Inland Waters & Catchment Ecology

Murray cod (*Maccullochella peelii*) movement during regulator operation and passage efficiency of Slaney and Pipeclay Creek fishways, Chowilla, 2016–17

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SARDI Publication No. F2017/000349-1
SARDI Research Report Series No. 961

SARDI Aquatics Sciences
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January 2018

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This publication may be cited as:
Fredberg, J. and Zampatti, B.P. (2018). Murray cod (*Maccullochella peelii*) movement during regulator operation and passage efficiency of Slaney and Pipeclay Creek fishways, Chowilla, 2016–17. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2017/000349-1. SARDI Research Report Series No. 961. 57pp.

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SARDI Research Report Series No. 961

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Date:	30 January 2018
Distribution:	DEWNR, SAASC Library, Parliamentary Library, State Library and National Library
Circulation:	Public Domain

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

This project has been funded through the *Chowilla Intervention Monitoring* program, a component of *The Living Murray* (TLM) program of the Murray-Darling Basin Authority. The project was managed by Jan Whittle (Department of Environment, Water and Natural Resources, DEWNR). The authors thank the following SARDI staff who assisted with this project: Ian Magraith, Arron Strawbridge and Neil Wellman for technical assistance; Charles James for post-processing of ADCP data and analyses; and Chris Bice for statistical analysis and assistance throughout the report writing process. The authors also thank Jan Whittle, Allison Stokes and Tony Herbert (DEWNR) for oversight, and involvement in current and historical aspects of this project and ongoing support of fish ecology research in Chowilla. Many thanks to Warren Beer, Tony Waye and Robbie Bonner (SA Water) for on-going logistical support and hospitality at Lock 6. Thank you to Jan Whittle (DEWNR) and Chris Bice (SARDI) for constructive reviews of this document.

EXECUTIVE SUMMARY

The Chowilla floodplain is the largest remaining area of undeveloped floodplain in the lower River Murray. Due to the construction of Lock 6, the Chowilla Anabranch system exhibits permanent lotic (flowing water) habitats, which are ecologically important, yet rare in the highly regulated lower River Murray. Nonetheless, the Chowilla floodplain has become increasingly degraded as a consequence of river regulation, grazing and drought. In response, the Chowilla Creek regulator and ancillary structures were constructed with the objective of using large-scale artificial floodplain inundation to maintain or improve floodplain condition (e.g. the health of long-lived vegetation). In addition, regulators on Slaney and Pipeclay creeks were upgraded, including integrated Denil and vertical-slot fishways to improve fish passage between Chowilla and the River Murray.

Artificially raising water levels with a regulator has the potential to alter the hydrodynamics of lotic habitats, interrupt longitudinal connectivity, and decouple riverine and floodplain hydrographs. As such, operation of the Chowilla Creek regulator poses significant risks to the movement, habitat use, spawning and recruitment of native fish, in particular, Murray cod.

The current project comprised two distinct components: 1) an assessment of fish passage efficiency at the Slaney and Pipeclay Creek fishways, and 2) maintenance of existing radio telemetry infrastructure and investigation of Murray cod movement and habitat use in Chowilla, in relation to a high level (~19.78 m) regulator operation from 10 August to 10 November 2016.

As part of the fishway assessment component, we:

1. Sampled the entrance and exit of each fishway to evaluate passage efficiency against design criteria in regards to the abundance and size classes of species able to successfully ascend; and
2. Make recommendations on future fishway operation in light of results of the current project.

As part of the Murray cod movement component, we:

1. Manually located radio-tagged Murray cod in Chowilla and the adjacent River Murray;
2. Interrogated remote logger data from the network of 9 receiver towers across Chowilla; and
3. Characterised the hydraulic nature of the habitats used by Murray cod during regulator operation.

Fishway assessments

A total of 3,036 fish from 10 species were sampled collectively across the Denil and vertical-slot fishways at Slaney and Pipeclay weirs in February 2017. The overall catch was dominated by unspecked hardyhead (*Craterocephalus fulvus*) and bony herring (*Nematalosa erebi*), with smaller contributions from common carp (*Cyprinus carpio*), Australian smelt (*Retropinna semoni*) and golden perch (*Macquaria ambigua ambigua*). At both weirs, fish assemblages were significantly different between the Denil and vertical-slot fishways. These differences were driven by greater abundances of the small-bodied (adult length <100 mm) unspecked hardyhead, Australian smelt and eastern gambusia (*Gambusia holbrookii*) at the vertical-slot fishways, and greater abundances of the medium- to large-bodied (adult length >100 mm) bony herring and golden perch at the Denil fishways.

In regards to passage efficiency, the Denil fishways facilitated the passage of golden perch and bony herring, but the passage of small-bodied species (e.g. unspecked hardyhead) was obstructed. This was expected, given the Denil fishways were specifically designed for the passage of fish >100 mm total length, TL. Conversely, the vertical-slot fishways were designed for the passage of small-bodied fishes (<100 mm TL), and demonstrated high passage efficiency for these species (e.g. unspecked hardyhead and Australian smelt) and large-bodied fishes (golden perch). Fish as small as 21 mm in length successfully ascended the vertical-slot fishways. Several species were found in greater numbers in the fishway exit than the entrance suggesting high passage efficiency and potential entrance trap ‘shyness’ (aversion to the fishway entrance trap) caused by the trap being visible to fish entering the fishway. Overall, this study suggests the Denil and vertical-slot fishways on Slaney and Pipeclay weirs are functioning as designed.

Murray cod movement and hydraulic characterisation

Over the period of regulator operation (10 August to 10 November 2016), the movements of radio-tagged Murray cod (n = 54) could be grouped into three distinct categories based on total linear ranges: 1) localised small-scale movement (<2 km), 2) medium-scale (2–10 km) movement within Chowilla and 3) broad-scale movement (>10 km) within Chowilla or the main channel of the River Murray, or between these habitats. These movements are similar to those previously reported for radio-tagged Murray cod in Chowilla during a range of conditions, including low within-channel flows and overbank flooding (with no regulator in place), and during previous regulator operations.

Six radio-tagged cod were located in the immediate vicinity of the regulator during operation. Four fish moved downstream through the Chowilla system (via Chowilla Creek) until reaching the regulator and either immediately returned upstream or remained in the vicinity of the regulator for 1–3 months before returning upstream. Another two radio-tagged Murray cod approached the regulator from downstream. One fish approached the regulator in early September and remained downstream for just under a month before returning to the River Murray. The other fish demonstrated similar movement patterns, but after 3 months in close proximity to the regulator, this fish ascended the regulator vertical slot fishway after multiple attempts.

Throughout the River Murray, Murray cod show an affinity for hydraulically diverse, flowing water (lotic) habitats, with abundant physical structure, particularly large woody debris. Alteration of the unique hydrodynamic characteristics of lotic habitats in the Chowilla system is considered a substantial risk of operating the Chowilla Creek regulator. During the peak of regulator operations in both 2014 and 2016, mean water velocities in core habitats in Chowilla and Slaney Creek decreased significantly (up to 50%) compared to periods of no regulator operation.

Future Research and Management

The following research and management priorities will assist with the operation of regulating structures at Chowilla, including mitigating risks and ultimately improving conservation outcomes for Murray cod and other fishes:

- Establishing and maintaining appropriate entrance conditions (hydraulics) at the Slaney and Pipeclay fishways, thus enabling fish to find and enter the fishways, is imperative to successful fishway function. Determining attraction efficiency at these fishways over a range of hydraulic/hydrological conditions, will assist with understanding fishway function and maximising fishway effectiveness at these sites.

- Installation of PIT readers on Slaney and Pipeclay fishways would enable further exploration of fishway function (including attraction efficiency) and the broader scale movement of fishes within Chowilla and between Chowilla and the River Murray.

- Ongoing monitoring of the demographics and abundance of Murray cod in the Chowilla region remains crucial. This would be bolstered by the allied monitoring of these pararmeters in a control region of the lower River Murray where Murray cod remain reasonably abundant, but are not influenced by regulator operation (e.g. in the River Murray downstream of Lock 4).

- A water velocity threshold of ≥0.18 m s^{-1} is currently used to maintain favourable hydraulic conditions for Murray cod. Data from recent investigations, however, indicate that a more biologically relevant threshold would be ≥0.30 m s^{-1}, in core Murray cod habitats throughout the Chowilla region.

- The hydraulic and biological function of the fishways on the Chowilla Creek regulator should be assessed. In parallel, fishway attraction efficiency could be investigated using electronic tagging approaches (e.g. combined PIT and radio tags).

Keywords: Fish passage, radio telemetry, River Murray, Chowilla Creek Regulator.

1. INTRODUCTION

1.1. Background

The Chowilla floodplain is the largest remaining area of undeveloped floodplain in the lower River Murray (O'Malley and Sheldon 1990). Due to the construction of Lock 6, the Chowilla Anabranch system exhibits permanent lotic (flowing water) habitats in what previously would have been ephemeral streams. Lotic habitats are now uncommon in the South Australian section of the River Murray, as the construction of locks and weirs has transformed the river into a series of cascading weir-pools that, under low flows (i.e. <10,000 ML.day^{-1}), are predominantly lentic (still water) in character (Walker 2006). The presence of flowing habitats within Chowilla has been attributed to the maintenance of remnant populations of endangered flora and fauna that are uncommon elsewhere in the lower Murray, including Murray cod (*Maccullochella peelii*).

