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Assessment of passage efficiency at the Deep Creek vertical-slot fishway

C. M. Bice, B. P. Zampatti and J. Fredberg

SARDI Publication No. F2016/000453-1
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SARDI Aquatics Sciences
PO Box 120 Henley Beach SA 5022

October 2016

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EXECUTIVE SUMMARY

The restoration of biological connectivity and facilitation of fish passage in the Pike Anabranch, South Australia, is a key objective of management interventions under the *Riverine Recovery Project* (RRP) and *South Australian Riverland Integrated Floodplain Infrastructure Project* (SARFIIP). A component of the RRP was the replacement of the regulator, including the incorporation of a vertical-slot fishway, on an inlet to the Pike system at Deep Creek. The fishway was designed to pass a range of fish species and size classes from 30 to 850 mm in length. The fishway consists of eight baffles and seven pools (four = 1.8 m wide x 3.0 m long, three = 3.6 m wide x 3.0 m long), and each baffle consists of two 'key-hole' vertical-slots with widths of 150 and 250 mm, respectively. At normal Lock 5 pool level (16.3 m Australian Height Datum) and baseflow of 150 $ML.d^{-1}$, the fishway discharges ~23 $ML.d^{-1}$ across a total head differential of ~1.0 m (~120 mm per baffle), resulting in maximum water velocity of 1.54 $m.s^{-1}$ and maximum turbulence of 53 $W.m^{-3}$ (Coefficient of Discharge [Cd] = 0.7). Fundamental to any fishway construction is assessment of passage efficiency against biological design specifications. Passage efficiency is defined as the ability of fish that locate the fishway entrance to successfully ascend and exit the fishway. The objective of the current study was to sample the entrance and exit of the Deep Creek fishway to evaluate passage efficiency against design criteria, in regards to the abundance and size classes of species able to successfully ascend.

From 3 November 2015 to 12 February 2016, over 16 paired-day samples of the fishway entrance and exit, a total of 20,704 fish (entrance = 8,965; exit = 11,739) were sampled from eight species (entrance = 7; exit = 8), comprising the majority of fishes expected to move frequently between the Pike Anabranch and lower River Murray. The catch was dominated by the small-bodied Australian smelt (*Retropinna semoni*; ~95% of the total catch) and medium-bodied bony herring (*Nematalosa erebi*; ~4% of the total catch), whilst unspecked hardyhead (*Craterocephalus fulvus*), Murray rainbowfish (*Melanotaenia fluviatilis*), carp gudgeon (*Hypseleotris* spp.), golden perch (*Macquaria ambigua ambigua*), silver perch (*Bidyanus bidyanus*) and common carp (*Cyprinus carpio*) comprised smaller proportions (<1%).

The abundances of Australian smelt and bony herring were not significantly different (PERMANOVA $\alpha = 0.05$) between entrance and exit samples indicating high passage efficiency. Other species were sampled in abundances too low to allow statistical comparison, but with the exception of carp gudgeon, were generally sampled in similar numbers at the entrance and exit. Fish as small as 23 mm in length successfully ascended the fishway. Comparison of length-

frequency distributions between the entrance and exit indicated no significant difference for Australian smelt (Kolmogorov-Smirnov 'goodness-of-fit' test, $D_{401,\ 367} = 0.03$, $p = 0.99$), but a significant difference for bony herring ($D_{195,\ 175} = 0.14$, $p = 0.047$), due to a slightly greater proportion of individuals <50 mm FL (fork length) at the entrance (~19%) than the exit (~9%). Nonetheless, substantial numbers of bony herring <50 mm FL successfully ascended the fishway.

The Deep Creek vertical-slot fishway is operating to biological design criteria, with multiple species and individuals ranging 23–481 mm in length successfully ascending. Consequently, the fishway has effectively reinstated connectivity at this site for the first time since construction of the original Deep Creek Regulator in the 1950s. The design of the Deep Creek fishway appears suitable for other structures in the Pike Anabranch and more broadly in the lower River Murray, where fish movement requirements are similar.

To optimise fish passage at Deep Creek, operation of the Regulator and fishway must consider variability in headwater (i.e. upstream of Lock 5) and tailwater levels (downstream Deep Creek Regulator), and entrance hydraulics. Discharge through the regulator must be manipulated in response to changes in water level to maintain head loss across the fishway at <1 m and appropriate internal water velocity and turbulence for small-bodied fish. Additionally, discharge through the two flume gates on the regulator must be manipulated and appropriately 'proportioned', upon any change to overall regulator operation, to ensure there is no or only minimal flow recirculation that may hinder attraction of fish to the entrance of the fishway.

The Deep Creek fishway represents the first component of a broader program improving connectivity and fish passage at the Pike Anabranch. The capacity for fish to move freely through the entire system, however, will only be fully realised upon the construction of other regulators and associated fishways (e.g. on Tanyaca Creek) under SARFIIP. Importantly, for fish passage to be optimised across the Pike Anabranch, the hydraulic design criteria of fishways on downstream structures must, at a minimum, match those of the Deep Creek fishway in regards to species and size classes targeted for passage.

1. INTRODUCTION

1.1. Background

The obstruction of fish movement by dams, weirs, barrages and other regulatory structures is among the greatest threats to freshwater and diadromous fish populations globally (Lucas and Baras 2001). Instream barriers restrict access to spawning, nursery and feeding habitats, and prevent dispersal and recolonisation (Gehrke *et al.* 1995). Fishways are now commonly used to reinstate connectivity in regulated river systems and partially mitigate the impacts of instream barriers (Clay 1995).

Since the early 1900s, river regulation in the Murray-Darling Basin (MDB) has resulted in the construction of an estimated 10,000 barriers to fish migration (Baumgartner *et al.* 2014). On the River Murray alone, flow is regulated by several large dams, 14 low-level main channel weirs and a series of barrages in the Lower Lakes and Coorong region, and a multitude of smaller off-channel structures. Native fish populations in the MDB are considered to be just 10% of those present pre-European colonisation and the obstruction of fish movement by regulating structures is considered a primary driver of these declines (Koehn and Lintermans 2012).

The Murray-Darling Basin Authority's *Sea to Hume Dam* fish passage program involved the construction of fishways on all main channel weirs of the River Murray and the Murray Barrages (Barrett and Mallen-Cooper 2006), greatly improving longitudinal connectivity for fishes along ~2225 km of river. The incorporation of fish passage on structures on smaller tributaries and anabranches within the MDB is now of interest to national and state agencies.

