony herring, for which a significantly greater proportion of individuals <80 mm FL were sampled from the entrance. This result was unexpected given the generally strong swimming ability of this species and may be an artefact of sampling. Generally, for the conditions experienced (head differential range = 1.3–1.8 m), the Pike River fishway was considered to be meeting its design objectives of passing fish 30–800 mm in length. Nonetheless, this fishway may, during events of maximum level inundation in the Pike system, operate at head differentials from 1.8–2.6 m. At these head differentials, internal hydraulics favourable to small-bodied fish passage (e.g. <30 $W.m^{-3}$) cannot be maintained and passage will likely be impeded.

At the Lock 5 vertical-slot fishway, a total of 355 fish from seven species was sampled at the entrance and 983 fish from four species at the exit. For the most abundant species sampled, golden perch (47% of catch), no significant difference was detected between abundances at the entrance and exit, whilst bony herring (28% of catch) were significantly more abundant at the exit. Two small-bodied species (adult length <100 mm TL), Australian smelt and unspecked hardyhead (*Craterocephalus fulvus*), were sampled from the entrance but not the exit. Fish that successfully ascended the Lock 5 fishway ranged 105–700 mm in length. This result was expected as this fishway was designed to facilitate passage of fish >100 mm in length.

In an effort to understand differences in upstream movement via different pathways (i.e. via the River Murray main channel or via the Pike 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 the small-bodied Australian smelt at Tanyaca Creek, and the large-bodied golden perch and silver perch (*Bidyanus bidyanus*) at Lock 5. The results of the current study suggest that in the vicinity of Lock 5, the bulk of upstream movement was occurring via the main river channel rather than via the Pike Anabranch; this result is not unexpected given the greater discharge and accompanying greater rheotactic cues for movement occurring in the river channel relative to the Pike Anabranch. Nonetheless, for common carp and bony herring, relative abundance was similar among fishways.

This study demonstrated that the Tanyaca Creek and Pike River vertical-slot fishways facilitated the passage of the majority of species likely to undertake movements between the River Murray and the Pike Anabranch during ‘normal operating conditions’ and during a low-level managed inundation. As such, no specific changes to the fishway or operation are suggested. Monitoring of these fishways at maximum inundation, however, would better inform on fish passage during a full range of operating scenarios. Future operation of the fishways should adhere to fishway performance tables in the SARFIIP Pike final design report to ensure attraction and passage are maximised.

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

1. INTRODUCTION

1.1. Background

The Pike Anabranch and associated floodplain spans an area of approximately 6,700 ha and is one of three large anabranch systems (Katarapko and Chowilla are the others) in the Riverland region of the South Australian Murray-Darling Basin (MDB). The Pike Anabranch bypasses Lock and Weir no. 5 (hereafter 'Lock'), generating a head differential of approximately 3.0 m between the inlets to the system and downstream confluence with the River Murray. As such, the Pike Anabranch system is comprised of a mosaic of aquatic habitats, including permanent fast-flowing and slow-flowing creeks. Flowing habitats are now rare in the main channel of the River Murray (Mallen-Cooper and Zampatti 2018). Subsequently, the Pike Anabranch supports 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. 2016a). Nonetheless, the system 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 the 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 the Pike Anabranch system 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. SARFIIP works at the Pike Anabranch were completed in 2020 and followed the Murray Futures Riverine Recovery Program (RRP), which included various in-channel remediation works in the system (e.g. upgrade on inlet regulators at Deep Creek and Margaret-Dowling Creek) (DEW 2011). Together, this infrastructure will be used to promote a hydrological regime at Pike and Katarapko that includes: 1) improved connectivity and extension of lotic habitats under normal operating conditions; and 2) more frequent floodplain inundation than would otherwise occur naturally under current conditions (i.e. current rates of water abstraction and environmental water availability).

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 MDB. In the Pike Anabranch under SARFIIP, new regulating structures were constructed on Tanyaca Creek and the Pike River in 2020 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 Tanyaca Creek and the Pike River fishways with comparison to concurrent catches from the existing vertical-slot fishway on Lock 5 on 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 Tanyaca Creek and the Pike River fishways, and the Lock 5 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 through the three fishways with regards to species composition and abundance; and

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

2. METHODS

2.1. Study site and fish fauna

The Pike Anabranch system is situated in the Riverland region of South Australia, between the townships of Paringa and Lyrup, and bypasses Lock 5 on the River Murray (Figure 1). Inflows to the system are regulated via Margaret-Dowling Creek and Deep Creek. In 2020, two further regulating structures were completed on the Pike River and Tanyaca Creek (Figure 1); these structures regulate outflow from the system and are critical in supporting managed floodplain inundation. Fishways incorporated on these structures represent the primary pathways for movement of fish into the upper Pike system from downstream.

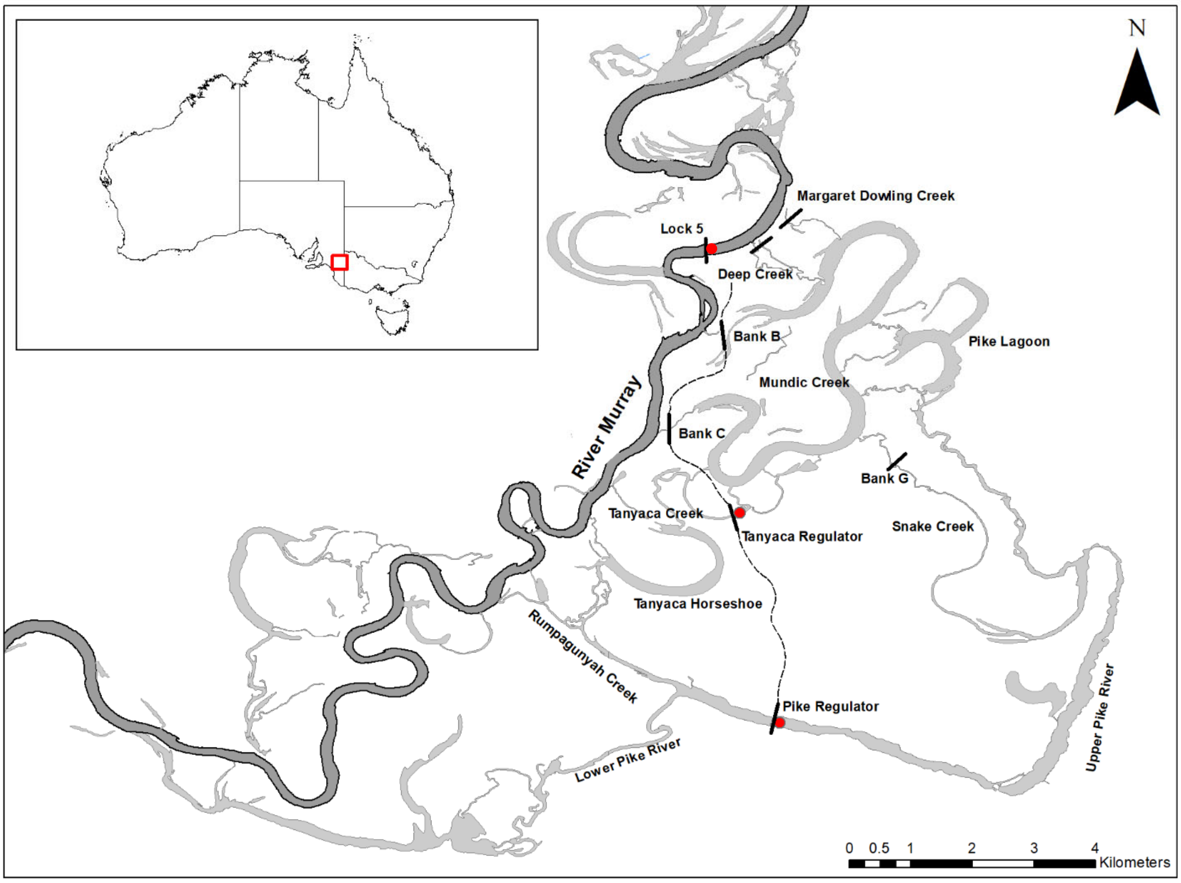

Figure 1. Map of the Pike Anabranch system and adjacent River Murray. Red circles indicate Lock 5 and the Pike River and Tanyaca Creek regulators, and associated vertical-slot fishways that were assessed as part of this study in 2020/21. The solid black lines also represent regulating structures found in the region, whilst the dashed black line represents the blocking bank that facilitates engineered floodplain inundation.

A total of 17 species of fish (12 native and 5 non-native) have been recorded from the Pike Anabranch (Fredberg and Bice 2021). In the context of the lower River Murray, this represents a diverse fish assemblage and includes species of conservation concern, namely Murray cod (*vulnerable* under the EPBC Act 1999), silver perch (*critically endangered* under the EPBC Act 1999) and freshwater catfish (*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). The specific detail of movements of many other species, particularly small-bodied fishes (adult length <100 mm), are less well understood, but several studies suggests both longitudinal and lateral movements are important (Baumgartner et al. 2008, Connallin et al. 2011). A large proportion of the species present in the lower River Murray are likely to attempt movements between the River Murray and Pike Anabranch system via regulators on the Pike River and Tanyaca Creek, comprising species with a range of different sizes, morphologies and swimming abilities.