The Chowilla floodplain is also characterised by significant river red gum (*Eucalyptus camaldulensis*) and black box (*Eucalyptus largiflorens*) woodlands that have become increasingly degraded as a consequence of river regulation, grazing and drought (MDBC 2006). In response, the Chowilla Creek regulator and ancillary structures were constructed with the objective of using large-scale artificial floodplain inundation to maintain or improve ‘floodplain condition’. Operation of the regulator, however, may pose several ecological risks, including: 1) altering riverine hydraulics (conversion of flowing water to still) to the detriment of lotic biota, such as Murray cod; and 2) altering biological connectivity between habitats downstream and upstream of the regulator. Ultimately, operation of the regulator may impact the movement and habitat use, and population dynamics of Murray cod (Mallen-Cooper *et al.* 2011, Koehn *et al.* 2014). In light of these risks, the Chowilla Creek regulator, is operated in accordance with guidelines for operation and risk mitigation outlined in an *Operations Plan* and an *Event Plan and Hazard Mitigation Strategy* (DEWNR, unpublished). Understanding the influence of regulator operation on the ecology and population dynamics of Murray cod is integral to minimising risk to the existing ecological values of the Chowilla system.

In 2014–15, the Goyder Institute funded a one-year investigation of Murray cod movement and habitat use during initial operation of the Chowilla Creek regulator (SARDI unpublished data). This study demonstrated that regulator operation (water raised to a level of 19.1 m AHD) at River Murray discharge at the South Australian border (QSA) of ~9,000–10,000 ML.day^{-1} significantly altered the hydraulic characteristics of Murray cod habitats and impeded the movement of Murray cod in Chowilla Creek. In 2016, it was proposed to operate the Chowilla Creek regulator to a height of ~19.4 m AHD if QSA reached ~15,000 ML.day^{-1} and up to ~19.75 m AHD if QSA reached ~35,000 ML/d over a period of approximately 3 months.

Slaney and Pipeclay creeks are two of the primary influent creeks to Chowilla, and since 1930, have been regulated by weirs constructed in association with Lock 6. A lack of fish passage at the weirs has inhibited the movement of fishes between the Chowilla system and the River Murray, and caused substantial accumulations of both small and large-bodied native fishes downstream of the weirs in spring–autumn (Zampatti *et al.* 2011). In association with the construction of the Chowilla Creek regulator in 2014, the weirs on Pipeclay and Slaney creeks were replaced, including the construction of integrated Denil and vertical-slot fishways. These 'paired' fishways represented novel designs and aimed to enhance connectivity with the River Murray for a variety of species and size class of fish. Critical to any fishway construction program is the assessment of the effectiveness of the fishways against their design specifications and biological objectives. These data can inform fishway operations and future fishway designs.

1.2. Objectives

The current project comprised two distinct components: 1) assessment of fish passage efficiency of the Slaney and Pipeclay fishways; and 2) maintenance of an array of remote radio-telemetry receivers and investigation of Murray cod movement in Chowilla, including in relation to regulator operation.

As part of the fishway assessment component, we:

1. Sampled the entrance and exit of each fishway to evaluate passage efficiency against design criteria in regards to the abundance and size classes of fish species able to successfully ascend; and
2. Make recommendations on future fishway operations in light of results of the current project.

As part of the Murray cod movement component, we:

1. Manually located radio-tagged Murray cod in Chowilla and the adjacent River Murray;
2. Interrogated remote logger data from the network of 9 receiver towers across the anabranch; and
3. Characterised the hydraulic nature of the habitats used by Murray cod during regulator operation.

These tasks are fundamental to improving confidence in risk mitigation and management of the Chowilla Creek regulator, enhancing understanding of the spatial ecology of Murray cod and optimising fishway operation.

2. METHODS

2.1. Study Site

The Chowilla Anabranch and Floodplain system is comprised of a series of anabranching creeks, backwaters, wetlands and terminal lakes that bypass Lock 6 on the River Murray, South Australia (Figure 1). The Chowilla system is part of the Riverland Ramsar site, a Wetland of International Importance for nationally threatened species, habitats and communities, and is considered an *Icon Site* under the Murray-Darling Basin Authority's *The Living Murray Program* (MDBA 2016).

Two of the primary influent creeks, Pipeclay and Slaney, were regulated with weirs in association with the construction of Lock 6 in the 1930's (Figure 1). In 2014, these weirs were upgraded, including construction of integrated Denil and vertical-slot fishways to facilitate fish passage between the creeks and the main river channel. Also in 2014, an inaugural mid-level testing operation of the Chowilla Creek regulator was undertaken. This was followed by a low level testing operation in 2015 to generate within-channel variability in water levels and then in 2016 a further high-level testing operation occurred with the aim of using large-scale artificial floodplain inundation to maintain or improve floodplain condition.

In order to investigate the spatial ecology of fishes in the Chowilla system, a network of nine ATS radio receiver towers has been established enabling the tracking of radio tagged fish throughout Chowilla and the adjacent River Murray (Figure 1).

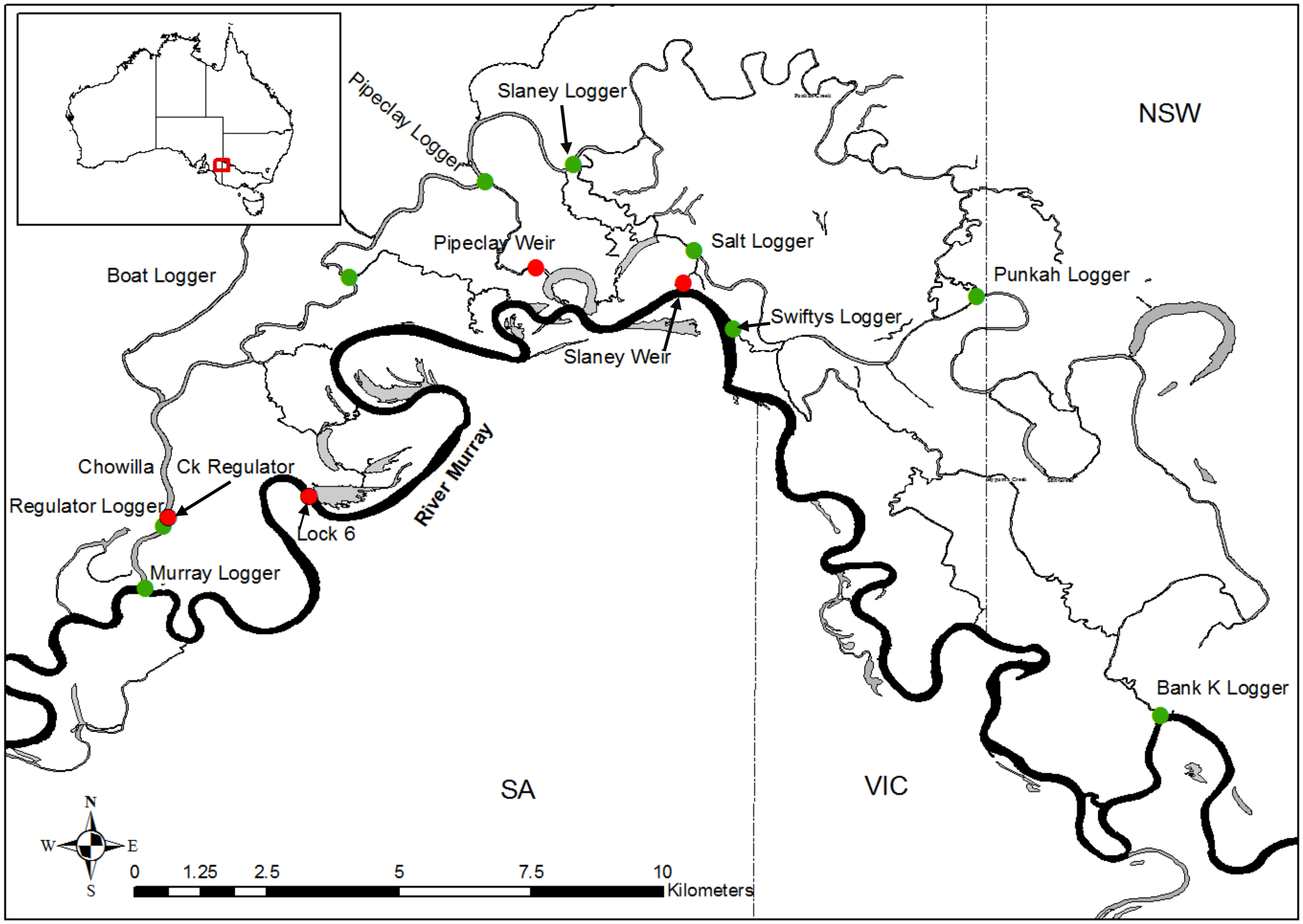

Figure 1. Map of the Chowilla Anabranch system, in the lower River Murray, South Australia. The red circles depict major regulating structures within the system (Chowilla Creek regulator, Pipeclay and Slaney Creek Weirs, and Lock and Weir 6), whilst the green circles depict the nine ATS radio receiver towers used to monitor fish movement throughout Chowilla.

2.2. Pipeclay/Slaney weirs and fishways

In 2014, Pipeclay and Slaney weirs were upgraded with automated overshot gates (used to manipulate discharge through the structure) and fishways. Dual, integrated Denil and vertical-slot fishways were constructed on each weir. The high gradient (1:10) Denil fishways and small-pool (1.5 m by 1.1 m), high-gradient (1:16.6), low-turbulence (32 W/m^3) vertical-slot fishways were designed to facilitate the passage of large-bodied fish (>100 mm TL) and small-bodied fish (<100 mm TL), respectively (Figure 2).