The Pike Anabranch and Floodplain is one of three large (~6,700 ha) anabranch systems (Chowilla, Katarapko and Pike) in the Riverland region of the lower River Murray, South Australia. The Pike Anabranch is fed by two inlet creeks (Deep Creek and Margaret Dowling Creek) that flow from the Lock 5 weir pool into Mundic Creek, before flowing through a series of creeks and lagoons, and finally re-entering the River Murray downstream of Lock 5 via the lower Pike River. Earthen banks with embedded pipe culverts were constructed on Margaret Dowling Creek and Deep Creek in the 1950s to manage discharge to the system and represented barriers to the upstream movement of fish from the Pike River system to the River Murray. Furthermore, a range of other structures (primarily earthen banks and pipe culverts) were constructed downstream in the Pike system, which further fragment this system and obstruct fish movement.

The Pike Anabranch system is now the focus of substantial environmental rehabilitation effort under both the *Riverine Recovery Project* (RRP; *Murray Futures Program*) and *South Australian Riverland Floodplain Integrated Infrastructure Project* (SARFIIP). A key component of RRP was the replacement of the Deep Creek regulator, including the incorporation of a vertical-slot fishway, to increase capacity to vary flow to the system and improve connectivity, and facilitate fish movement. Fundamental to any fishway construction is assessment of passage efficiency against biological design specifications. Passage efficiency is defined as the ability of fish that locate the fishway entrance to successfully ascend and exit the fishway. Such assessment can inform on modifications required to improve passage and future fishway design.

1.2. Objectives

The objective of the current study was to sample the entrance and exit of the Deep Creek fishway to evaluate passage efficiency against design criteria in regards to the abundance and size classes of species able to successfully ascend.

2. METHODS

2.1. Study site and fish fauna

The Pike Anabranch system is situated between the townships of Lyrup and Paringa, in the Riverland, South Australia. The system bypasses Lock and Weir No. 5 (Figure 1), resulting in a head differential (total >3 m) that creates a diverse range of aquatic habitats across the system, comprised of permanently flowing creeks, lagoons and backwaters. Water flows into the system through Deep Creek and Margaret-Dowling Creek, which both enter Mundic Creek. Water then flows through two routes: 1) the inner, via Tanyaca and Rumpagunyah Creeks; and 2) the outer, via the upper and lower Pike River, before re-entering the River Murray. A series of significant barriers to fish movement, primarily earthen banks and culverts, are present on both the inner and outer flow paths.

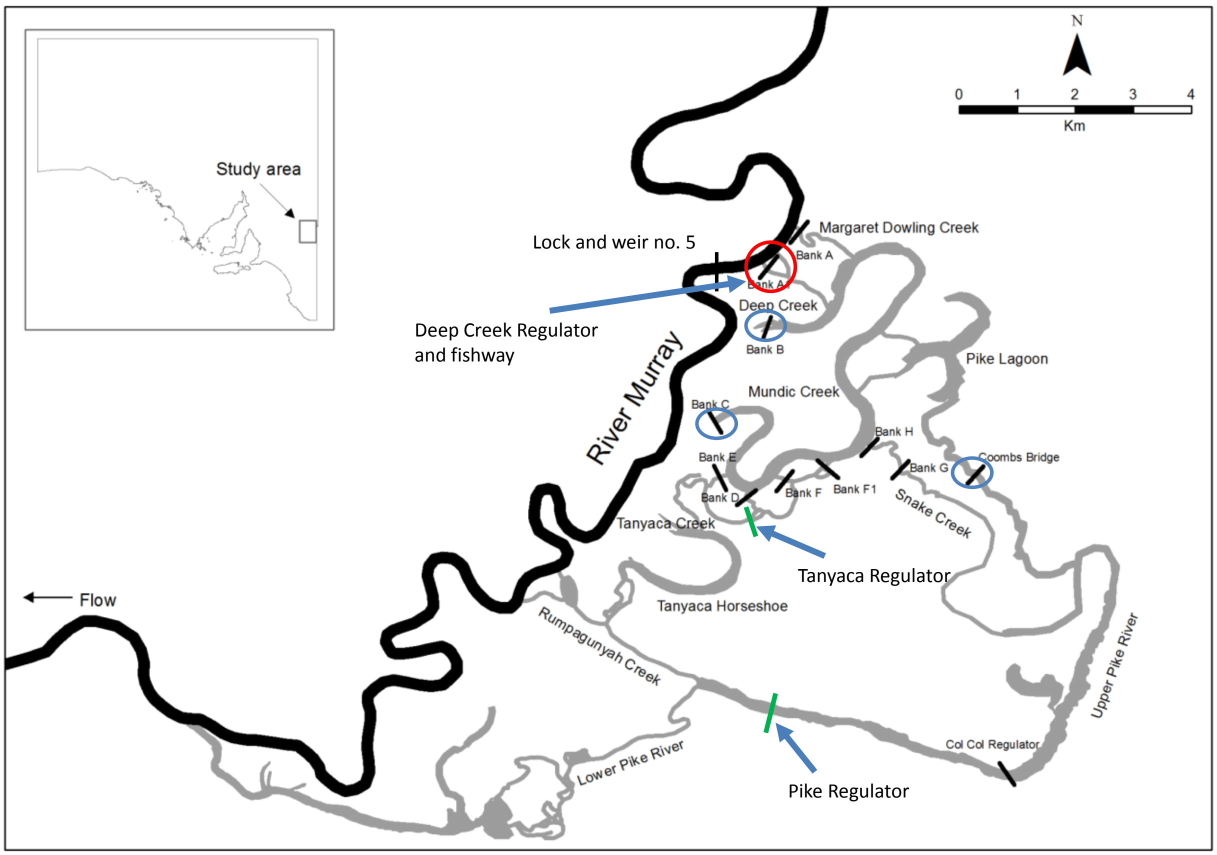

Figure 1. Map of the Pike Anabranch system, in the lower River Murray South Australia, depicting the location of key creeks and regulating structures. The location of the Deep Creek regulator and associated fishway is indicated by the *red circle*, other structures recently removed or upgraded under RRP are indicated by *blue circles,* whilst the position of proposed regulators on Tanyaca Creek and the Upper Pike River to be constructed under SARFIIP are indicated by *green lines*.