2.2. Fishways

Tanyaca Creek and Pike River

The Tanyaca Creek and Pike River regulators are similar in design, with both regulators comprised of three bays and six, two-metre wide overshot lay-flat regulator gates that are designed to discharge between 0 $ML.day^{-1}$ (gates fully closed) and 3,000 $ML.day^{-1}$ (modelled flood flows) (DEW 2017). These regulators maintain a water level in the upper Pike system of 14.55 m AHD under normal operating conditions. Together with associated blocking banks, they can also be used to promote managed inundations upstream of up to 16.3 m AHD.

The vertical-slot fishways incorporated on the Tanyaca Creek and Pike River regulators were 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 (DEW 2017). As such, both fishways have sought to maintain, as far as practicable, maximum pool turbulence (energy dissipation factor, EDF) of 30 $W.m^{-3}$, which represents current best-practice design for passing Australian small-bodied fishes at vertical-slot fishways (O'Connor et al. 2015). This, however, is not the case for the Pike fishway under conditions of high head differential (see below).

The Tanyaca Creek fishway is incorporated on the northern abutment of the regulator and consists of 21 baffles and 20 pools (3 m x 2 m, with larger 'turning pools') (Figure 2). The fishway has a sloped concrete floor with a hydraulic gradient of 1:25.6 and was designed to operate at headwater levels from 14.25–16.30 m AHD with a maximum head differential of 2.55 m. This head differential represents the maximum likely to be experienced during a maximum level managed inundation (i.e. 16.30 m AHD). The Tanyaca Creek fishway consists of common entrance and exit baffles, but the length of the fishway is governed by three internal exit gates that operate under different head differentials and headwater levels (potential headwater ranges: exit 1 = 14.25–16.40 m AHD; exit 2 = 14.50–16.40 m AHD; and exit 3 = 15.00–16.40 m AHD). As such, maximum pool turbulence of ≤30 $W.m^{-3}$, can be maintained throughout the range of head differentials likely to be experienced. Aluminum inserts provide a 'key-hole' baffle, a wide lower slot of 250 mm wide x 500 mm high and a narrow lower slot of 140 mm wide x 1000 mm high, separated by a block-out section of 250 mm high. These key-hole slots are provided to produce internal hydraulics favourable for small-bodied fish (i.e. 140 mm slot), but also capacity for large-bodied fish to pass (i.e. 250 mm slot).

The Pike River fishway is incorporated on the southern abutment and consists of 14 baffles and 13 pools (3 m x 2 m with larger 'turning pools') (Figure 2). The fishway has a sloped concrete floor with hydraulic gradients of 1:23.6 and was designed to operate at headwater levels from 13.50–16.40 m AHD. The Pike River fishway consists of common entrance and exit baffles, but the length of the fishway is governed by two internal exit gates that operate under different headwater levels (potential headwater ranges: exit 1 = 13.50–16.40 m AHD; and exit 2 = 14.00–16.40 m AHD). A maximum head differential of ~2.55 m may be experienced at the structure during maximum level managed inundations (i.e. 16.30 m AHD). Nonetheless, during the design phase, a compromise in function was made for this fishway, whereby it consisted of fewer pools than at Tanyaca, and thus only maintains maximum pool turbulence <30 $W.m^{-3}$ up to a head differential of 1.64 m. At head differential >1.64 m, maximum pool turbulence increases and conditions become increasingly unfavourable for the passage of small-bodied fish. The Pike River fishway incorporates the same aluminum inserts and keyhole vertical-slots as the Tanyaca Creek fishway.

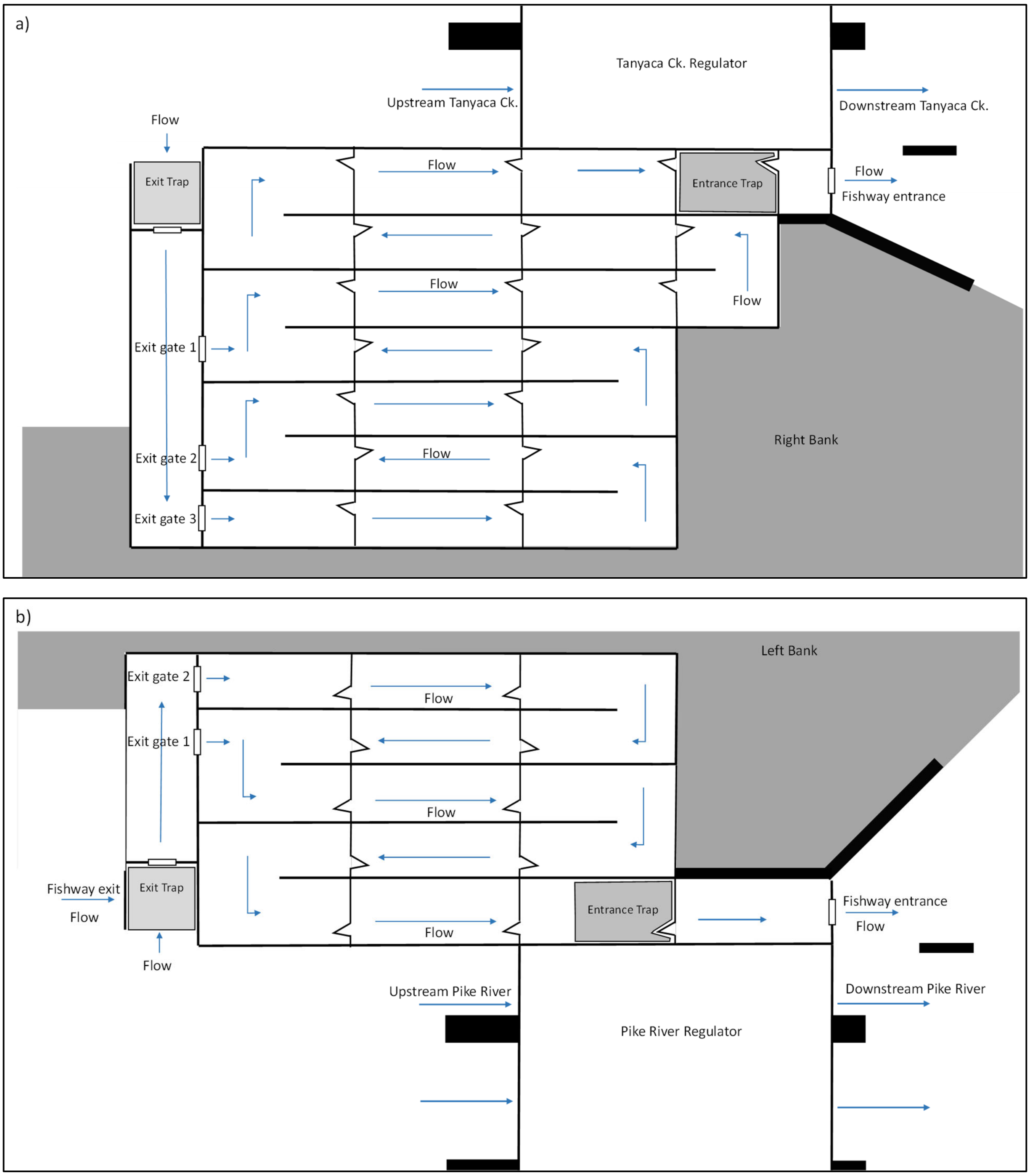

Figure 2. Schematic of the a) Tanyaca Creek and b) Pike River vertical-slot fishways. The location of fishway traps for both entrance and exit trapping events are indicated on both fishways.

Lock 5

The weir component of Lock and Weir No. 5 on the River Murray comprises of 12 bays, and 'stoplogs' are used to regulate discharge. A vertical-slot fishway and fish lock are incorporated on the northern bank of the weir. The was designed to pass fish ranging from ~100-1000 mm in length, while an 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 12, and consists of 22 baffles and 21 pools with the majority of pools being 3 m long and 2 m wide, and a number of larger resting pools measuring 3 m long and 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 hydraulic gradient of 1:23 (Baumgartner *et al.* 2014). The greatest operational head differential is 3.13 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).

2.3. Fishway sampling

Fish were sampled from entrances and exits of the Tanyaca Creek, Pike River and Lock 5 fishways over 16 nights from 1–11 December, 2020 and 2–12 February, 2021. Sampling in December coincided with a low-level (15.25 m AHD at the Pike River Regulator) engineered inundation of the Pike floodplain, while February sampling coincided with 'normal operating conditions' (headwater 14.55 m AHD at the Pike River Regulator). Entrance and exit trapping allows comparison of species, abundance and size range of fish attempting to ascend (entrance) with those that successfully ascend (exit) the fishway. The entrance and the exits of each fishway were sampled for a total of 8 sampling events with traps set overnight (~24 hours) during each event.

The entrance and exit traps at both the Tanyaca Creek and Pike River 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 to ensure fish >25 mm in length are retained in the trap. The entrance and exit traps for the Tanyaca Creek and Pike River fishways were designed to fit within the concrete channel of the entrance and exit of the fishways, respectively. Entrance traps incorporated a single 'cone-shaped' entrance funnel (250 mm wide x 1000 mm high) with both the Tanyaca and Pike traps having the overall dimensions of 1950 mm width, 2490 mm length and 1500 mm height. Exit traps also incorporated a single 'cone-shaped' entrance funnel (250 mm wide x 1150 mm high) with both fishway traps having the overall dimensions of 1900 mm width, 1800 mm length and 1950 mm height. The Lock 5 entrance and exit traps (2.5 m height x 1.2 m long x 1.7 m wide and 1.5 x 1.7 x 1.8 m, respectively) were 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) 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. Total headloss (the difference between the upstream and downstream water surface level) across the fishway, and headloss across the entrance and exit baffles were measured daily.