The fishways at Pipeclay and Slaney weirs are of the same design/layout, except that Pipeclay fishway is on the left bank (looking downstream) and has a typical maximum head difference of 2.8 m (up to 3.4 m, if Lock 6 pool is raised), while Slaney fishway is on the right bank and has a typical maximum head difference of 1.92 m (up to 2.52 m, if Lock 6 pool is raised). In both fishways, multiple internal gates are used to adjust head differential across the fishways as headwater and tailwater change. The vertical-slot fishways are covered with grating that can be removed during periods of high tailwater (e.g. regulator operation) to allow greater access for fish attempting to use the fishway.

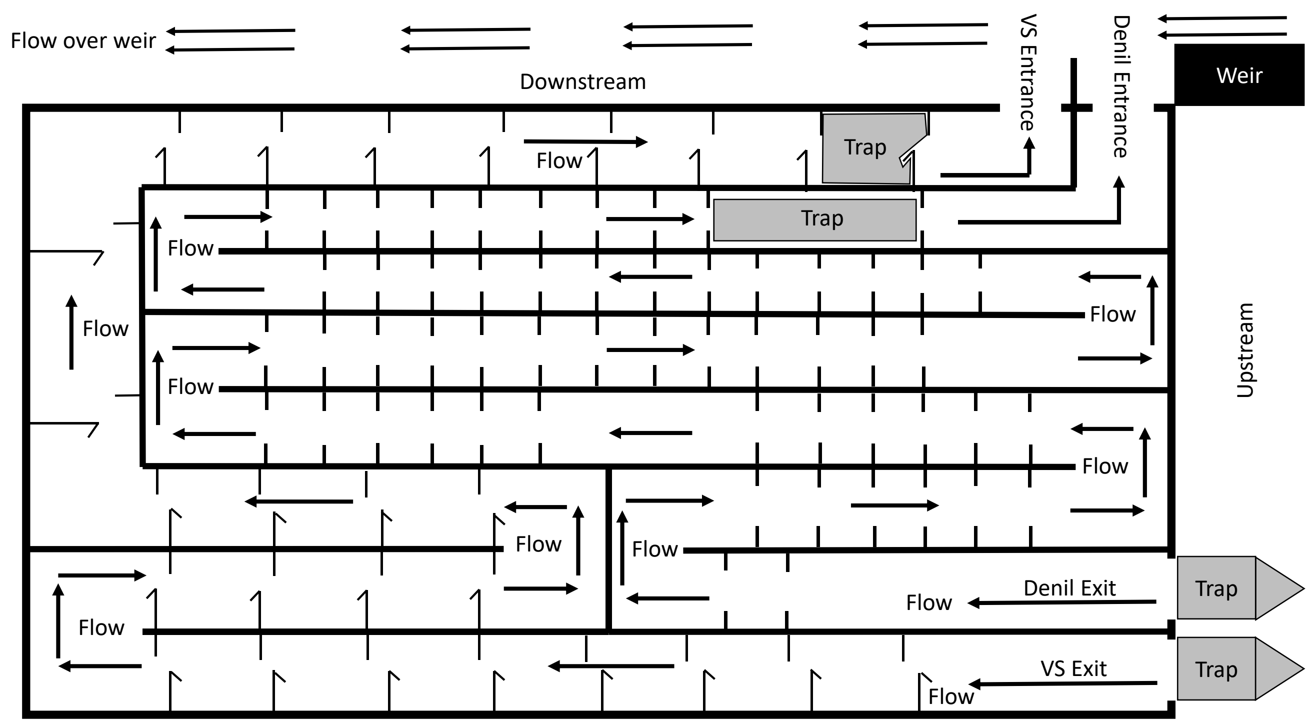

Figure 2. Schematic representation of the Denil and vertical-slot fishway at Pipeclay weir. The location of fishway traps for both entrance and exit trapping events are indicated.

2.3. Fish trapping

Operation of the Chowilla Creek regulator in August–November 2016 (reaching a peak level of 19.78 m AHD in late September) and natural flooding in November–December 2016 (peak QSA = ~95,000 ML/day) inundated (drowned-out) Pipeclay and Slaney Creek fishways, delaying sampling until early 2017. Fish were sampled from Pipeclay and Slaney Creek fishways over three weeks (Monday-Friday) from 30 January to 24 February 2017 when flow and upstream water levels were ~9,500 ML day^{-1} (QSA) and ~19.30 m AHD, respectively.

During each week, fish were simultaneously sampled from the Denil and vertical-slot fishways at Pipeclay and Slaney weirs. On consecutive days, the entrance and the exit of the fishways were sampled overnight (~24 hours). As such, fishway entrances and exits were sampled twice within each sampling week. Thus, six sampling events were conducted for the entrance and exit of the Denil and vertical-slot fishways at each weir, and these sampling events were treated as replicates for subsequent statistical analysis.

The entrances of the fishways were sampled using specifically designed cage traps constructed from 'Qubelok' aluminium square tube (25 x 25 mm) and clad with a combination of 3 mm perforated aluminium sheet and 6 mm knotless mesh (Figure 3a and b). These traps were designed to fit within the first cells of the fishways (Figure 2), and configured to sample all fish entering the fishway, with nylon brushes used to ensure fish could not bypass the trap (Figure 3a and b). Entrance traps incorporated double 'cone-shaped' entrances (vertical-slot: top and bottom cone: 100 mm wide x 550 mm high; Denil: top and bottom cone: 200 mm wide x 550 mm high) to minimise escape. The exit traps were mounted against the upstream side of the fishway exits, using guides for the fishway 'de-watering gates' and oriented to catch all fish exiting the fishways. The exit traps incorporated a collapsible 'net-bag' to increase holding room for sampled fish and ease of lifting (Figure 3c). Both exit traps utilised single 'cone-shaped' entrances (vertical-slot cone: 100 mm wide x 850 mm high; Denil cone: 200 mm wide x 1360 mm high).

All fish collected were removed from traps and transferred to aerated 200 L holding tubs. Fish were identified to species and enumerated, and a sub-sample of up to 50 individuals per species were measured for length, per trapping event. Large-bodied species (i.e. Murray cod, golden perch, silver perch, freshwater catfish and common carp) collected ascending the fishways were externally tagged (dart tag) and PIT (passive integrated transponder) tagged. Water physico-chemical parameters (dissolved oxygen, pH, Conductivity and temperature) and upstream and downstream water levels (m AHD Australian Height Datum) were measured daily during sampling. Headloss (the height difference between the upstream and downstream water surface level) across the first baffle at the fishway entrance was also measured daily at the vertical-slot fishways.

Figure 3. Sampling traps for both fishway designs: a) vertical-slot entrance trap, b) Denil entrance trap, and c) vertical-slot and Denil exit traps.

2.4. Fishway data analysis

Fishway use

Fishway use, in regards to species identity and abundance (fish.hour^{-1}.trap event^{-1}, entrance and exit samples pooled), was compared between Denil and vertical-slot fishways at both Pipeclay and Slaney weirs using multidimensional scaling (MDS) ordination and PERMANOVA (Permutational Anova) ($\alpha = 0.05$). 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). Similarity percentage (SIMPER) analysis was used to determine the species that contributed substantially to differences in fishway use. A 60% cumulative contribution cut-off was applied.

Passage efficiency

Passage efficiency at each fishway was assessed by comparing the relative abundance (fish.hour^{-1}.trap event^{-1}) of the most abundant species (i.e. where >20 individuals were sampled over the study period) sampled 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.

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

2.5. Radio-tagged Murray cod and tracking

Radio transmitters, passive integrated transponders (PIT) and dart tags

Radio-transmitters have been implanted into Murray cod across multiple tagging events from 2007–2016, as part of investigations on the ecology of Murray cod in the Chowilla region (Leigh and Zampatti 2011, Wilson *et al.* 2015, Wilson *et al.* 2016, Fredberg and Zampatti 2017). Radio transmitters implanted into Murray cod were cylindrical 150 MHz, internal transmitters with a 30 cm long (0.7 mm diameter) trailing antenna (Advanced Telemetry Systems (ATS), Insanti, MN, USA). Three sizes of transmitter were used: models F1850, F1855 and F1860, weighing 25, 87 and 150 g in air and having warranted battery lives of 560, 1657 and 3937 days, respectively. Transmitters were fitted with a mortality circuit that activated and produced a distinct signal if the fish (i.e. transmitter) did not move for a period of ≥8 hours. Each radio-tagged fish was also implanted with a passive integrated transponder (PIT) tag (Texas Instruments RI-TRP-REHP half-duplex eco-line glass transponders, 23.1 mm long, 3.85 mm in diameter and weighing 0.6 g in air) to facilitate detection of these fish in fishways fitted with PIT tag readers on the Chowilla Creek regulator and main channel Locks and Weirs of the River Murray (Barrett and Mallen-Cooper 2006). Plastic tipped dart tags (PDA or PDS, Hallprint, Victor Harbour, SA, Australia) were used to enable external visual identification of radio-tagged fish and reporting of captures by anglers.