A total of 16 species of fish have been recorded from the Pike Anabranch (Bice *et al.* 2016). This represents a diverse fish assemblage and includes species of conservation concern, namely Murray cod (*Maccullochella peelii*; *vulnerable* under the *Environment Protection and Biodiversity Conservation Act* (*EPBC*) *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 ambigua*) are known to undertake long-distance riverine migrations and regular movements between anabranch and riverine habitats (O'Connor *et al.* 2005, Leigh and Zampatti 2013). Movements of many other species, particularly small-bodied fishes (adult length <100 mm), are less well understood, but recent research suggests both longitudinal and lateral movements are important (Baumgartner *et al.* 2008, Connallin *et al.* 2011). As such, a large proportion of the species present in the lower River Murray are likely to attempt movements between the Pike Anabranch and River Murray, comprising species with a range of different sizes, morphologies and swimming abilities.

2.2. Deep Creek Regulator and Fishway

The original structure at the junction of Deep Creek and the River Murray consisted of an earthen bank and embedded pipe culvert (~1 m diameter), which limited discharge to Deep Creek to 150 $ML.d^{-1}$ and likely represented a complete barrier to the upstream movement of fish, due to high water velocity and low light conditions. A new regulator and associated fishway was constructed in 2014 with the objective of increasing the capacity to vary discharge to Deep Creek and improve biological connectivity with the River Murray.

The new Deep Creek regulator is comprised of a concrete channel with two flume gates, collectively capable of regulating flow from 0 to 600 $ML.d^{-1}$ (Figure 2). The associated vertical-slot fishway was designed with the objective of providing passage for a range of fish species and size classes from 30 to 850 mm in length, with the design informed by physical modelling (Mallen-Cooper 2011). The fishway is incorporated on the southern side of the regulator, with the entrance positioned slightly downstream of the flume gate outflows. A short wall (0.7 m high x 1.5 m long) extends from the fishway to protect the fishway entrance from excessive turbulence and water velocity from the flume gates, limit recirculation and maintain the integrity of the fishway attraction flow. The fishway consists of eight baffles and seven pools (four = 1.8 m wide x 3.0 m long; three = 3.6 m wide x 3.0 m long). Each baffle consists of two 'key-hole' vertical-slots with widths of 150 and 250 mm, respectively (Figure 3). The fishway has a flat concrete floor and the hydraulic gradient (1:22.2) is provided by decreasing height of vertical-slot baffles moving in a downstream direction. The fishway has been designed to operate at a range of headwater levels from 15.7 m AHD (Australian Height Datum) to 16.8 m AHD (Lock 5 normal pool level = 16.3 m AHD) and discharge from 150 to 600 $ML.d^{-1}$. Internal hydraulics vary with head loss and are presented for three different scenarios in Table 1. Head loss across the fishway should be maintained at <1 m under all scenarios and as such, results in maximum water velocity of 1.54 $m.s^{-1}$ and maximum turbulence of 53 $W.m^{-3}$ (Coefficient of Discharge [Cd] = 0.7).

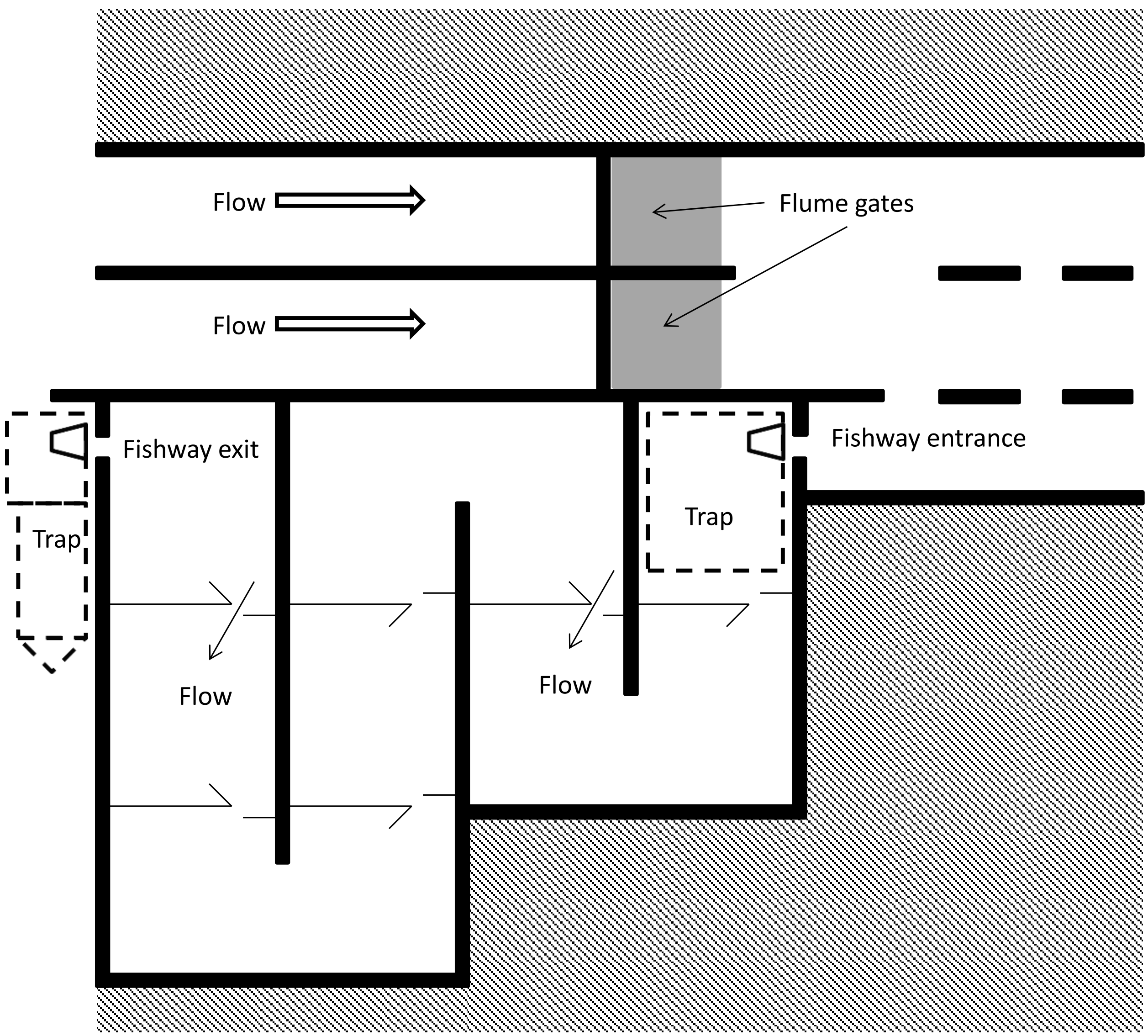

Figure 2. Plan view of the Deep Creek Regulator and associated vertical-slot fishway. The location of fishway traps for both entrance and exit trapping events are indicated.