2.4. Data Analysis

For each fishway, 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 two-factor (trap position and month, i.e. December and February) PERMANOVA (Permutational Multivariate Analysis of Variance) ($\alpha = 0.05$). 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). 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 (i.e. cumulative number of fish sampled >200) 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. Fish relative abundance data were fourth-root transformed prior to all analyses.

The length 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 at individual fishways to determine any size-related obstruction of passage. 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 December 2020 and February 2021, flow at the South Australian border (QSA) ranged 13,327–16,945 $ML.d^{-1}$ and 8,308–8,429 $ML.d^{-1}$, respectively. Mean discharge at Lock 5 was 14,292 $ML.d^{-1}$ during December sampling and 6,548 $ML.d^{-1}$ during February sampling. Mean discharge at the Tanyaca Creek and Pike River regulators during December sampling was 545 and 804 $ML.d^{-1}$ and in February 372 and 474 $ML.d^{-1}$, respectively.

Total headloss across the Lock 5 weir ranged 2.79–2.89 m in December and 2.88 – 2.89 m February. At the Tanyaca Creek and Pike River regulators, headloss was more variable due to the managed inundation during December sampling and normal operating conditions in February. At both fishways, headloss was greater in December (>1.6 m; Table 1). At the Pike River fishway, during both December and February, exit gate 2 was in operation (this gate provides the lowest maximum pool turbulence for this fishway), and when coupled with lower headloss in February, resulted in lower pool turbulence (~21 $W.m^{-3}$) than during the December trapping events (25–38 $W.m^{-3}$). At the Tanyaca Creek fishway, exit gate 2 was in operation during December and exit gate 1 was in operation in February when headloss was reduced. This resulted in similar pool turbulence during both trapping events (24–25 $W.m^{-3}$).

Table 1. Details of fishway hydraulics during December 2020 and February 2021 sampling events. Metrics include overall head differential (m), exit gate configuration, calculated flow ($ML.day^{-1}$), calculated maximum pool turbulence ($W.m^{-3}$), minimum pool depth (m) and calculated maximum average slot velocity ($m.s^{-1}$).

Sampling event	Head differential	Exit gate no.	Calculated flow	Calculated max pool turbulence	Calculated minimum pool depth	Calculated maximum average slot velocity
Pike fishway						
December	1.60–1.79	2	16.7–21.3	25.3–38.3	1.43–1.59	0.99-1.16
February	1.28–1.32	2	12.2–12.5	21.3–21.9	1.14–1.16	1.03
Tanyaca fishway						
December	1.69–1.79	2	15.5–17.1	24.0–24.8	1.37–1.51	0.97–0.99
February	1.30–1.34	1	14.8–15.9	24.6–25.3	1.07–1.15	1.05

3.2. Catch summary

A total of 13,231 fish from 12 species were sampled from the Tanyaca Creek, Pike River and Lock 5 fishways (Table 2). The overall catch was dominated by the native small-bodied Australian smelt (~73%) and medium-bodied bony herring (~14%), with smaller contributions from the native large-bodied species golden perch (5%) and non-native common carp (3%). The remaining eight species collectively comprised ~4% of the total catch (Table 1).

Table 2. Species, total number and length range of fish sampled from the entrance and exit of the vertical-slot fishways at Tanyaca Creek, Pike River and Lock 5 during assessment in December and February 2020/21.

		Tanyaca Creek Vertical-Slot			**Pike River Vertical Slot**			**Lock 5 Vertical-Slot**			**Total**
Common name	**Scientific name**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	
	Sampling events	8	8		8	8		8	8		
	No. of species	10	10		9	9		7	4		
Native Species											
Golden perch	*Macquaria ambigua*	5	42	269–454	14	60	294–570	127	487	264–480	**735**
Silver perch	*Bidyanus bidyanus*	4	12	103–172	0	6	131–414	16	39	123–408	**77**
Murray cod	*Maccullochella peelii*	0	0	-	0	1	244	0	0	-	**1**
Bony herring	*Nematalosa erebi*	138	539	42–365	580	248	41–385	15	353	100–393	**1,873**
Unspecked hardyhead	*Craterocephalus fulvus*	168	17	26–59	4	1	45–56	1	0	52	**191**
Australian smelt	*Retropinna semoni*	4,665	4,332	30–64	350	231	27–93	93	0	30–46	**9,671**
Carp gudgeon	*Hypseleotris spp.*	127	1	20–47	12	1	17–27	0	0	-	**141**
Murray rainbowfish	*Melanotaenia fluviatilis*	7	111	50–57	4	3	55–64	0	0	-	**125**
Flat-headed gudgeon	*Philypnodon grandiceps*	5	2	17–32	1	0	24	0	0	-	**8**
Non-native species											
Common carp	*Cyprinus carpio*	20	68	54–720	31	117	123–710	102	64	96–700	**402**
Goldfish	*Carassius auratus*	4	1	76–236	0	0	-	1	0	72	**6**
Eastern gambusia	*Gambusia holbrooki*	0	0	-	1	0	26	0	0	-	**1**
	Total	**5,143**	**5,125**		**997**	**668**		**355**	**943**		**13,231**

3.3. Passage efficiency

Tanyaca Creek

At the Tanyaca Creek vertical-slot fishway, a total of 5,143 fish from ten species were sampled from entrance trapping, and 5,125 fish from ten species from exit trapping (Table 1). All ten species sampled at the entrance were also sampled at the exit of the fishway. PERMANOVA indicated there was a significant difference in fish assemblages among entrance and exit trap samples ($Pseudo\text{-}F_{1,\ 15}$ = 5.78, p = 0.002) and between December and February sampling ($Pseudo\text{-}F_{1,\ 15}$ = 7.15, p < 0.001). There was no significant interaction between trap location and month ($Pseudo\text{-}F_{1,\ 15}$ = 1.85, p = 0.10), suggesting temporal differences were consistent for both entrance and exit trapping events. MDS ordination supported this result with fish assemblage data exhibiting dispersion of samples based on trap location (Figure 3a) and month (Figure 3b). SIMPER suggested differences among entrance and exit samples was driven by greater abundance of unspecked hardyhead and carp gudgeon at the entrance, and greater abundance of bony herring from the exit. Differences among months were driven by greater abundance of unspecked hardyhead, carp gudgeon, bony herring and Australian smelt in December 2020 than February 2021.

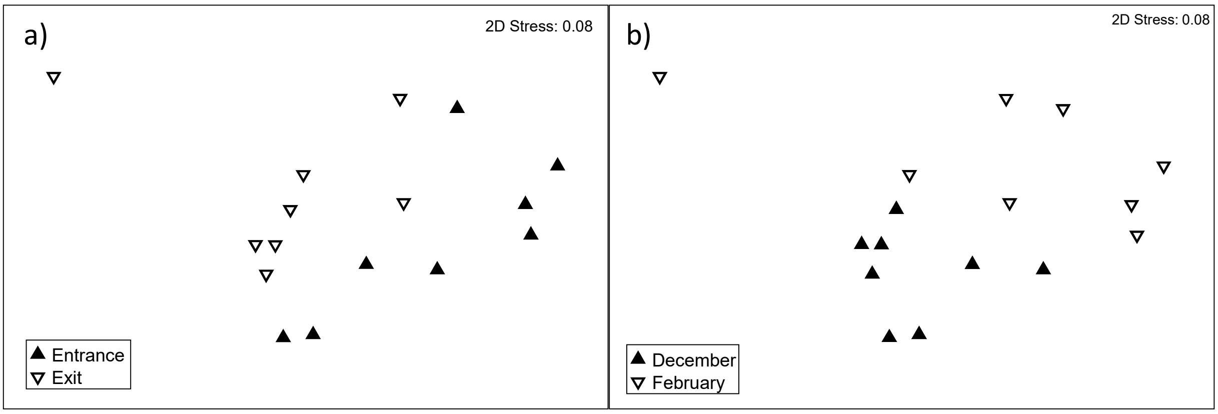

Figure 3. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at the Tanyaca Creek Regulator.

For the most common species, relative abundances of silver perch ($Pseudo\text{-}F_{1,\ 15}$ = 0.246, p = 0.639), Murray rainbowfish ($Pseudo\text{-}F_{1,\ 15}$ = 0.148, p = 0.883) and Australian smelt ($Pseudo\text{-}F_{1,\ 15}$ = 0.012, p = 0.917) were similar between the fishway entrance and exit. Common carp (*Pseudo-*

$F_{1,15}$ = 6.08, p = 0.027), bony herring (*Pseudo*-$F_{1,15}$ = 6.04, p = 0.037) and golden perch (*Pseudo*-$F_{1,15}$ = 5.54, p = 0.033) were significantly more abundant at the fishway exit than the fishway entrance (Figure 4). Alternatively, carp gudgeon was significantly more abundant at the fishway entrance (*Pseudo*-$F_{1,15}$ = 19.194, p = 0.002), whilst unspecked hardyhead also appeared more abundant at the fishway entrance, albeit without statistical significance (*Pseudo*-$F_{1,15}$ = 0.030, p = 0.851) (Figure 4) due high within group variability (i.e. entrance samples).