Fish capture and tag implantation

The 54 Murray cod tracked in this study were originally tagged between October 2007 and May 2016 (Table 1). Fish were captured throughout Chowilla and in the adjacent River Murray main channel using a Smith-Root® 5.0 KVA boat mounted electrofishing unit. Following capture, Murray cod were anaesthetised using 1.5 ml of AQUI-S® (Aqui-s, Lower Hutt, New Zealand) per 50 L of river water. Length and weight were recorded and fish were inverted onto a v-shaped cradle. The gills were irrigated throughout the surgery with a 50 % dilute solution of AQUI-S. An incision of 3–4 cm was made through the ventral wall slightly dorsal to the mid-ventral line beginning adjacent the pelvic fin and extending towards the anus. The sex of the fish was determined and the transmitter inserted into the abdominal cavity. To ensure fish buoyancy was not compromised transmitter weight was ≤2 % of total body mass.

A shielded-needle technique (Adams *et al.* 1998) was used to guide the trailing antenna through the lateral body wall posterior to the incision. The incision was closed with two internal and three external sutures. A long-term (2 weeks) antibiotic Baytril® (Bayer Australia, Pymble, NSW, Australia) at a dose of 0.1 mL kg^{-1} was then injected in the dorsal musculature. A PIT tag was inserted in the dorsal musculature forward of the dorsal fin or, in large fish, in the cheek muscle, and a dart tag was positioned between the dorsal pterygiophores. Following recovery, fish were released at their capture location.

Table 1. Original capture date and location, sex, total length (mm) and weight (g) of 54 radio-tagged Murray cod tracked from July 2016 to May 2017 in association with operation of the Chowilla Creek regulator.

Fish Number	Date Tagged	Location	Sex	Length at capture (mm)	Weight at capture (g)
150.302 (24)	23/10/2007	Slaney Creek 310m D/S Salt Creek logger	Unknown	810	9000
150.302 (19)	1/04/2008	Slaney Creek opposite billabong	Unknown	910	12700
150.483 (24)	1/04/2008	Slaney Creek ~700m U/S Chowilla Creek junction	Male	975	19000
150.503 (24)	10/04/2008	Chowilla Creek near Slaney Creek	Female	1050	21000
150.362 (21)	20/01/2009	Salt Creek U/S Little Slaney Creek junction	Unknown	1150	26500
150.483 (25)	20/01/2009	Little Slaney Creek junction	Male	1230	30000
150.481(50)	5/12/2012	Chowilla Creek ~400m u/s Boat Creek Junction	Unknown	583	3400
150.502(54)	14/05/2013	River Murray ~1300m U/S Chowilla Creek	Male	1005	18200
150.521(53)	14/05/2013	River Murray U/S Chowilla woolshed	Female	885	16000
150.362(53)	15/05/2013	U/S Boat Creek (Chowilla Creek condition monitoring site)	Female	825	13000
150.502(50)	15/05/2013	Below Boat Creek logger tower	Female	514	2058
150.302(52)	16/05/2013	Lower Slaney Creek	Male	955	16200
150.521(52)	16/05/2013	Slaney Creek (mid)	Male	970	22500
150.542(52)	16/05/2013	Lower Slaney Creek ~100m U/S Chowilla junction	Female	910	16500
150.542(55)	16/05/2013	Slaney Creek (mid)	Female	820	11000
150.521(55)	17/05/2013	Chowilla Creek D/S Boat Creek	Female	920	13500
150.302(50)	21/05/2013	Slaney Creek ~750m D/S billabong	Immature	485	1395
150.481(51)	21/05/2013	Slaney Creek ~800m D/S billabong	Male	581	3623
150.481(54)	21/05/2013	Slaney Creek immediately outside billabong	Male	1180	33000
150.502(51)	21/05/2013	Island opposite Pipeclay Creek junction	Immature	454	1379
150.342(53)	4/06/2013	Little Slaney Creek	Male	1100	29000
150.481(53)	4/06/2013	Slaney Creek at Punkah Island launch	Male	1180	37000
150.542(56)	4/06/2013	Slaney Creek at Punkah Island launch	Female	1170	31000

Table 1 cont. Original capture date and location, sex, total length (mm) and weight (g) of 54 radio-tagged Murray cod tracked from July 2016 to May 2017 in association with operation of the Chowilla Creek regulator.

Fish Number	Date Tagged	Location	Sex	Length at capture (mm)	Weight at capture (g)
150.302(54)	2/12/2013	River Murray immediately opposite Chowilla Junction	Male	675	4930
150.362(52)	2/12/2013	River Murray ~1km us Murray/Chowilla Junction	Female	1080	22000
150.302(53)	3/12/2013	Chowilla Creek 400m U/S bridge	Male	920	13000
150.342(51)	5/12/2013	Slaney Creek ~ 1500m u/s Chowilla Creek	Unknown	450	1300
150.481(52)	5/12/2013	Slaney Creek D/S old island	Male	1190	32000
150.521(59)	5/12/2013	Slaney/Chowilla Creek junction	Male	770	10000
150.542(53)	6/12/2013	Chowilla Creek U/S Boat Creek	Female	1010	20000
150.361(59)	17/05/2016	Chowilla Creek U/S Hancock Ck	Male	800	9100
150.362(50)	17/05/2016	Chowilla Creek ~ 100m U/S Boat Creek	Male	622	3400
150.521(58)	17/05/2016	Chowilla Creek U/S Boat Creek	Female	775	5800
150.542(59)	17/05/2016	Slaney Creek logger	Male	718	7100
150.301(58)	18/05/2016	Slaney Creek ~ 800m U/S gauging station	Female	1090	20500
150.302(51)	18/05/2016	Slaney Creek condition monitoring site	Male	620	3900
150.361(58)	18/05/2016	Slaney Creek entrance	Female	816	7800
150.362(51)	18/05/2016	Slaney Creek U/S condition monitoring site	Male	579	3200
150.481(57)	18/05/2016	Slaney Creek (lower)	Male	1200	32000
150.481(58)	18/05/2016	Slaney Creek (mid)	Female	782	10900
150.502(56)	18/05/2016	Slaney Creek ~ 800m U/S gauging station	Immature	473	2100
150.521(54)	18/05/2016	Slaney Creek condition monitoring site	Female	772	7700
150.502(58)	19/05/2016	Chowilla Creek D/S Bridge	Male	980	18000
150.301(59)	24/05/2016	Slaney Creek at Billabong	Male	920	15000
150.341(58)	24/05/2016	Slaney Creek at Billabong	Male	1050	21000
150.342(52)	24/05/2016	Slaney Creek at Salt Creek Junction	Female	650	4500

Table 1 cont. Original capture date and location, sex, total length (mm) and weight (g) of 54 radio-tagged Murray cod tracked from July 2016 to May 2017 in association with operation of the Chowilla Creek regulator.

Fish Number	Date Tagged	Location	Sex	Length at capture (mm)	Weight at capture (g)
150.361(57)	24/05/2016	Little Slaney Creek (upper)	Female	1060	23500
150.502(57)	24/05/2016	Slaney Creek ~300m D/S Billabong	Male	658	5000
150.502(59)	24/05/2016	Slaney Creek just D/S Billabong	Male	1190	34500
150.542(54)	24/05/2016	Slaney Creek D/S Salt Creek Junction	Female	950	16500
150.542(57)	24/05/2016	Little Slaney Creek (mid)	Female	920	13000
150.341(57)	26/05/2016	Salt Creek ~ 500m U/S Slaney Logger	Male	1210	36000
150.542(58)	26/05/2016	Salt Creek 1.5km D/S Swifty's Creek	Female	1080	23000
150.361(56)	27/05/2016	River Murray D/S Lock 6	Male	515	2800

Fish tracking

Murray cod were manually tracked from a vessel on six occasions between July 2016 and May 2017 (5–7 Jul, 26–28 Sept, 8–10 Nov, 6–8 Dec, 20–22 Feb and 9–11 May) using a 3-element Yagi antenna and an Advanced Telemetry Systems (ATS) radio receiver/logger (model No. RC4500C). Radio signals could be detected from a distance of approximately 600 m and once a fish was detected the line of strongest signal was followed to the point of greatest signal strength, which was recorded by handheld Global Positioning System (GPS). Trials using this technique with hidden transmitters indicated that transmitters could be located consistently to within an area of 2 m^2.

Data were also continuously recorded at nine remote fixed logging stations (ATS radio receiver/loggers model No. RC4500C) located on junctions of major tributaries throughout Chowilla, the junction of Chowilla Creek and the River Murray, and the Chowilla Creek regulator (Figure 1). Three Yagi antennas were positioned on each logging station: one upstream, one downstream and one in the direction of the tributary. The presence of fish in the vicinity of an antenna was recorded automatically as a frequency, antenna number, time and signal strength, thus enabling the timing and direction of movement to be established. These data were remotely transmitted to a central database.

PIT tagging enabled radio-tagged fish to be detected by PIT tag readers installed in vertical-slot fishways on the Chowilla Creek regulator and those that had exited Chowilla to be detected by PIT tag readers installed in vertical-slot fishways on River Murray locks and weirs (Barrett and Mallen-Cooper 2006). Any fish moving upstream in the River Murray were identified by interrogating PIT tag reader records from fishways at the Chowilla Creek regulator and Locks No. 6–10.

2.6. Fish movement data analysis

Movement plots were generated to describe the movement of individual fish, incorporating the period of regulator operation (10 August–10 November 2016), by calculating the distance moved between an initial location (determined from manual tracking or remote logger data) in July 2016 and each subsequent detection (manual or remote), until January 2017. Movement in a downstream direction was represented by a negative value and upstream movement by a positive value.