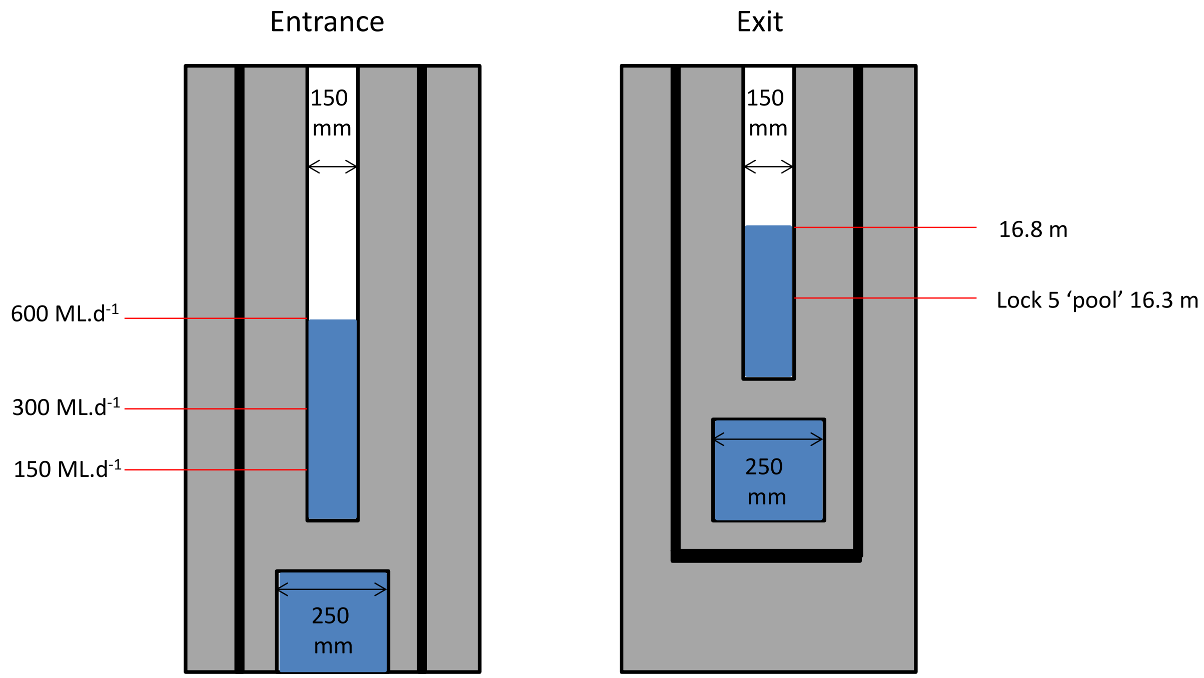

Figure 3. Front view of the entrance and exit baffles of the Deep Creek vertical-slot fishway depicting 'key-hole' vertical-slots. Water level through the entrance vertical-slot baffle is indicated for a series of different regulator discharges (i.e. 150, 300 and 600 $ML.d^{-1}$), whilst water level through the exit vertical-slot baffle is indicated for different Lock 5 pool heights (normal pool level (NPL) = 16.3 m, +0.5 NPL = 16.8 m).

Table 1. Hydraulic characteristics of the Deep Creek vertical-slot fishway including fishway discharge ($ML.d^{-1}$), vertical-slot water velocities ($m.s^{-1}$) and turbulence ($W.m^{-3}$) for three scenarios of varying head loss and regulator discharge.

Scenario	Headwater level (m AHD)	Tailwater level (m AHD)	Head loss (m)	Regulator discharge ($ML.d^{-1}$)	Fishway discharge ($ML.d^{-1}$)	Slot water velocity ($m.s^{-1}$)	Turbulence ($W.m^{-3}$)
1	16.8	16.10	0.70	600	30	1.31	32
2	16.3	15.33	0.97	150	23	1.54	53
3	15.7	15.33	0.37	150	11	0.95	16

The presence of various barriers throughout the Pike Anabranch system, particularly Banks D to F1 and Col Col, dictates that, at present, fish cannot move freely from the lower part (e.g. the lower Pike River, Tanyaca Creek) to the upper part of the system (e.g. upper Pike River, Mundic Creek, Deep Creek) (Figure 1). As such, the Deep Creek fishway currently can only be accessed by fish present upstream of the aforementioned barriers. Construction of the Tanyaca Creek and Pike River regulators and associated fishways, and removal of Banks E to F1 and part removal of Col Col under *SARFIIP* will partially restore connectivity between the lower and upper portions of the Pike Anabranch system and, together with the Deep Creek fishway (and proposed Margaret Dowling Creek fishway), potentially facilitate movement throughout the system.

2.3. Fish sampling

Fish were sampled from the Deep Creek fishway over four sampling weeks (Monday–Friday) from 3 November 2015 to 12 February 2016. During each sampling week, fish were sampled for ~24 hours on consecutive days at the entrance and exit of the fishway; as such, the entrance and exit were sampled twice within each sampling week. Thus, eight sampling events were conducted for the entrance and exit of the fishway, and these sampling events are treated as replicates for subsequent statistical analyses.