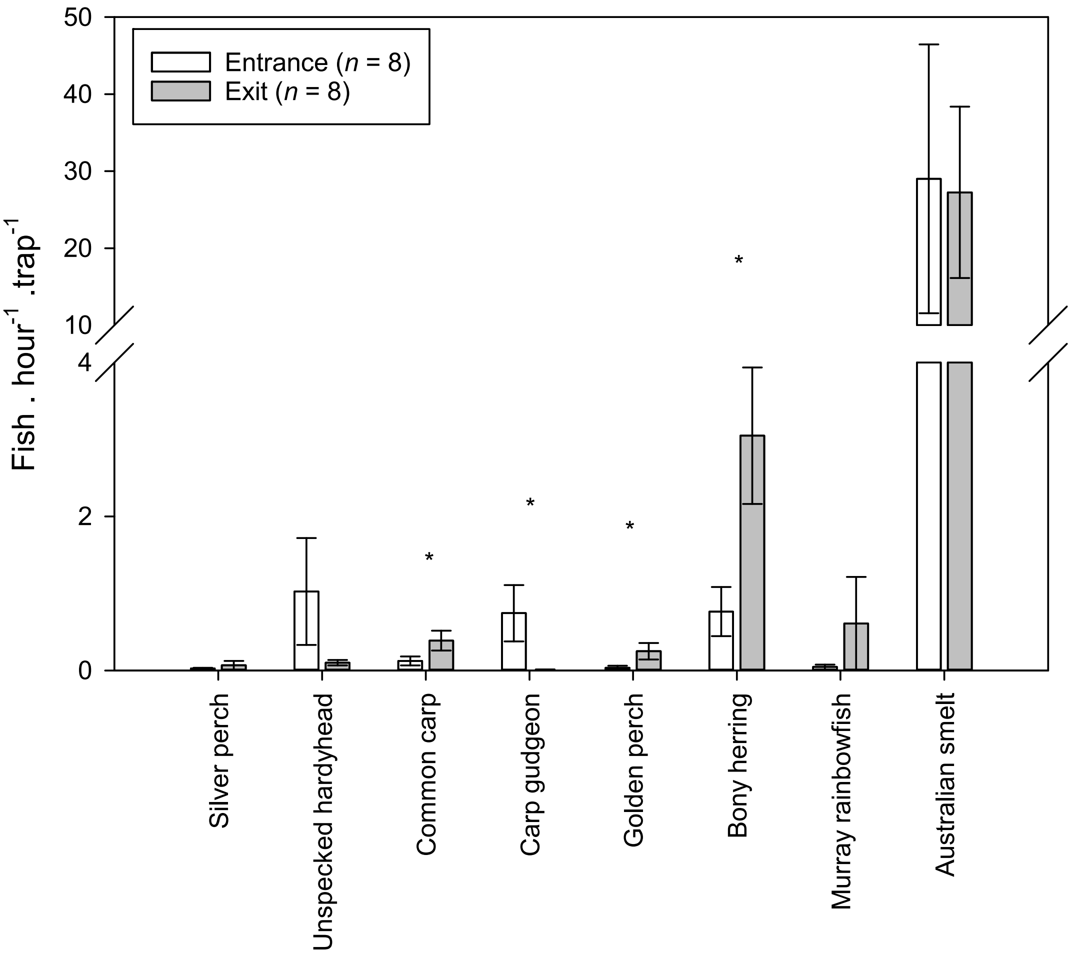

Figure 4. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Tanyaca Creek Regulator vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 17–620 mm in length, whilst those that successfully ascended the fishway ranged 24–720 mm in length (Figure 5). Length frequency distributions for Australian smelt ($D_{399,\ 370}$ = 0.110, p = 0.017) were significantly different between the fishway entrance and exit, with generally greater proportions of individuals <40 mm FL sampled from the entrance (Figure 5). A similar pattern appeared evident for unspecked hardyhead, but statistical analysis was prohibited by limited sample size. Bony herring also exhibited differences in length distributions between the entrance and exit ($D_{120,\ 293}$ = 0.230, p < 0.001), likely reflecting minor differences in the proportion of individuals 40–79 mm FL at the entrance (~14%) and exit (~33%). Common carp, golden perch and carp gudgeon were not sampled in adequate numbers to allow statistical analysis. Nonetheless, for golden perch and common carp, length frequency distributions appeared similar at the entrance and exit (Figure 5). Carp gudgeon sampled at the entrance ranged from 20–45 mm TL, and 20–25 mm TL at the exit, but represented just two individuals from the exit (Figure 5).

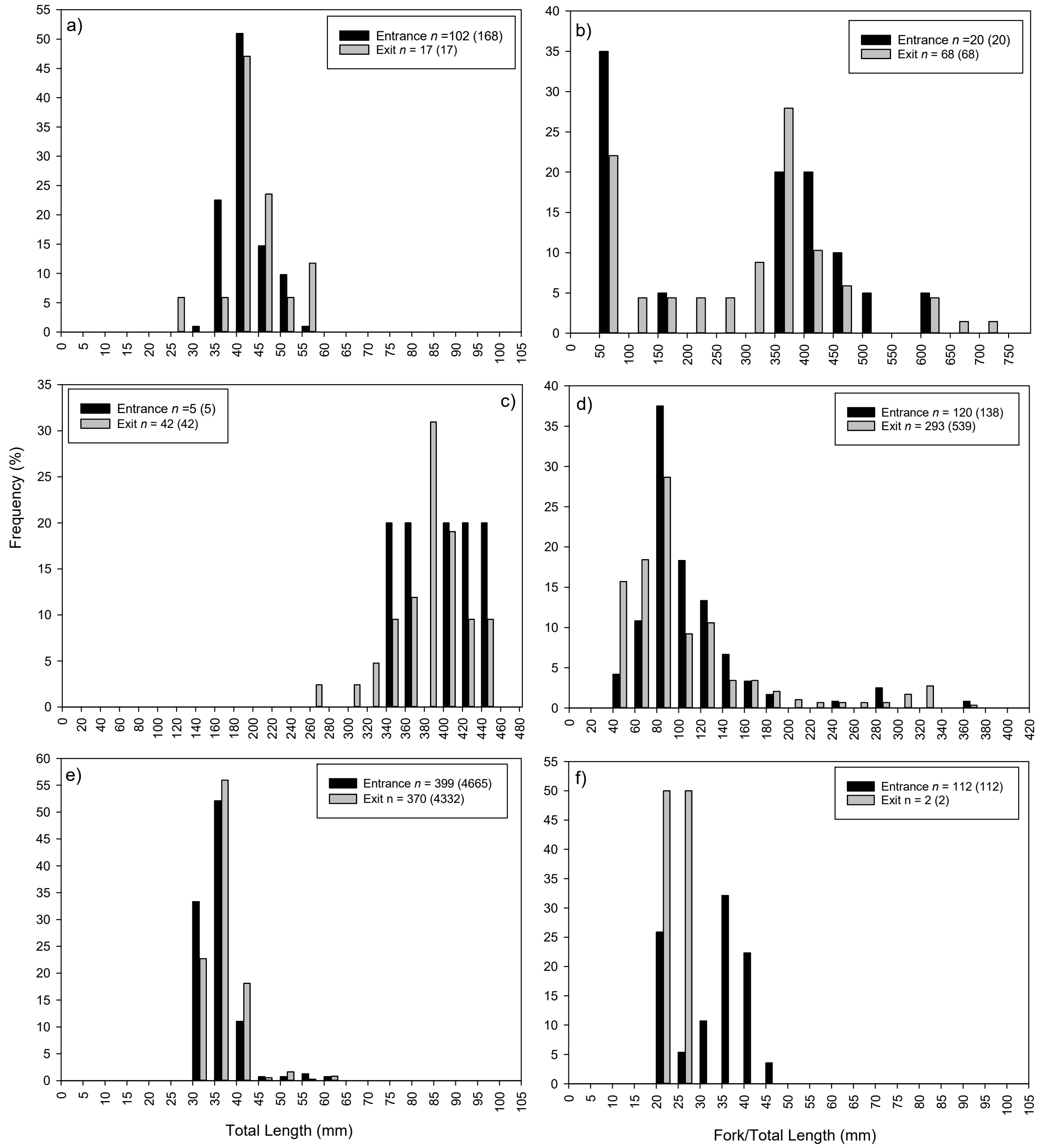

Figure 5. Length-frequency distributions of a) unspecked hardyhead (mm FL), b) common carp (mm FL), c) golden perch (mm TL), d) bony herring (mm FL) e) Australian smelt (mm FL) and f) carp gudgeon (mm TL) captured from the entrance (black bar) and exit (shaded bar) of the Tanyaca Creek Regulator vertical-slot 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.