The total linear range of each fish during the period of regulator operation was calculated as the difference between the most upstream and downstream detection measured along the middle of the river channel (Jones and Stuart 2009) and is analogous to a 100% home range (Crook 2004).

To assess gender-related variation in movement patterns, total linear ranges were quantitatively compared between male and female fish using univariate single-factor (i.e. sex) PERMANOVA (permutational ANOVA and MANOVA) in the software package PRIMER V 6. 1. 12 and PERMANOVA + (Anderson *et al.* 2008). Analyses were performed on Euclidean Distance similarity matrices of untransformed data ($\alpha = 0.05$).

2.7. Hydraulic characterisation

The hydraulic characteristics of the micro (0.1–10s m) and meso-habitats (‘reaches’, 10s–100s m) used by radio-tagged Murray cod during regulator operation were investigated by generating cross-sectional velocity profiles using a vessel-mounted SonTek River Surveyor M9 acoustic Doppler current profiler (ADCP). In brief, ADCP measure the Doppler shift in acoustic signals as they are reflected off of suspended particles in the water column. Transducers on the unit send acoustic pulses vertically into the water column and, after a brief blackout period, begin recording pulses reflected from suspended particles, assuming that the velocity of suspended particles equates to fluid flow velocities (Shields and Rigby 2005). The water column is divided into depth ‘cells’ and the instrument uses the speed of sound in water to group reflected signals from given depth cells. Data, including water depth, heading, echo intensity and velocity are recorded at intervals of ~1 second and are used to produce measures of mean velocity for each depth cell. The ADCP unit is mounted on the gunwale of the vessel and transects are driven across a creek/river to generate cross-sectional flow velocity profiles for the given transect. These data can also be used to investigate complex flow phenomena such as turbulence and circulation or flow rotation (e.g. eddies) (Crowder and Diplas 2002), which may be biologically relevant to habitat use by fish.

Meso-habitat scale

Meso-habitat or 'reach' scale evaluation of hydraulic habitat was undertaken to quantify differences in the hydraulic habitat of creeks with a high frequency of use by Murray cod (hereafter 'cod reaches') and those with a low frequency of use by Murray cod (hereafter 'non-cod reaches'). Creeks were qualitatively defined as 'cod reaches' or 'non-cod reaches' based on previous data on the movement and habitat use of Murray cod at Chowilla (Zampatti *et al.* 2011, SARDI unpublished data). Both 'cod reaches' (n = 5) and 'non-cod reaches' (n = 4) were characterised on two occasions: 1) during peak regulator operation at the end of September 2016, (upstream level = 19.76 m AHD, downstream level = 17.82 m AHD, QSA = 33,121 ML day^{-1}, Chowilla Creek discharge = 6,732 ML day^{-1}) (Table 2) and 2) during high flows immediately following cessation of regulator operation in early November 2016 (upstream and downstream level ~18.75 m AHD, QSA = 59,172 ML day^{-1}, Chowilla Creek discharge = 14,346 ML day^{-1}) (Table 2).

Within each reach, three cross-sectional velocity profiles were measured, with each cross-section separated by 100–300 m. Changes in the hydraulic character of meso-habitats in association with regulator operation, was assessed by comparing data with that collected from two 'cod reaches' in May 2014, when the Chowilla Creek regulator was not being operated and flows were at entitlement (QSA = ~3,695 ML day^{-1}, Chowilla Creek discharge = 2,340 ML day^{-1}) (Table 2).

Table 2. Details of sites where meso-habitats hydraulic parameters were characterised, including the reach/creek, classification as a 'cod' or 'non-cod' reach, latitude and longitude, and conditions (regulator operating, regulator not in operation, and regulator not in operation and high flows) under which hydraulic characteristics were assessed.

Reach	Cod/non-cod	Latitude	Longitude	Assessed		
				May 2014 (No Regulator)	Sept 2016 (Peak Regulator operation)	Nov 2016 (No regulator and high flow)
Little Slaney Creek	Cod	S33.95786	E 140.95361	No	Yes	Yes
Slaney Creek	Cod	S33.94685	E 140.93887	Yes	Yes	Yes
Pipeclay Creek	Cod	S33.94671	E 140.92255	No	Yes	Yes
Chowilla Creek us Boat Creek	Cod	S33.95839	E 140.89247	Yes	Yes	Yes
Murray River at Chowilla Creek	Cod	S34.014042	E140.858467	No	Yes	Yes
Monoman Creek	Non-cod	S33.97487	E 140.85643	No	Yes	Yes
Chowilla Creek u/s regulator	Non-cod	S33.99310	E 140.86320	No	Yes	Yes
Chowilla Creek d/s regulator	Non-cod	S34.00726	E 140.85719	No	Yes	Yes
River Murray u/s Lock 6	Non-cod	S33.96846	E 140.90060	No	Yes	Yes

Data generated from ADCP transects were first viewed in the SonTek ADCP software package RiverSurveyor Live and then exported to MATLAB (The Mathworks Inc. 2010) and interpolated across grids with equal cell sizes using the Delaney triangulation scattered data function, to produce cross-sectional velocity plots. From these data, a series of hydraulic metrics were calculated for each site based on the three transects: 1) mean discharge (m^3 s^{-1}); 2) mean cross-sectional area (m^2); 3) mean velocity in the downstream direction (U, m s^{-1}); 4) the mean modified vertical circulation metric (M_3, s^{-1}); and 5) mean modified horizontal circulation metric (M_4, s^{-1}) (sensu Crowder and Diplas 2000). Calculation of M_3 and M_4 are explained by Equations 1a and b. Absolute values of velocity are used so that the direction of calculation (i.e. clockwise or counter-clockwise) does not result in the cancelation of eddies of equal strength in opposing directions. Higher values of M_3 and M_4 indicate greater frequency and strength of eddies or greater levels of circulation (i.e. flow rotation) within a cross-section, in the vertical and horizontal planes, respectively.

a)

$$M_3 = \frac{\sum\left|\left(\frac{\Delta w}{\Delta y}-\frac{\Delta v}{\Delta z}\right)\right| * \Delta y * \Delta z}{\sum \Delta y * \Delta z}$$

b)

$$M_4 = \frac{\sum\left|\left(\frac{\Delta v}{\Delta x}-\frac{\Delta u}{\Delta y}\right)\right| * \Delta x * \Delta y}{\sum \Delta x * \Delta y}$$

Equation 1. Calculation of a) M_3, the modified vertical circulation metric and b) M_4, the modified horizontal circulation metric. *u, v* and *w* are velocity components in the *x* (streamwise), *y* (lateral) and *z* (vertical) directions.

Micro-habitat scale

ADCP derived cross-sectional velocity profiles were also used to determine the hydraulic character of micro-habitats (0.1–10s m) used by radio-tagged Murray cod. Hydraulic habitat was characterised at select sites where radio-tagged Murray cod were manually located during low flows (QSA = ~3,695 ML day^{-1}) and no regulator operation in May 2014 (*n* = 8 fish) and again in November 2016 (*n* = 8 fish) during high flows (QSA = 59,172 ML day^{-1}), post operation of the Chowilla Creek regulator (we had aimed to characterise micro-habitat use during the peak of regulator operation, but equipment malfunction delayed measurements). A total of five transects were measured at each location, upstream (positive values) and downstream (negative values) of the fishes location: i) +10 m; ii) +5 m; iii) 0 m (transect undertaken directly over fish location); iv) -5 m; and v) -10 m. This 20 m reach was deemed to represent the hydraulic habitat being utilised by a fish at that point in time. Data generation and metric calculation followed the method described above for meso-habitat scale evaluation.

Differences in the hydraulic characteristics of Murray cod micro-habitats between no regulator operation with entitlement flows and no regulator operation with high flows were determined by quantitatively comparing mean velocity (*U*, m s^{-1}), vertical circulation (M_3, s^{-1}) and horizontal circulation (M_4, s^{-1}) using uni-variate single factor PERMANOVA (permutational ANOVA and MANOVA) in the software package PRIMER v. 6. 1. 12 and PERMANOVA+ (Anderson *et al.* 2008). All analyses were performed on Euclidean Distance similarity matrices of untransformed data and α = 0.05 for all comparisons.

3. RESULTS

3.1. Environmental conditions

During regulator operation (10 August-10 November, 2016), QSA increased steadily from ~27,900 ML day^{-1} in August to ~59,172 ML day^{-1} by early November. Over the same period, discharge in Chowilla Creek increased from ~5,340 to ~14,340 ML day^{-1}. Water levels immediately upstream of the Chowilla Creek regulator were 17.35 m AHD at the beginning of operations, 19.78 m AHD at the peak of regulator operation in late September 2016, and 18.77 m AHD when the regulator operation ceased in early November 2016. Whilst the Chowilla Creek regulator was operated, the Lock 6 weir pool was raised by 0.57 m to ~19.83 m AHD, to increase discharge into the anabranch system in an effort to maintain water velocity (nominally ≥0.18 m s^{-1}) in core Murray cod habitats and to maintain daily water exchange within the impounded area at ≥20% to avoid negative water quality impacts (DEWNR, unpublished). Following regulator operation in 2016, flow in the River Murray peaked at ~95, 000 ML day^{-1} in early December 2016 (Figure 4)

During fishway sampling in February 2017, QSA ranged ~7,800 to ~10,600 ML day^{-1}, whilst discharge in Chowilla Creek ranged ~3,500 to ~4,500 ML day^{-1} (Figure 4). The Chowilla Creek regulator was not in operation during this time, and upstream pool level at Lock and Weir 6 was 19.25 m AHD. Discharge at both Slaney and Pipeclay weir was unknown at the time of sampling, but head- and tail-water levels were maintained at approximately 19.28 m and 18.16 m AHD, respectively, for Slaney weir and 19.21 m and 17.21 m AHD, respectively, for Pipeclay weir.