The entrance and exit of the fishway were sampled using specifically designed aluminium-framed cage traps. The entrance trap was designed to fit within the first cell of the fishway and sample all fish entering the fishway, with nylon brushes used to ensure a tight seal (Figure 2 and Figure 4a). The exit trap was mounted against the upstream side of the fishway exit, using guides for the fishway ‘de-watering gate’ and oriented to catch all fish exiting the fishway (Figure 2 and Figure 4b). The exit trap incorporated a collapsible ‘net-bag’ to increase holding room for sampled fish and ease of lifting. Both traps utilised double ‘cone-shaped’ entrances (top cone: 150 mm wide x 750 mm high, bottom cone: 250 mm wide x 500 mm high) and were clad with a combination of 3 mm perforated aluminium sheet and 6 mm knotless mesh. All fish sampled were identified to species and enumerated, and length measurements (fork length (FL) or total length (TL) depending on tail morphology) taken for up to 50 individuals per species per trapping event. Following processing, all sampled fish were released into the Lock 5 weir pool, upstream of the fishway. Head loss across the structure (i.e. the difference between headwater and tailwater levels) was measured during each sampling event.

a) b)

Figure 4. Sampling traps positioned to capture fish from the fishway a) entrance and b) exit.

2.4. Data analysis

The relative abundance (fish.hour^{-1}.trap event^{-1}) of the most numerous species sampled at the fishway (i.e. >200 individuals over the study period) was compared between entrance and exit samples using uni-variate single-factor PERMANOVA, performed on Euclidean Distance similarity matrices. Fish relative abundance data were fourth-root transformed prior to all analyses. To determine if there was size-related variation in passage success, a two-tailed Kolmogorov-Smirnov 'goodness-of-fit' test was used to determine differences in length-frequency distributions between entrance and exit samples (pooled over the study period) for species sampled in adequate numbers (i.e. >25 individuals sampled at both the entrance and exit).

3. RESULTS

3.1. Environmental conditions

A weir pool manipulation in the Lock 5 weir pool in spring 2015 raised headwater levels upstream of the Deep Creek Regulator from 16.3 m AHD to ~16.8 m AHD from August to November, before receding back to 16.3 m AHD through November and December (Figure 5). This necessitated manipulation of discharge through the Deep Creek Regulator throughout the study period to maintain a head loss across the fishway of ≤ 1000 mm and optimal fishway hydraulics. In late October, during peak headwater levels and prior to the first sampling event, discharge through the regulator was increased to 350 ML.day^{-1} to increase tailwater level (Figure 5). As water level in the Lock 5 weir pool receded, flow through the Deep Creek Regulator was reduced to ~250 ML.day^{-1} through November and early December. Once the Lock 5 weir pool receded to normal pool level in late December, regulator discharge was reduced to 130 ML.day^{-1}, and remained so for the remainder of the study. Subsequently, head loss across the fishway ranged 790–970 mm during sampling events. To ensure that water recirculation did not impact fish attraction to the fishway entrance, discharge through the flume gates was manipulated in a ratio (south:north, the southern gate is closest the fishway) of typically 1:3.

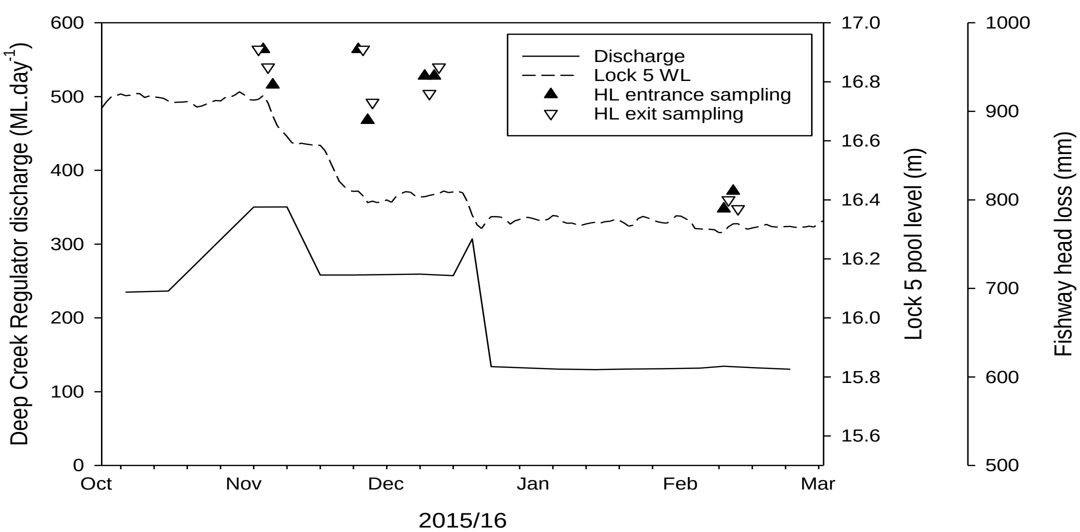

Figure 5. Discharge through the Deep Creek Regulator (ML.day^{-1}, *solid line*) and Lock 5 weir pool level (m) from 01/10/2015 to 01/03/2016. The timing and fishway head loss (mm) experienced during entrance (*closed triangles*) and exit (*open triangles*) sampling events is also indicated.

3.2. Entrance and exit comparison

A total of 20,704 fish, from eight species were sampled from the Deep Creek fishway, comprising of 8,965 fish (~43% of the total catch) and seven species from the entrance, and 11,739 fish (~57% of the total catch) and eight species from the exit (Table 2). The catch was dominated by the small-bodied Australian smelt (*Retropinna semoni*), which comprised ~95% of all fish sampled (Figure 6a). Bony herring was the next most abundant species, comprising ~4% of the catch (Figure 6b), whilst the remaining six species collectively comprised ~1% of the catch.

Table 2. Species and numbers of fish sampled from the entrance and exit of the Deep Creek vertical-slot fishway during assessment in 2015/16.

		Entrance		Exit		
Common name	**Scientific name**	**Number of fish**	**Length range (mm)**	**Number of fish**	**Length range (mm)**	**Total**
Silver perch	*Bidyanus bidyanus*	-	-	2	129–390 *FL*	2
Golden perch	*Macquaria ambigua ambigua*	1	431 *TL*	1	416 *TL*	2
Common carp	*Cyprinus carpio*	3	407–470 *FL*	6	318–481 *FL*	9
Bony herring	*Nematalosa erebi*	396	22–249 *FL*	428	37–229 *FL*	824
Australian smelt	*Retropinna semoni*	8,504	23–58 *FL*	11,283	26–58 *FL*	19,787
Murray rainbowfish	*Melanotaenia fluviatilis*	2	56–72 *FL*	2	65–77 *FL*	4
Unspecked hardyhead	*Craterocephalus fulvus*	12	35–49 *FL*	13	33–51 *FL*	25
Carp gudgeon complex	*Hypseleotris* spp.	47	17–41 *TL*	4	23–35 *TL*	51
	Total	**8,965**		**11,739**		**20,704**

a) b)

Figure 6. a) Australian smelt and b) bony herring were the two most abundant species sampled from the Deep Creek vertical-slot fishway.