Pike River

At the Pike River vertical-slot fishway, a total of 987 fish from nine species were sampled from entrance trapping, and 668 fish from nine species from exit trapping (Table 1). Silver perch (n = 6) and Murray cod (n = 1) were only sampled at the exit of the fishway, whilst flatheaded gudgeon (*Philypnodon grandiceps*) (n = 1) and eastern gambusia (*Gambusia holbrooki*) (n = 1) were exclusively sampled from the entrance. PERMANOVA indicated there was no significant difference in fish assemblages among entrance and exit trap samples ($Pseudo\text{-}F_{1,\ 15}$ = 2.00, p = 0.15) and no interaction between trap location and month ($Pseudo\text{-}F_{1,\ 15}$ = 2.72, p = 0.08). There was, however, a significant difference in fish assemblages between December and February sampling ($Pseudo\text{-}F_{1,\ 15}$ = 16.64, p < 0.001). This was supported by MDS ordinations of fish assemblage data, which exhibited interspersion of entrance and exit sampling events (Figure 6a), but dispersion of samples by month (Figure 6b). SIMPER suggested differences between months were primarily driven by greater abundance of Australian smelt in February, and golden perch and common carp in December.

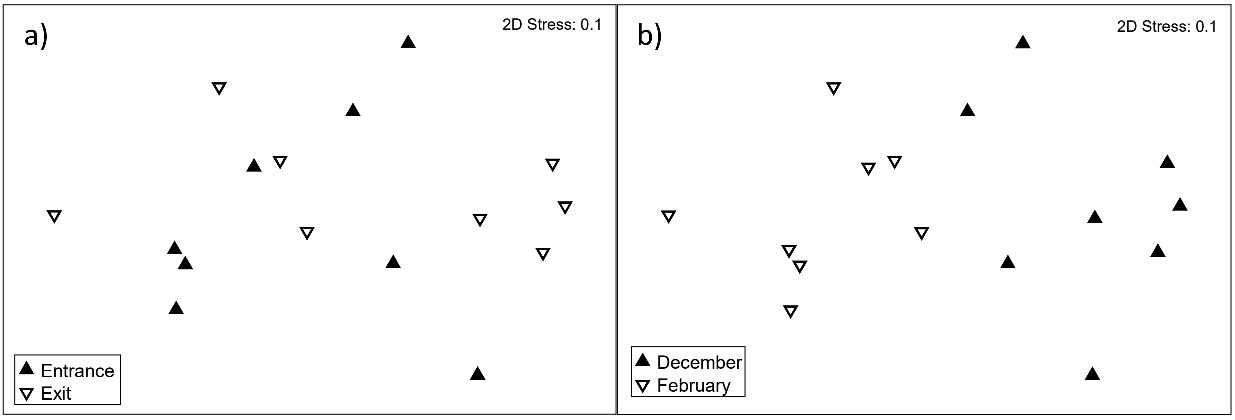

Figure 6. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at the Pike River Regulator.

Relative abundances of the two most numerous species, bony herring ($Pseudo\text{-}F_{1,\ 15}$ = 0.381, p = 0.596) and Australian smelt ($Pseudo\text{-}F_{1,\ 15}$ = 1.308, p = 0.263) were not statistically different between entrance and exit trapping. The remaining species were not sampled in adequate numbers to allow analysis.

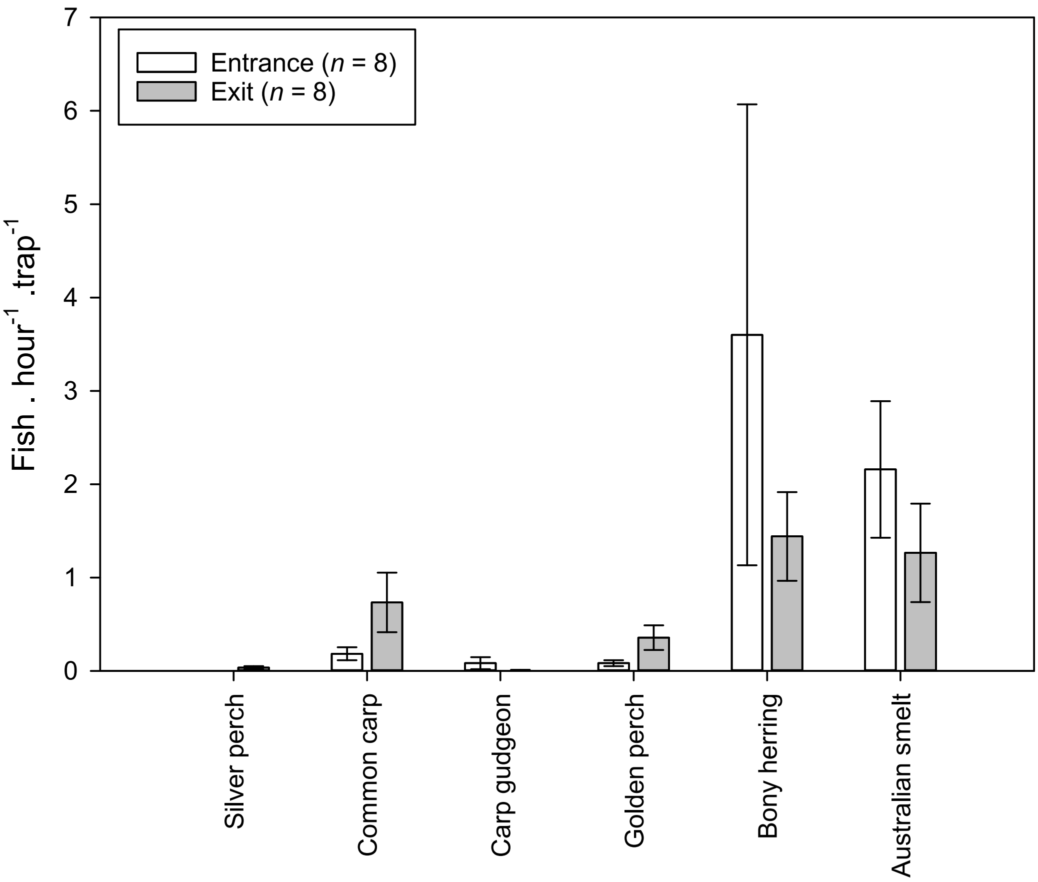

Figure 7. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Pike River Regulator vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the Pike River fishway ranged 17–640 mm in length, whilst those that successfully ascended the fishway ranged 27–710 mm in length (Figure 8). The length frequency distribution for bony herring ($D_{202,\ 193}$ = 0.584, p < 0.00) was found to be significantly different between the fishway entrance and exit with greater proportions of individuals <80 mm FL at the entrance (Figure 8). For Australian smelt ($D_{231,\ 146}$ = 0.107, p = 0.241) and common carp ($D_{31,\ 128}$ = 0.234, p = 0.109), length distributions were similar between the fishway entrance and exit (Figure 8). Golden perch were sampled in insufficient numbers to allow analysis, but length frequency distributions appeared similar between entrance and exit samples.

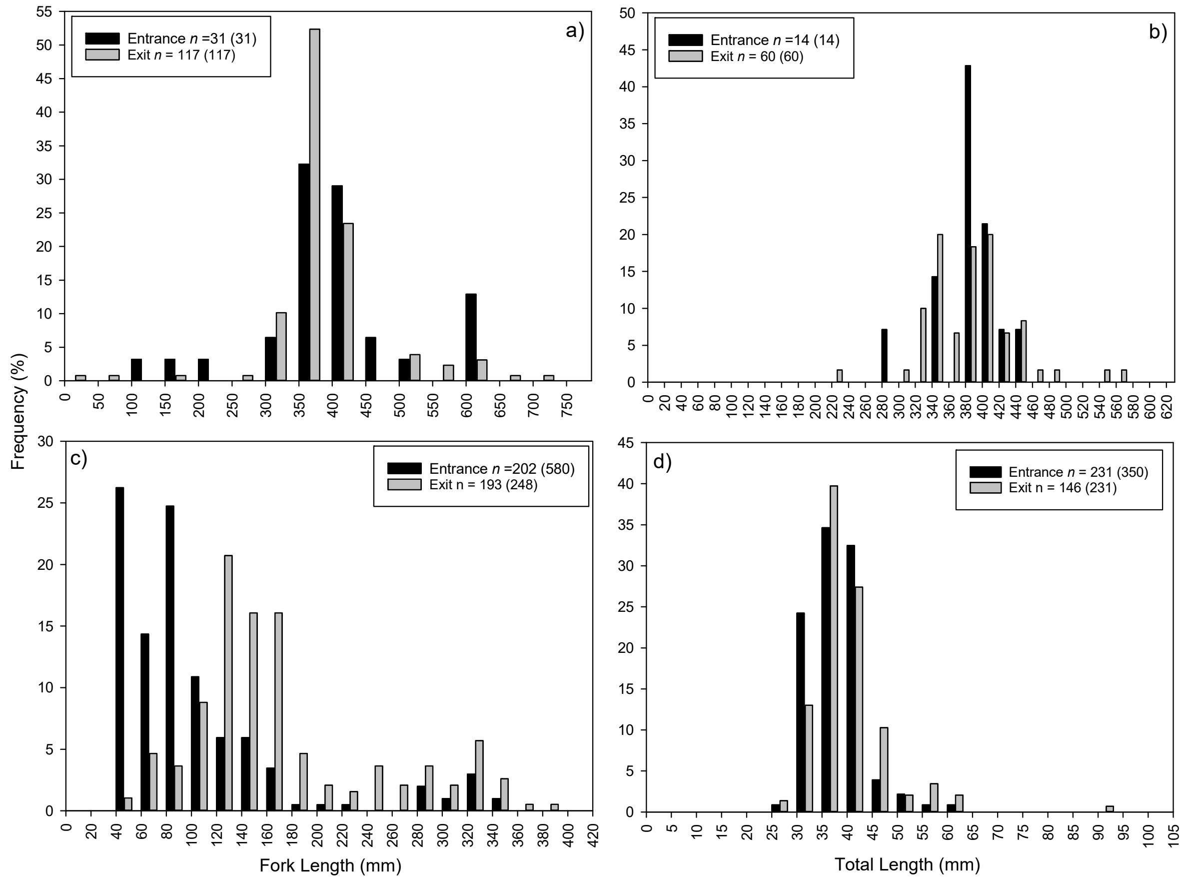

Figure 8. Length-frequency distributions of a) common carp, b) golden perch, c) bony herring and d) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of the Pike River Regulator vertical-slot fishway. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