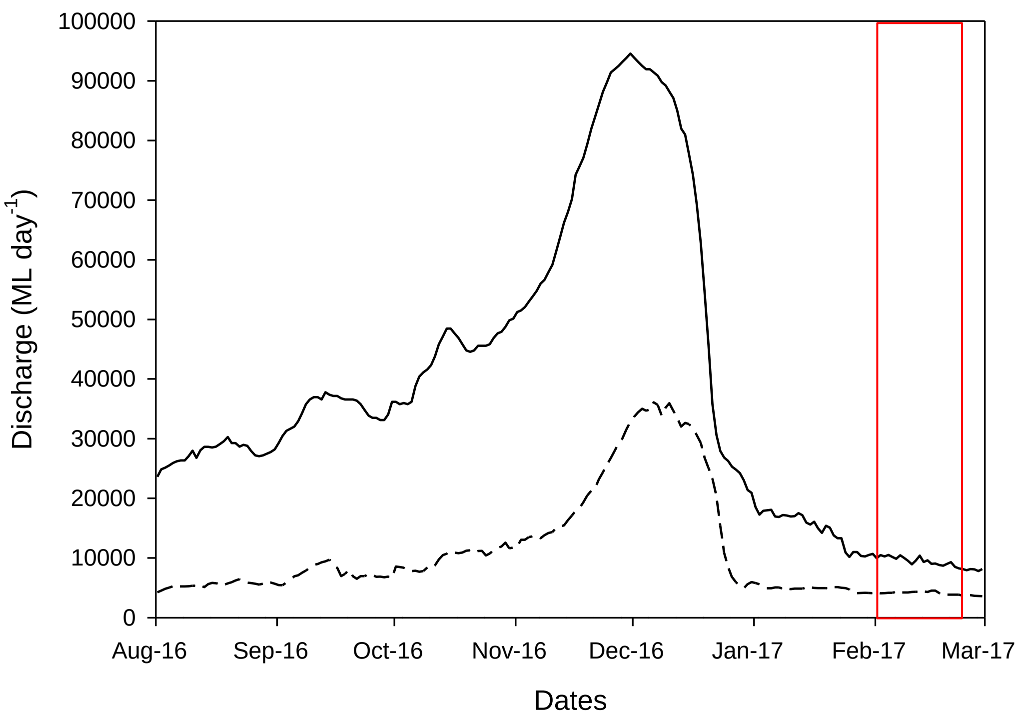

Figure 4. Mean daily flow (ML day^{-1}) in the River Murray at the South Australian Border (site A4610010) (solid black line) and Chowilla Creek (site A4261091) (dashed black line) from August 2016–March 2017. The grey box indicates the period over which the Chowilla Creek regulator was in operation and the red box indicates when fishway assessments occurred.

3.2. Fishway assessments

Catch summary at Fishways

A total of 3,036 fish from 10 species were sampled collectively from all fishways across Slaney and Pipeclay weirs (Table 3). The overall catch was dominated by the native small-bodied unspecked hardyhead (*Craterocephalus fulvus,* ~37%) and medium-bodied bony herring (*Nematalosa erebi,* ~26%), with smaller contributions from the invasive common carp (*Cyprinus carpio*, 18.6%), native small-bodied native Australian smelt (*Retropinna semoni*, 12.5%) and large-bodied golden perch (*Macquaria ambigua ambigua*, 2.8%). The remaining five species collectively comprised of ~4.1% of the total catch.

Table 3. Species, total number and length range of fish sampled from the entrance and exit of Denil and vertical-slot fishways at Slaney and Pipeclay weirs during assessment in February 2017.

		Pipeclay Creek Denil			**Pipeclay Creek Vertical-slot**			**Slaney Creek Denil**			**Slaney Creek Vertical-slot**			**Total**
Common name	**Scientific name**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	**Entrance**	**Exit**	**Length range (mm)**	
	Sampling events	6	6		6	6		6	6		6	6		
	No. of species	5	3		7	8		7	3		7	6		
Native Species														
Golden perch	*Macquaria ambigua ambigua*	5	5	198 - 400	0	23	229 - 429	9	22	206 - 451	0	22	178 - 431	**86**
Silver perch	*Bidyanus bidyanus*	1	0	175	0	0	-	0	0	-	0	0	-	**1**
Bony herring	*Nematalosa erebi*	90	446	67 - 387	1	9	20 - 253	26	217	36 - 376	1	0	25	**790**
Unspecked hardyhead	*Craterocephalus stercusmuscarum fulvus*	4	0	42 - 54	119	595	32 - 66	103	0	40 - 60	27	269	21 - 63	**1,117**
Australian smelt	*Retropinna semoni*	0	0	-	3	126	31 - 49	92	0	30 - 48	4	125	32 - 52	**351**
Carp gudgeon	*Hypseleotris spp.*	0	0	-	14	5	22 - 38	3	0	29 - 37	10	10	27 - 42	**42**
Flat-headed gudgeon	*Philynodon grandicepts*	0	0	-	0	11	23 - 32	0	0	-	2	1	23 - 32	**14**
Non-native Species														
Common carp	*Cyprinus carpio*	27	23	112 - 640	54	68	81 - 426	266	40	78 - 585	38	51	68 - 368	**567**
Goldfish	*Carassius auratus*	0	0	-	1	3	84 - 126	0	0	-	0	0	-	**4**
Eastern gambusia	*Gambusia holbrooki*	0	0	-	37	0	22 - 46	15	0	24 - 41	12	0	21 - 36	**64**
	Total	**127**	**474**		**229**	**840**		**513**	**279**		**94**	**478**		**3,035**

Pipeclay Weir fishways

Fishway use comparison

At the Pipeclay Weir, a total of 601 fish from five species were sampled from the Denil fishway, and 1,069 fish from nine species were sampled from the vertical-slot fishway. The MDS ordination of the fish assemblage data displayed a strong grouping of trapping events by fishway (Figure 5), supported by PERMANOVA which indicated assemblages were significantly different between the two fishways (*Pseudo*-$F_{1,\,23}$ = 28.81, p < 0.001). SIMPER analysis indicated differences in fishway use were characterised by greater relative abundances of the unspecked hardyhead, Australian smelt and eastern gambusia in the vertical-slot fishway, and greater abundances of golden perch and bony herring in the Denil fishway.

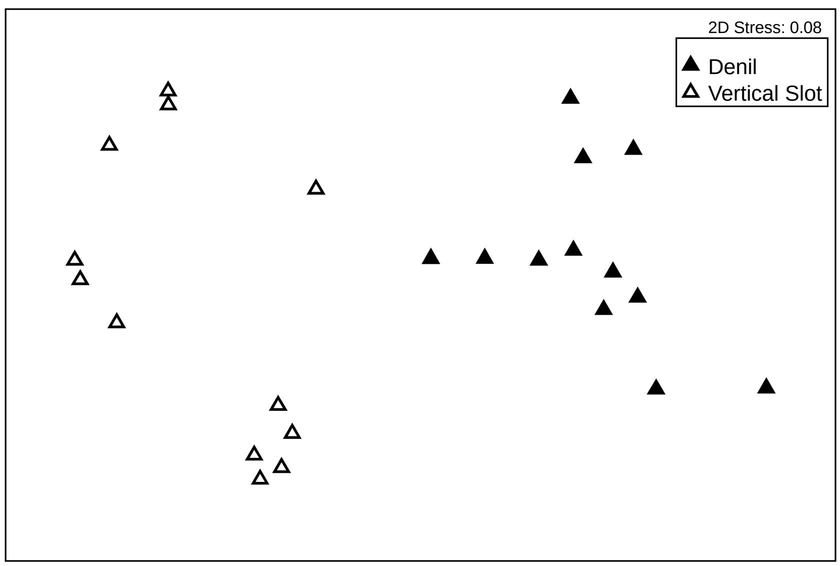

Figure 5. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages (entrance and exit samples pooled) sampled at the Pipeclay weir Denil (solid black triangles) and vertical-slot (open triangles) fishways.

Pipeclay passage efficiency

Denil fishway

A total of five species were sampled from the fishway entrance and three from the exit (Table 3). No significant difference in relative abundance between entrance and exit trapping events was found for golden perch ($Pseudo\text{-}F_{1,\ 11}$ = 1.00, p = 0.354), bony herring ($Pseudo\text{-}F_{1,\ 11}$ = 3.29, p < 0.098) or common carp ($Pseudo\text{-}F_{1,\ 11}$ = 0.77, p = 0.483), suggesting high passage efficiency for these species (Figure 6 and Table 3).