All seven species sampled at the entrance were also sampled at the exit of the Deep Creek fishway. Numbers of fish entering the fishway ranged from 3 to 137 fish.hour^{-1} (mean ± SE = 49.15 ± 18.2 fish.hour^{-1}), whilst numbers of fish successfully ascending the fishway ranged from 1 to 251 fish.hour^{-1} (mean ± SE = 59.7 ± 33.27 fish.hour^{-1}). The abundances of the two most numerous species, Australian smelt and bony herring, captured across the 16-paired day samples, were compared between entrance and exit samples. Analyses indicated there was no significant difference in the abundance of Australian smelt ($Pseudo\text{-}F_{1, 15}$ = 0.16, p = 0.70; α = 0.05) and bony herring ($Pseudo\text{-}F_{1, 15}$ = 0.08, p = 0.81) between the fishway entrance and exit (Figure 7). The remaining species were sampled in inadequate abundances to enable statistical comparisons, but most species were sampled in similar numbers from the entrance and exit of the fishway, with the exception of carp gudgeon and silver perch. Higher numbers of carp gudgeon were sampled from the entrance than the exit (Table 2 and Figure 7), whilst two silver perch were sampled at the exit of the fishway, but the species was absent from entrance sampling.

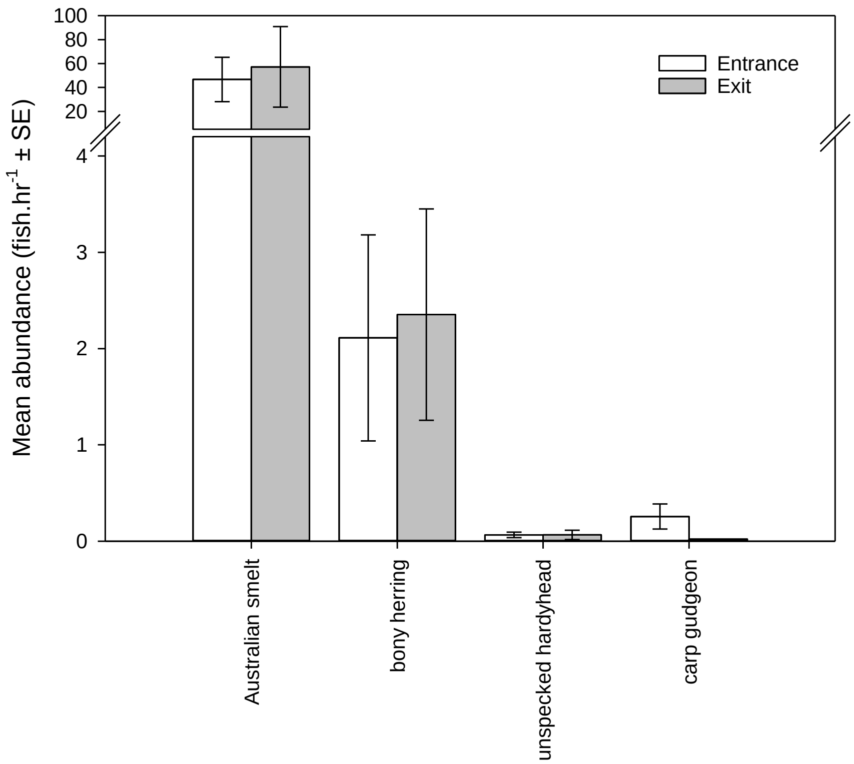

Figure 7. Relative abundance (mean number of fish hour^{-1}.trap event^{-1}) of Australian smelt, bony herring, unspecked hardyhead and carp gudgeon sampled at the entrance (*white bar*, n = 8) and exit (*grey bar, n* = 8) of the Deep Creek vertical-slot fishway in 2015/16.

Fish sampled at the entrance ranged from 17 to 470 mm in length, whilst those that successfully ascended the fishway ranged from 23 to 481 mm in length (Table 2). There was no significant difference in length-frequency distributions of Australian smelt from entrance and exit samples ($D_{401,\ 367}$ = 0.03, p = 0.99; α = 0.05) (Figure 8a). Alternatively, length-frequency distributions of bony herring were significantly different between entrance and exit samples ($D_{195,\ 175}$ = 0.14, p = 0.047), likely reflecting minor differences in the proportion of individuals <50 mm FL (entrance = 19%, exit = 9%) and 130–159 mm (entrance = 8%, exit = 29%) (Figure 8b). Unspecked hardyhead and carp gudgeon were not sampled in adequate numbers to allow statistical analysis, but length-frequency distributions appeared similar between entrance and exit trapping events (Figure 8c, d). All golden perch (>400 mm TL) and common carp sampled (>300 mm FL) were reproductively mature adults, whilst the two silver perch sampled represented juvenile (129 mm FL) and adult individuals (390 mm FL).