Lock 5

At the Lock 5 vertical-slot fishway, a total of 355 fish from seven species were sampled from entrance trapping, and 943 fish from four species from exit trapping (Table 1). Golden perch, silver perch, bony herring and common carp were all captured at both the entrance and exit of the fishway, however, unspecked hardyhead, Australian smelt and goldfish (*Carassius auratus*) were only sampled at the entrance of the fishway (Table 1). PERMANOVA indicated there was a significant interaction between trap location and month ($Pseudo\text{-}F_{1,\ 15}$ = 3.48, $p = 0.02$), suggesting assemblages differed between entrance and exit samples, but this difference was not consistent across months. Despite this apparent difference in patterns of variability, assemblages were significantly different between entrance and exit samples in both December and February (pairwise comparisons $p < 0.05$). The results of PERMANOVA were generally supported by MDS ordination of the fish assemblage data which displayed dispersion of samples by trapping location-month grouping (Figure 9). SIMPER suggested differences among assemblages sampled at the entrance and exit, were driven in December 2020 by greater abundance of Australian smelt at the entrance and bony herring at the exit, and in February 2021 by greater abundance of silver perch and bony herring at the exit.

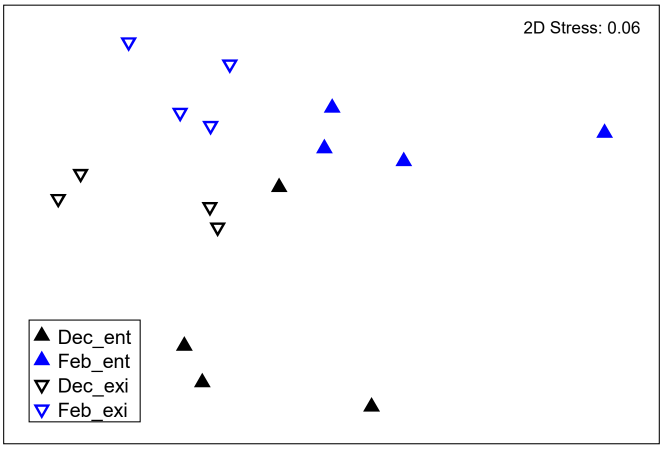

Figure 9. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the entrance and exit sampled at the vertical-slot fishway at the Lock 5 Regulator.

At the Lock 5 fishway, relative abundances of golden perch ($Pseudo\text{-}F_{1,\ 15} = 1.788$, $p = 0.224$) and common carp ($Pseudo\text{-}F_{1,\ 15} = 3.247$, $p = 0.098$) were not significantly different between the entrance and exit. Both silver perch ($Pseudo\text{-}F_{1,\ 15} = 6.178$, $p = 0.034$) and bony herring ($Pseudo\text{-}F_{1,\ 15} = 20.741$, $p = 0.001$), however, were significantly more abundant at the fishway exit (Figure 10). Alternatively, Australian smelt were only sampled from the fishway entrance.

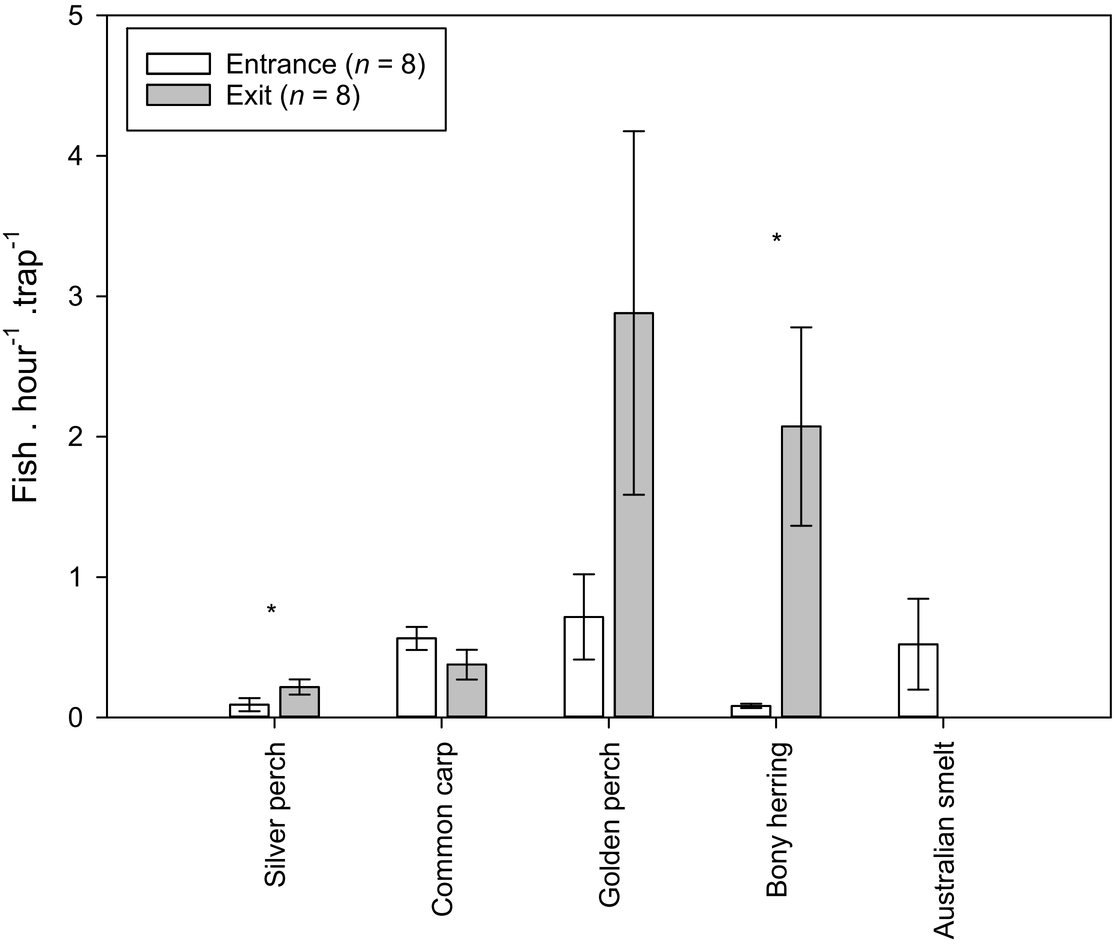

Figure 10. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the Lock 5 Regulator vertical-slot fishway. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the Lock 5 fishway ranged 30–705 mm in length, whilst those that successfully ascended the fishway ranged 105–700 mm in length (Figure 11). The length frequency distributions for golden perch ($D_{128,\ 282}$ = 0.072, p = 0.733) and common carp ($D_{102,\ 62}$ = 0.206, p = 0.066) were statistically similar between the fishway entrance and exit (Figure 11). Silver perch (entrance = 123–402 mm FL; exit = 120–400 mm FL) and bony herring (entrance = 100–382 mm FL; exit = 105–393 mm FL) both exhibited similar length ranges from the entrance and exit, but limited numbers from the exit precluded statistical analysis (Figure 11).