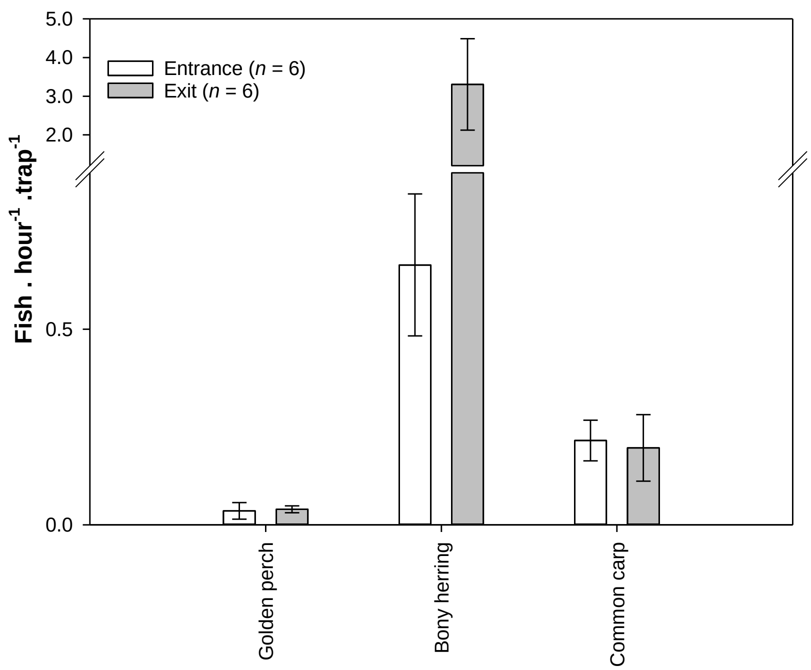

Figure 6. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (open bar) and exit (shaded bar) of the Denil fishway at Pipeclay weir in February 2017.

Fish sampled at the entrance of the fishway ranged 42–618 mm in length, whilst those that successfully ascended the fishway ranged 67–640 mm in length (Figure 7). Length-frequency distributions were significantly different between entrance and exit samples for common carp ($D_{27, 23}$ = 0.394, p = 0.03) due to a greater abundance of fish <120 mm caught at the entrance (Figure 7c). Bony herring had similar length-frequency distributions ($D_{90, 208}$ = 0.092, p = 0.64) at the fishway entrance and exit (Figure 7b). Golden perch ranged from 180 to 400 mm (Figure 7a), with similar length-frequency distributions between the entrance and exit, however statistical comparison could not be performed due to a limited sample size.

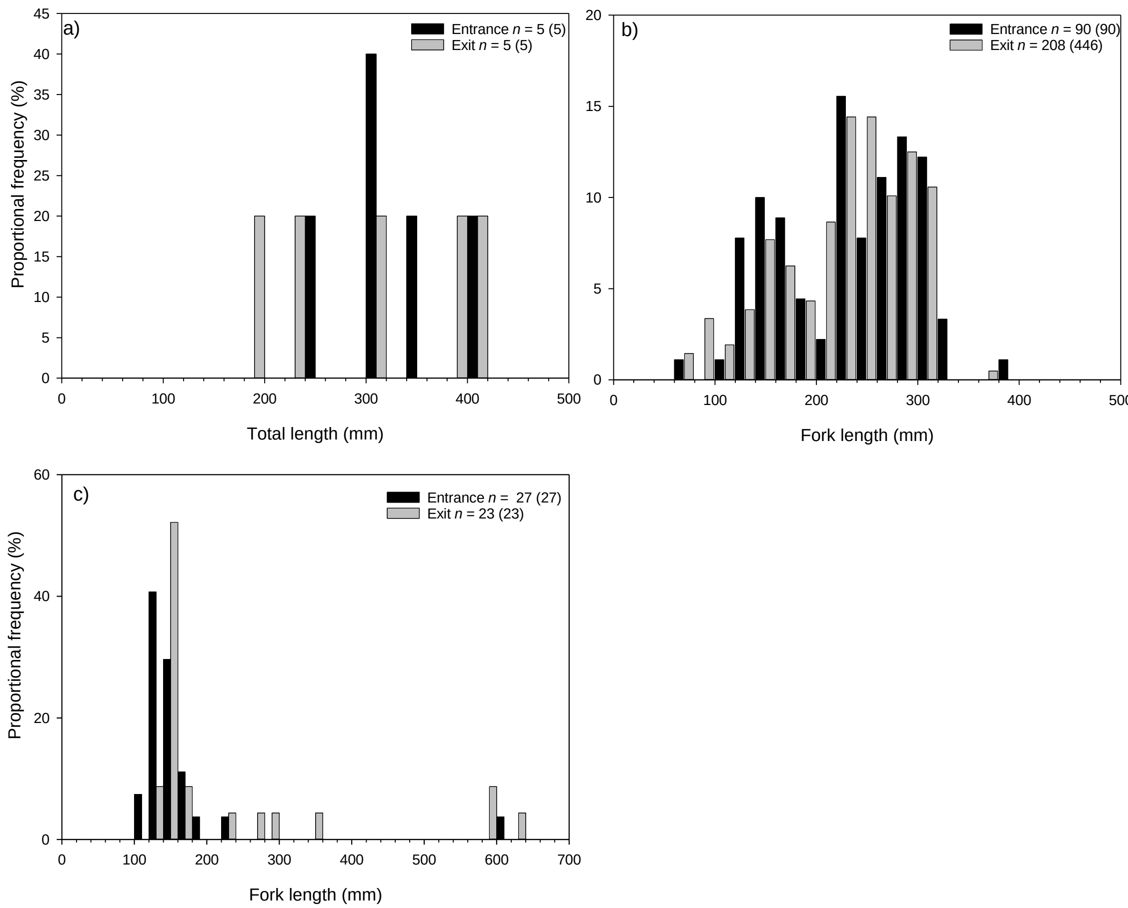

Figure 7. Length-frequency distributions of a) golden perch, b) bony herring and c) common carp captured from the entrance (black bar) and exit (shaded bar) of the Denil fishway at Pipeclay weir in February 2017. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

Vertical-slot fishway

A total of seven species were sampled from the entrance of the vertical-slot fishway and eight from the exit (Table 3). Significantly higher relative abundances of golden perch (*Pseudo-*$F_{1,11}$ = 19.98, p = 0.016), bony herring (*Pseudo-*$F_{1,11}$ = 8.72, p < 0.032), unspecked hardyhead (*Pseudo-*$F_{1,11}$ = 13.13, p < 0.008) and Australian smelt (*Pseudo-*$F_{1,11}$ = 27.23, p = 0.001) were caught at the fishway exit than at the entrance (Figure 8 and Table 3). Common carp was sampled in similar relative abundances at the entrance and exit (*Pseudo-*$F_{1,11}$ = 0.49, p = 0.473) (Figure 8 and Table 3).

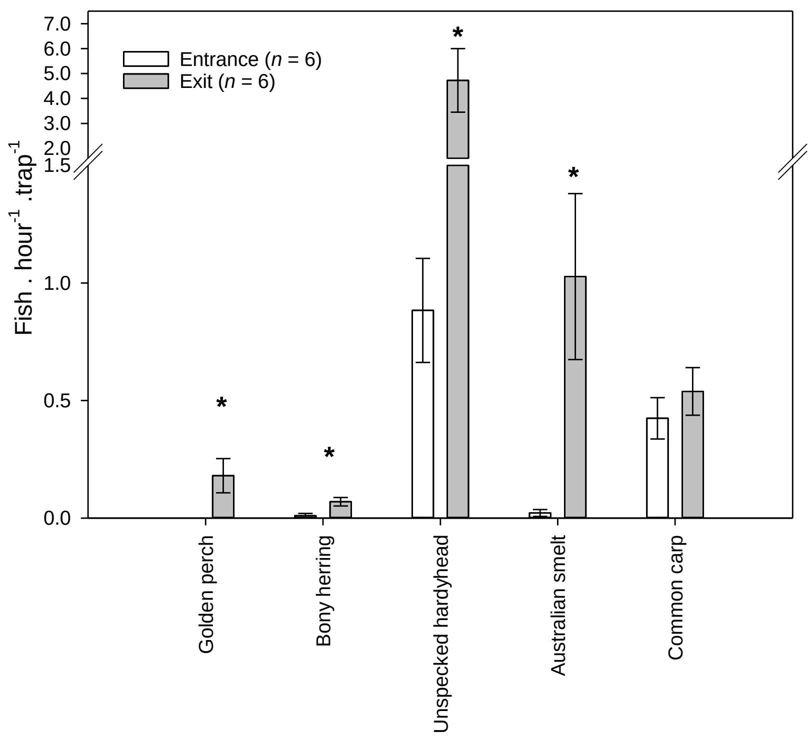

Figure 8. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most abundant species sampled at the entrance (open bar) and exit (shaded bar) of the vertical-slot fishway at Pipeclay weir in February 2017. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 22–426 mm in length, whilst those that successfully ascended the fishway ranged 20–429 mm in length (Figure 9). Unspecked hardyhead had similar length-frequency distributions ($D_{119,\ 270}$ = 0.134, p = 0.094) between entrance and exit samples, and overall ranged from 32–66 mm (Figure 9a). Australian smelt collected at the entrance and exit of the fishway ranged 31–49 mm, but due to limited sample sizes from entrance trapping, a statistical comparison could not be performed (Figure 9b). Golden perch were only collected at the fishway exit and ranged 229–429 mm (Figure 9c). Length-frequency distributions for common carp, however, were significantly different between entrance and exit samples ($D_{54,\ 68}$ = 0.246, p = 0.043), due to a greater abundance of fish <120 mm at the fishway exit (Figure 9d).