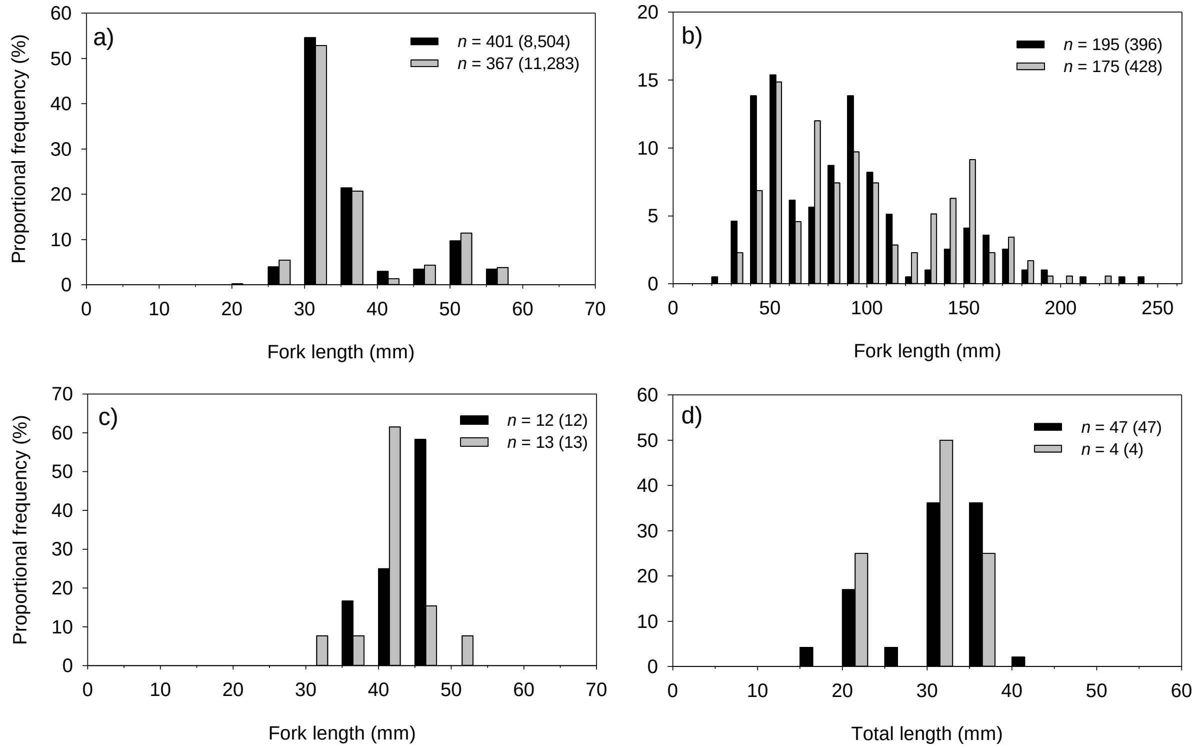

Figure 8. Length-frequency distributions of a) Australian smelt, b) bony herring, c) unspecked hardyhead and d) carp gudgeon, sampled from the entrance (*black bar*) and exit (*grey bar*) of the Deep Creek vertical-slot fishway in 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species.

4. DISCUSSION

The restoration of hydrological and biological connectivity, through the removal of barriers to movement or construction of fishways, is a central focus of management interventions in the Pike Anabranch under RRP and SARFIIP. The Deep Creek Regulator vertical-slot fishway represents the first of four new fishways proposed for the system; a fishway is being constructed as part of the upgrade of the Margaret-Dowling inlet regulator (planned for completion late-2016), whilst others will be incorporated in the proposed Tanyaca Creek and Pike River regulators (planned for completion in 2019). Fundamental to effective fishway construction programs, is assessment of passage efficiency against design criteria. The specific objective of the current study was to sample the entrance and exit of the Deep Creek fishway to evaluate passage efficiency, in regards to the abundance and size classes of species able to successfully ascend.

4.1. Fishway use

A total of eight species were recorded using the Deep Creek fishway in 2015/16, comprising 50% of the species previously recorded at the site from 2009 to 2016 (Beyer *et al.* 2010, Bice *et al.* 2016). This represents the majority of species expected to use the fishway and those that were absent are either uncommon at the site (e.g. Murray cod *Maccullochella peelii* and redfin perch *Perca fluviatilis*) or are not commonly encountered in fishways in the lower River Murray (e.g. freshwater catfish *Tandanus tandanus*, dwarf flat-headed gudgeon *Philypnodon macrostomus* and goldfish *Carassius auratus*) (Baumgartner *et al.* 2008, Stuart *et al.* 2008).

Australian smelt and bony herring were the most abundant species sampled using the fishway. These two species are among the most abundant fishes in the Pike Anabranch (Bice *et al.* 2016) and more broadly in the lower River Murray (Leigh *et al.* 2007, Wilson *et al.* 2013, Bice *et al.* 2014). Despite no targeted studies on the movement of these species, they are commonly sampled in substantial numbers undertaking longitudinal riverine migrations at fishways on main channel weirs of the lower River Murray (Baumgartner *et al.* 2008, Stuart *et al.* 2008) and lateral movements between riverine and off-channel habitats (Connallin *et al.* 2011), suggesting both types of movement are important components of their life histories.

Only low numbers of golden perch (*Macquaria ambigua ambigua*), silver perch (*Bidyanus bidyanus*) and common carp (*Cyprinus carpio*) were sampled using the fishway, whilst Murray cod were absent. This is the first fishway on an anabranch in the lower River Murray to be sampled, so the potential biomass of large-bodied fish attempting to move upstream at the Deep Creek regulator was uncertain. Nonetheless, the presence of barriers to fish movement in the

Pike system downstream of Deep Creek likely had an influence on this result. Earthen banks on the Upper Pike River (i.e. Col Col), and between Mundic and Tanyaca creeks (i.e. Banks E to F1), dictate that at River Murray flow ≤40,000 ML.day^{-1}, fish are unable to reach Deep Creek from the lower part of the Pike Anabranch and River Murray downstream. As such, during assessment in the current project, only those fish currently residing upstream of the aforementioned barriers, and downstream of the Deep Creek regulator, could access the fishway. Sampling of eight sites in this reach using standardised boat-electrofishing in 2016 (12 x 90s 'on-time' electrofishing shots per site) detected only low numbers of golden perch (*n* = 11), silver perch (*n* = 1) and Murray cod (*n* = 1), and moderate numbers of common carp (*n* = 114) (Bice *et al.* 2016). Reinstatement of connectivity between the lower and upper segments of the Pike Anabranch, and the River Murray downstream, upon completion of regulators and fishways on the Pike River and Tanyaca Creek, will likely see increased movement of large-bodied fishes into the Pike and greater use of the Deep Creek fishway.

4.2. Passage efficiency

There was no significant difference in the abundance of Australian smelt and bony herring between the entrance and exit of the fishway, whilst for several less common species (common carp, Murray rainbowfish and unspecked hardyhead), numbers sampled were similar between entrance and exit trapping, suggesting high passage efficiency at this fishway for the majority of species sampled. Furthermore, length-frequency distributions for Australian smelt were similar between the entrance and exit, indicating passage was facilitated for the full size range of individuals (23–58 mm FL) attempting to ascend the fishway. A greater proportion of bony herring <50 mm FL were sampled at the entrance (~19% of catch) than the exit (~9% of catch) of the fishway, suggesting a level of obstruction for this size class, but differences were relatively minor and a substantial number of small size classes of bony herring successfully ascended the fishway. With all species combined, the fishway successfully provided passage for fish from 23 to 481 mm in length and thus, whilst few fish were sampled from the larger end of the size range design criteria (i.e. >500 mm), this fishway is operating to biological design criteria.