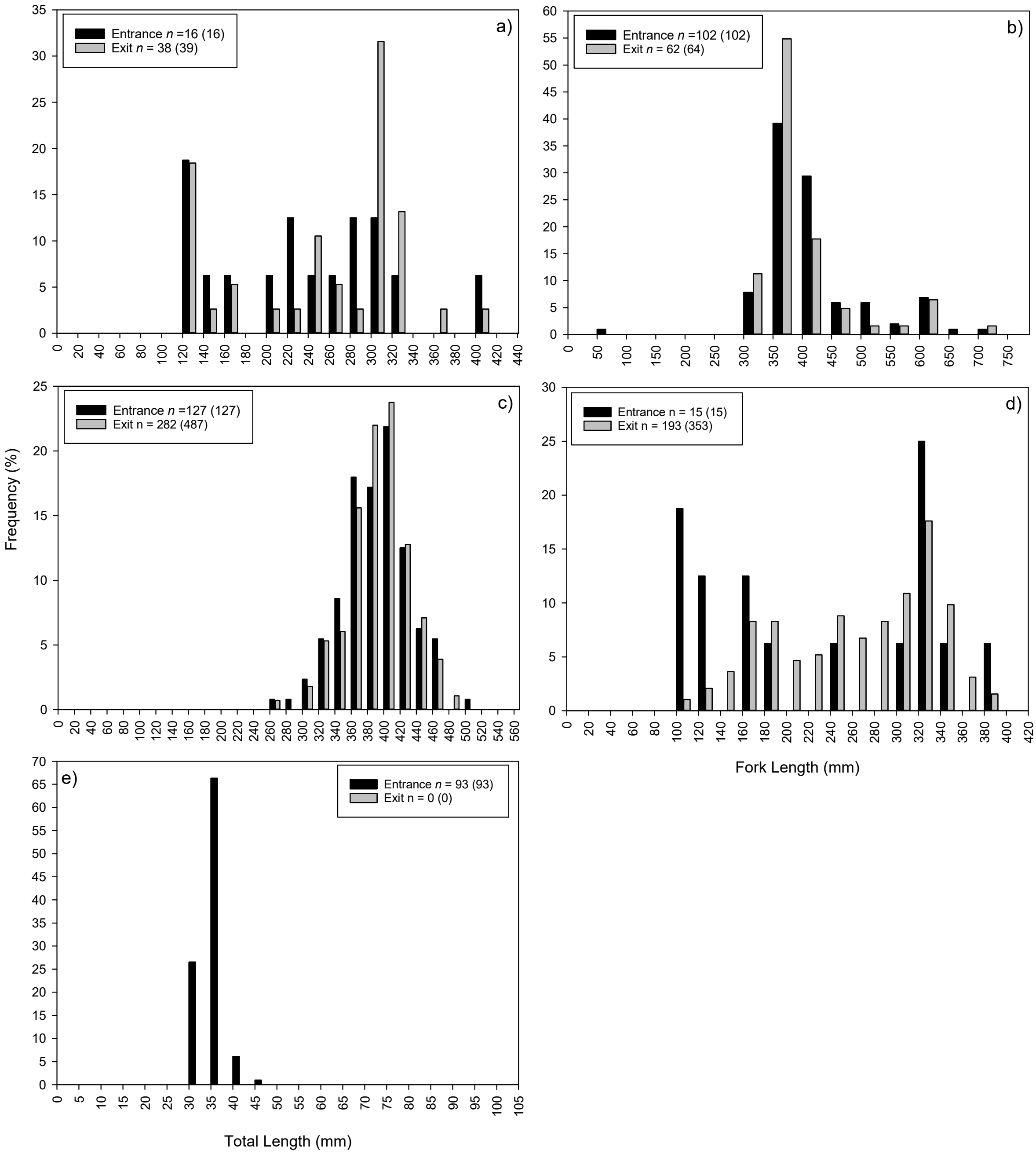

Figure 11. Length-frequency distributions of a) silver perch, b) common carp, c) golden perch d) bony herring and e) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of the Lock 5 vertical-slot fishway. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

Tanyaca Creek, Pike River and Lock 5 exit trapping comparison

During exit trapping, a total of 5,125 fish from ten species were sampled at the Tanyaca Creek fishway, 668 fish from eight species were captured from the Pike River fishway and 943 fish from four species were captured at the Lock 5 fishway (Table 1). Golden perch, silver perch, bony herring and common carp were collected at all fishway exits, while unspecked hardyhead, Murray rainbowfish (*Melanotaenia fluviatilis*) and carp gudgeon were only captured in low abundance at the exits of the Tanyaca Creek and Pike River fishways (Table 1). The MDS ordination of the fish assemblage data displayed strong grouping of samples by fishway (Figure 12), supported by PERMANOVA, which indicated assemblages were significantly different ($Pseudo\text{-}F_{2,\,23} = 7.0645$, $p = 0.001$).

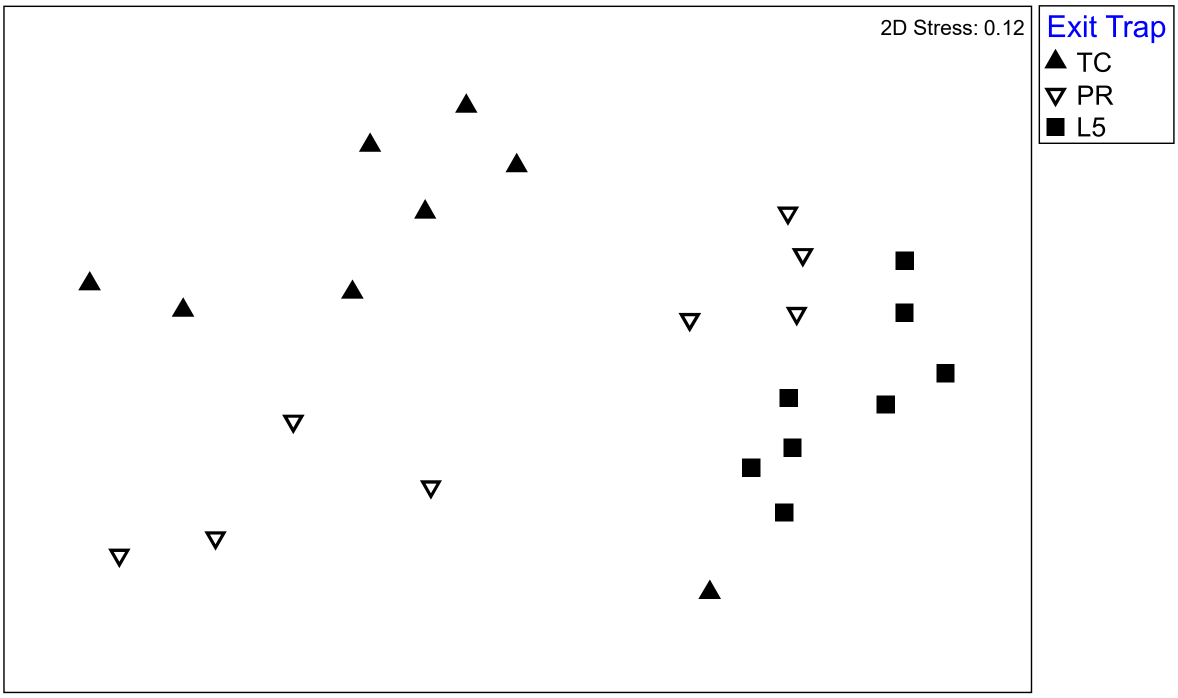

Figure 12. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages between the exits sampled at the vertical-slot fishways at the Tanyaca Creek, Pike River and Lock 5 Regulators.

Relative abundance of silver perch (*Pseudo-*$F_{2,\ 23}$ = 8.596, p = 0.008), golden perch (*Pseudo-*$F_{2,\ 23}$ = 4.185, p = 0.028) and Australian smelt (*Pseudo-*$F_{2,\ 23}$ = 18.124, p = 0.002) were significantly different between all three fishway with greatest abundance at Lock 5 for the former two species, and greatest abundance of Australian smelt at the Tanyaca Creek fishway (Figure 13). Abundances of common carp (*Pseudo-*$F_{2,\ 23}$ = 0.188, p = 0.845) and bony herring (*Pseudo-*$F_{2,\ 23}$ = 0.820, p = 0.451) were similar among all fishways (Figure 13).

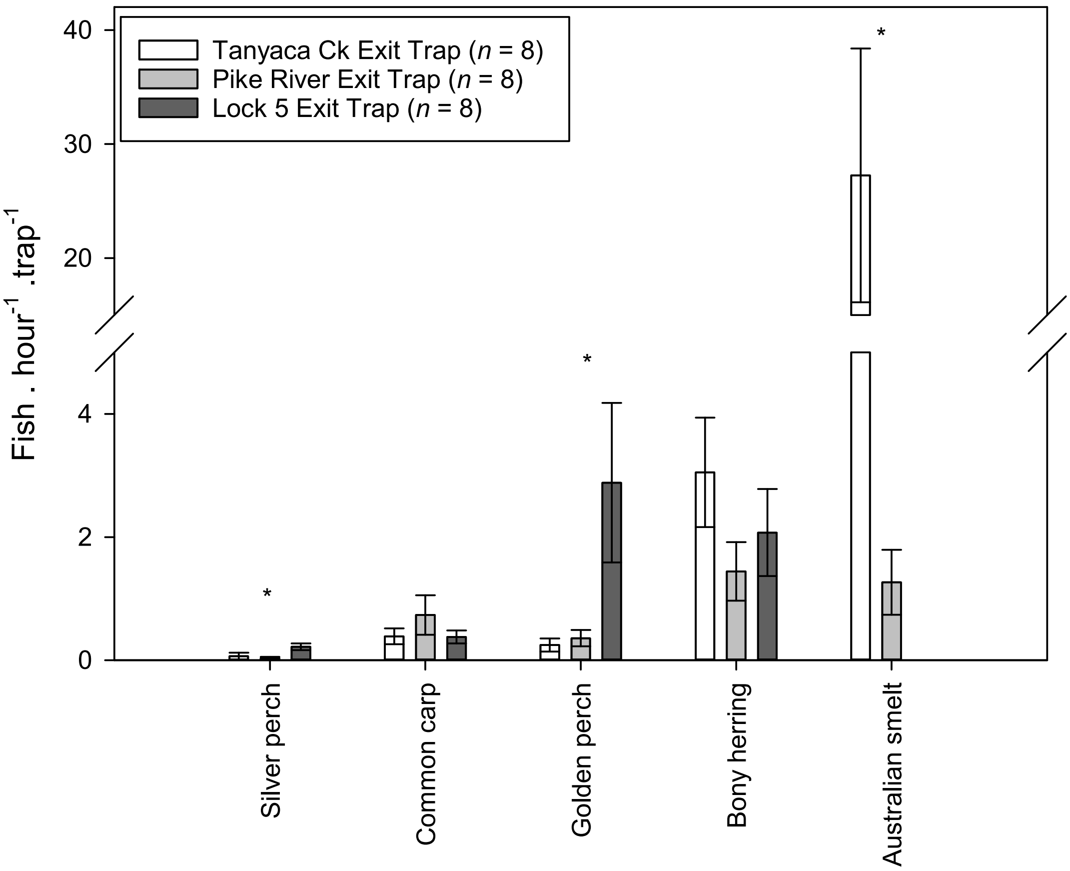

Figure 13. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the exits of the Tanyaca Creek (open bar), Pike River (light shaded bar) and Lock 5 (dark shaded bar) vertical-slot fishways. Significant differences between exit abundance are indicated by asterisks.

4. DISSCUSION

The restoration of hydrological and biological connectivity, through the removal of barriers to movement or construction of fishways, was a central focus of management interventions in the Pike Anabranch under RRP and SARFIIP. This has included the construction of four vertical-slot fishways within the system; on the influent creeks at Margaret-Dowling and Deep creeks, and floodplain regulators at Tanyaca Creek and the Pike River. 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 the Tanyaca Creek and Pike River fishways to evaluate passage efficiency, in regards to the abundance and size classes of species able to successfully ascend. Additionally, we aimed to compare fish movement through these fishways, with regard to species identity and abundance, to that through the Lock 5 vertical-slot fishway on the adjacent main channel of the River Murray.

4.1. Fishway use and passage efficiency

Tanyaca Creek

A total of ten species were sampled from the Tanyaca Creek fishway, comprising the majority (59%) of species previously detected in the system and expected to use the fishway during summer (Fredberg and Bice 2018, Fredberg and Bice 2021). Species not recorded were those either typically uncommon at the site (e.g. Murray cod and redfin perch *Perca fluviatilis*) or not commonly encountered in fishways in the lower River Murray (e.g. freshwater catfish, dwarf flat-headed gudgeon (*Philypnodon grandiceps*) and goldfish).

Fish assemblages were significantly different between the entrance and exit of the Tanyaca Creek fishway, driven primarily by greater relative abundances of common carp, golden perch and bony herring at the fishway exit and carp gudgeon at the fishway entrance. This is likely suggestive of high passage efficiency for these medium to large-bodied species, but also potential trap 'shyness' (i.e. aversion to the fishway entrance trap) influencing fish entering the fishway. This behavior has been observed in other assessments of vertical-slot fishways within the Chowilla, Katarapko and Pike anabranches (Bice et al. 2016b, Fredberg and Bice 2018, Fredberg et al. 2020).

Significantly greater abundances of carp gudgeon were detected at the entrance than at the exit of the Tanyaca Creek fishway, while a similar pattern was exhibited by unspecked hardyhead, albeit without statistical significance. Both are small-bodied species (adult length typically <60 mm

TL) and exhibit poor swimming ability compared to larger species. This is particularly true for carp gudgeon; laboratory trials suggest this species has among the poorest swimming ability of all small-bodied fishes native to the MDB (Bice 2004, Kilsby and Walker 2010). Alternatively, for Australian smelt, the most numerous species sampled at the Tanyaca 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.

Fish sampled at the entrance of Tanyaca Creek fishway ranged 17–620 mm in length, while those that that successfully ascended the fishway ranged 24–720 mm in length. For the species that were sampled in adequate numbers to allow comparisons of length distributions between entrance and exit samples, only Australian smelt and unspecked hardyhead exhibited statistically significant differences. Nonetheless, these differences were minor, with only slightly greater proportions of individuals <40 mm in length at the entrance than at the exit.

The vertical-slot fishway on the Tanyaca 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 1.3–1.79 m, maximum slot velocities of 0.99–1.05 $m.s^{-1}$ and maximum pool turbulence of 24–26 $W.m^{-3}$. This pool turbulence is low relative to 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 carp gudgeon complex; fishway 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). Given the benign internal hydraulics of the Tanyaca Creek fishway, poor passage of carp gudgeon may be related to the overall length of the fishway and exhaustion after passing multiple pools. Alternatively, it may be attributed to a lack of motivation to pass the fishway (Cooke and Hinch 2013). The results of this and other studies suggest that effectively passing high proportions of carp gudgeon may be a limitation of the vertical-slot design (Fredberg and Bice 2018).

Pike River

A total of nine species were sampled from the Pike River fishway, which, similar to the Tanyaca Creek fishway, comprises the majority (53%) of species previously detected in the system (Fredberg and Bice 2021) and expected to use the fishway during summer (Fredberg and Bice

2018, Fredberg and Bice 2021). Notably, a juvenile Murray cod (244 mm TL) was detected ascending this fishway (i.e. sampled from the exit). This is the first record of this species using a fishway in the Pike system and is an encouraging result given that increased abundance of Murray cod is an ecological objective of ongoing management of the Pike system.

Fish assemblages were generally similar between the entrance and exit of the fishway. The abundance of the two most numerous species – bony herring and Australian smelt – was similar between entrance and exit samples, suggesting high passage efficiency. Additionally, for the large-bodied silver perch, golden perch and common carp, abundance appeared greater at the exit than the entrance, albeit without statistical significance. Similar to the Tanyaca Creek fishway, this disparity may be the result of entrance trap 'shyness' caused by the trap being visible to fish entering the fishway.

Fish that entered the Pike River vertical-slot fishway ranged 17–640 mm in length, while those that successfully ascended ranged 27–710 mm in length. For common carp and Australian smelt length frequency distributions were statistically similar between entrance and exit samples, suggesting no size-related restriction of passage for these species. The same pattern also appeared for golden perch although statistical comparison was not possible due to low sample size. For bony herring, however, length frequency distributions were statistically different between entrance and exit samples, suggesting a size restriction of passage, namely for individuals <100 mm. This result, however, is unexpected given the generally strong swimming ability of bony herring even as juveniles (Mallen-Cooper 1999).

The vertical-slot fishway on the Pike River Regulator is functioning to biological design criteria. The fishway attracted and passed a diversity of species and a large range of sizes under normal operating conditions and a low-level inundation (up to a head differential of ~1.8 m). The exception to overall positive passage outcomes was poor passage efficiency for juvenile bony herring. Given the similarity in fishway design between the Pike and Tanyaca fishways, and lack of size-related passage obstruction for bony herring at Tanyaca, the causal mechanism of this result at Pike is unknown.

The conditions under which sampling occurred in December 2020 were likely at the limit of this fishway with regards to passing small-bodied fish. Higher level inundations (>15.25 m AHD) will result in high head differentials and maximum pool turbulence that will progressively retard the passage of larger fish.

Lock 5

A total of seven species were sampled from the Lock 5 vertical-slot fishway, however, only four species were sampled at the exit and all were medium- or large-bodied species (i.e. adult length >200 mm). Fish assemblages were significantly different between the entrance and exit of the vertical-slot fishway, driven primarily by greater relative abundances of silver perch, golden perch and bony herring at the fishway exit than the entrance. This pattern is similar to results of other sampling at 1:23 (hydraulic gradient) vertical-slot fishways in the lower River Murray (Lock 2–6) (Baumgartner et al. 2014, Fredberg et al. 2020), and as with Tanyaca and Pike fishways, may indicate a level of trap shyness. Nonetheless, results also suggest the fishway facilitates efficient passage for these three species.

Fish that entered the Lock 5 vertical-slot fishway ranged 30–705 mm in length, while those that successfully ascended ranged 105–700 mm in length. Unsurprisingly, for species such as unspecked hardyhead and Australian smelt that do not grow >100 mm in length, individuals were only recorded from the entrance of the fishway. This was expected as this fishway was designed to facilitate passage of fish >100 mm in length, while passage of smaller fish is facilitated by the co-located fish lock (the fish lock was not sampled in this study).

4.2. Comparison of movement through Tanyaca Creek, Pike River and Lock 5 fishways

Fish passing through fishways at the Pike system or River Murray (Lock 5) 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 via these different pathways, particularly for 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 Australian smelt at Tanyaca Creek, and golden perch and silver perch at Lock 5. The migratory tendencies of golden perch and silver 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). The results of the current study suggest that in the vicinity of Lock 5, the bulk of upstream movement was occurring via the main river channel rather than via the Pike Anabranch; this result is not unexpected given the greater discharge and accompanying greater rheotactic cues for movement occurring in the river channel relative to the Pike Anabranch. For common carp and bony herring, suggesting relatively greater use of habitats associated with the anabranch or use of these streams for upstream migration.

5. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to assess fish movement and passage efficiency at the newly constructed Tanyaca Creek and Pike River fishways, and as a complementary investigation, at the Lock 5 vertical-slot fishways. Our study has shown that the Tanyaca Creek and Pike River vertical-slot fishways facilitated the passage of the majority of species likely to undertake movements between the River Murray and the Pike Anabranch. 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 the conditions experienced. The current assessment occurred during 'normal operating conditions' and a low-level managed inundation. Future inundation events may be of greater height, which will influence gate operation and internal hydraulics and potentially passage efficiency. Additionally, passage efficiency – the ability for fish to ascend the 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 not been commonly 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 greatly benefit future 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 Tanyaca Creek and Pike River vertical-slot fishways, at maximum inundation height 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 southern MDB; and
- Future operation of these fishways should follow closely fishway performance tables in the SARFIIP Pike final design report to ensure appropriate fishway and regulator gate settings to maximise attraction and passage.

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