The number of carp gudgeon sampled at the entrance was 10-fold that from the exit, but the species was not sampled in sufficient numbers from the exit to allow statistical comparisons. These data suggest either poor passage efficiency for this species at Deep Creek and/or low migratory motivation. Carp gudgeon typically do not grow >50 mm TL and exhibit poor swimming ability (Bice 2004). In a laboratory trial, prolonged swimming was hindered at water velocities >0.2

m.s^{-1}, whilst mean burst velocities of ~0.5 m.s^{-1} were recorded (Bice 2004). Water velocities in the vertical-slots of the Deep Creek fishway range from 0.95 to 1.54 m.s^{-1}, depending on head loss, suggesting velocities are likely insurmountable by a large proportion of carp gudgeon, whilst internal turbulence and overall fishway length may also contribute to poor passage. Low passage efficiency has also been recorded for this species in fishways on main channel weirs of the lower River Murray (Baumgartner *et al.* 2008, Stuart *et al.* 2008). Altering the design of vertical-slot fishways to produce more benign internal hydraulics (e.g. larger pools, more baffles/pools, smaller slot widths) and thus cater for the passage of carp gudgeon would result in substantial increases in capital cost and potentially hinder the passage of other species. In the current study, a low number of carp gudgeon were able to ascend the fishway, suggesting passage has improved relative to before the upgrade of the Deep Creek Regulator, and no modifications are suggested to the current fishway given the unlikelihood of improving passage for this species in the existing vertical-slot fishway. Additionally, this species could be considered a 'generalist' and is highly abundant, and broadly distributed in the lower River Murray.

Whilst only low numbers of large-bodied fish were sampled from the fishway and passage efficiency could not be statistically assessed, the successful passage of Australian smelt and bony herring, including small size classes, suggests passage efficiency should be high for silver perch, golden perch and Murray cod. The swimming ability of fishes typically increases with size (Beamish 1978), and given Australian smelt <40 mm FL successfully ascended the fishway, successful passage is likely for larger species. Additionally, high passage efficiency has been recorded for juvenile and adult silver perch and golden perch from vertical-slot fishways on the lower River Murray that have similar internal water velocities and turbulence to the Deep Creek vertical-slot (Baumgartner *et al.* 2008, Stuart *et al.* 2008).

Fishway effectiveness is typically viewed as a function of passage efficiency and attraction efficiency, which is defined as the ability of fish attempting to migrate to locate the fishway entrance (Cooke and Hinch 2013). Reliably assessing attraction efficiency typically involves mark-recapture or telemetry studies, which are difficult when regarding small-bodied fishes and species that are not undertaking driven, often obligate migrations (e.g. salmonids). Whilst we assessed passage efficiency, but not attraction efficiency, we propose that the Deep Creek fishway is likely to have relatively high attraction efficiency, and subsequently, be highly effective. The proportion of overall discharge carried by a fishway is considered a primary determinant of fish attraction (Larinier 2002). The Deep Creek Regulator spans a narrow stream cross-section (~10 m) and fishway discharge is typically ~10% of overall regulator discharge; this proportion is greater than criteria commonly used for fishway design in Europe (i.e. 5%, Larinier 2002) and greater than is typical of fishways on main channel weirs of the River Murray. Additionally, whilst entrance hydraulics to the Deep Creek fishway may at times appear highly turbulent to an observer, the small sub-surface wall extending from the fishway entrance was developed using physical modelling to specifically promote favourable entrance hydraulics (Mallen-Cooper 2011). Indeed, measurements of water velocities immediately downstream of the entrance during sampling suggested the integrity of downstream flow was maintained below the entrance and water velocities were <0.9 $m.s^{-1}$.

5. CONCLUSION

Most of the fish species likely to undertake movements between the Pike Anabranch and lower River Murray successfully ascended the vertical-slot fishway on the Deep Creek Regulator. The fishway facilitated effective passage for the most abundant species sampled, including small individuals (i.e. 30–50 mm), and thus, has reinstated connectivity at this site for the first time since construction of the original Deep Creek Regulator in the 1950s.

In order to optimise fish passage at Deep Creek, future operation of the regulator and fishway should consider variability in headwater (Lock 5 weir pool) and tailwater levels (Deep Creek downstream of the regulator), and entrance hydraulics. Headwater levels are likely to vary by ±0.5 m as a result of weir pool manipulation (DEWNR 2015), whilst tailwater levels will vary up to +1.5 m with operation of the proposed Pike River and Tanyaca Creek Regulators. When the Lock 5 weir pool is raised, discharge through the Deep Creek Regulator needs to be increased to raise tailwater levels and maintain head loss across the fishway at <1 m. The operations manual for the regulator and fishway presents a guide for monitoring water levels and adjusting discharge to meet these head loss criteria (URS 2012). Importantly, discharge through the two flume gates on the regulator should be manipulated to ensure there is no or only minimal flow recirculation that may hinder attraction of fish to the entrance of the fishway. In most cases this will involve proportioning greater discharge to the northern gate than the southern gate in a ratio of typically 1:3. Nonetheless, specific gate configuration will be dependent upon overall regulator discharge and head loss, and should be reassessed by operators (DEWNR and/or SA Water) upon any change to these parameters.

This fishway represents the first component of a broader program aimed at improving connectivity and facilitating fish passage throughout the Pike Anabranch. The capacity for fish to move from the River Murray downstream of Lock 5 through the lower and upper portions of the Pike Anabranch, and into the River Murray upstream of Lock 5, will be fully realised following the construction of regulators and associated fishways on Tanyaca Creek and the upper Pike River, as well as the other inlet creek (e.g. Margaret-Dowling). The current study demonstrates the effectiveness of the vertical-slot fishway on the Deep Creek regulator and similar designs are likely applicable on other regulatory structures in the system or at other sites in the lower River Murray with similar fish movement requirements (e.g. Katarapko Anabranch system). Importantly, for fish passage to be optimised throughout the Pike Anabranch, the hydraulic and biological design criteria of fishways on downstream structures must, at a minimum, match those for Deep Creek.

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