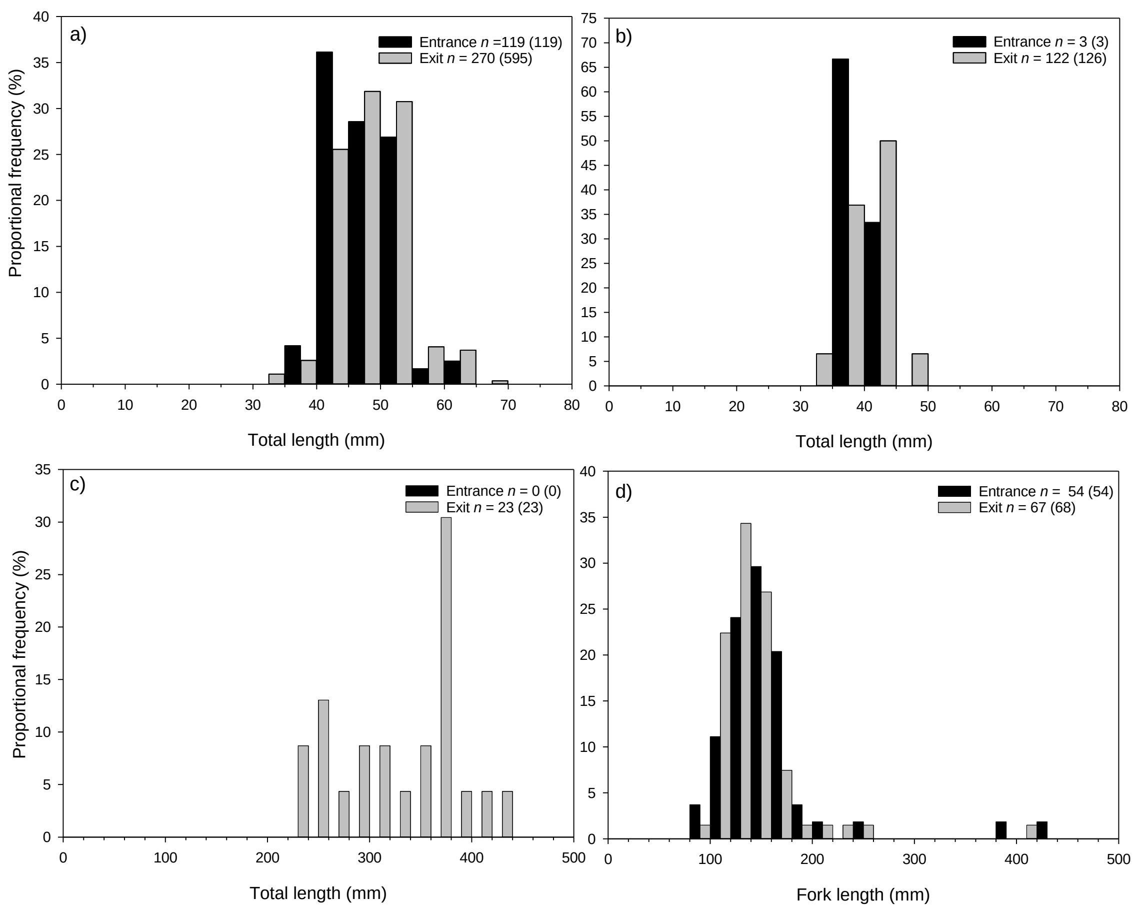

Figure 9. Length-frequency distributions of a) unspecked hardyhead, b) Australian smelt, c) golden perch and d) common carp captured from the entrance (black bar) and exit (shaded bar) of the vertical-slot fishway at Pipeclay weir in February 2017. Sample sizes represent the number of fish measured for length, and those in brackets represent the total number of fish sampled for each species.

Slaney Weir fishways

Fishway use comparison

At the Slaney Weir, a total of 793 fish from seven species were sampled from the Denil fishway, and 572 fish from eight species from the vertical-slot fishway. The MDS ordination of the fish assemblage data displayed a weak grouping of trapping events by fishway (Figure 10), but PERMANOVA indicated assemblages were significantly different between the two fishways ($Pseudo\text{-}F_{1,\,23} = 4.25$, $p < 0.016$). SIMPER analysis attributed differences in fishway use to greater relative abundances of golden perch, bony herring and common carp at the Denil fishway, and greater abundances of Australian smelt and unspecked hardyhead in the vertical-slot fishway.

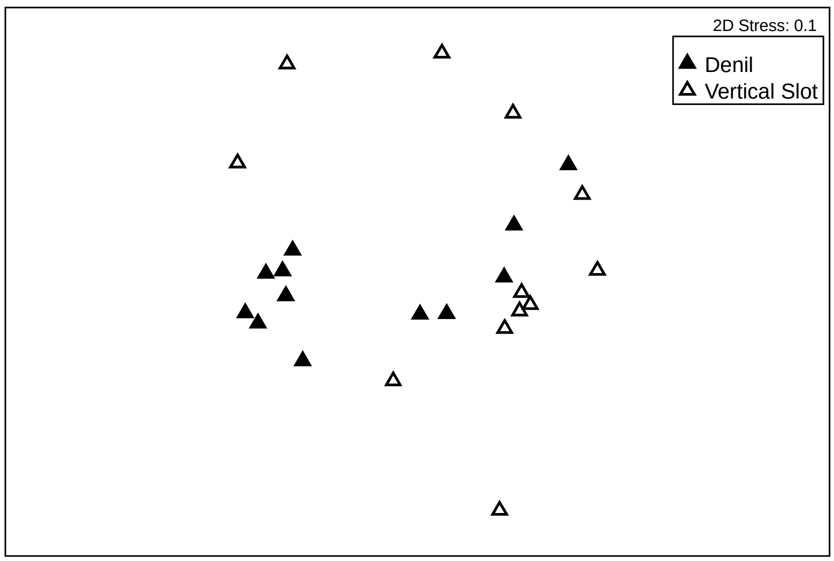

Figure 10. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages (entrance and exit samples pooled) sampled at the Slaney weir Denil (solid black triangles) and vertical-slot (open triangles) fishways.

Slaney passage efficiency

Denil fishway

A total of seven species were sampled from the entrance of the Denil fishway and three from the exit (Table 3). Significantly higher relative abundances of unspecked hardyhead ($Pseudo\text{-}F_{1,\,11}$ = 11.78, $p < 0.016$), Australian smelt ($Pseudo\text{-}F_{1,\,11}$ = 14.83, $p = 0.017$) and common carp ($Pseudo\text{-}F_{1,\,11}$ = 13.54, $p = 0.006$) were caught at the fishway entrance than the exit, with both unspecked hardyhead and Australian smelt absent from the exit (Figure 11 and Table 3). Bony herring, however, were collected in significantly higher relative abundances at the fishway exit than the entrance ($Pseudo\text{-}F_{1,\,11}$ = 11.05, $p < 0.013$) (Figure 11 and Table 3), whilst abundances of golden perch were similar between the fishway entrance and exit ($Pseudo\text{-}F_{1,\,11}$ = 2.89, $p = 0.088$) (Figure 11 and Table 3).

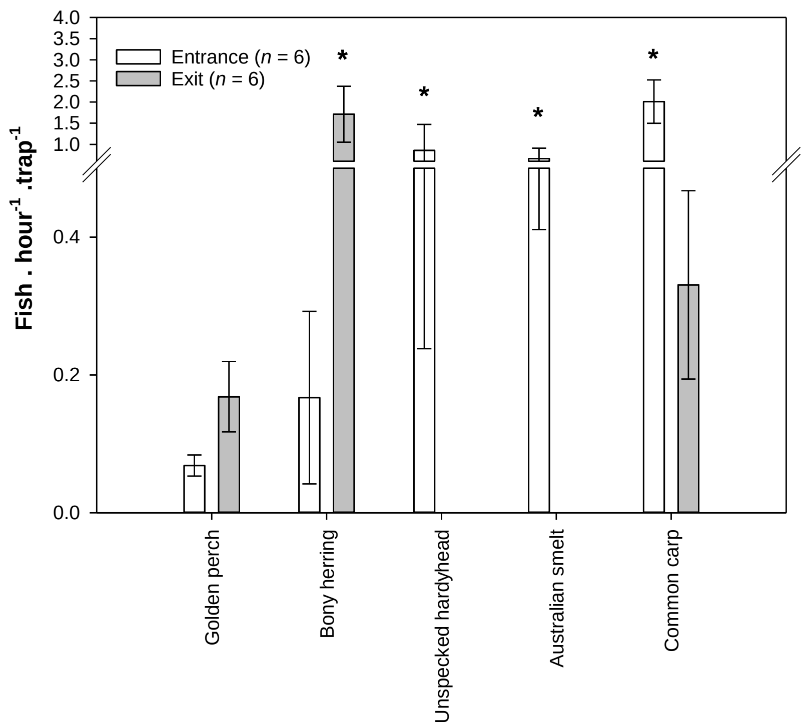

Figure 11. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (open bar) and exit (shaded bar) of the Denil fishway at Slaney weir in February 2017. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of the fishway ranged 24–421 mm in length, whilst those that successfully ascended the fishway ranged 39–585 mm (Figure 12). Length-frequency distributions were significantly different between entrance and exit samples for bony herring ($D_{26, 217}$ = 0.796, p = <0.001), as a greater proportion of fish <120 mm were caught at the entrance than the exit. Common carp had similar length-frequency distributions ($D_{266, 40}$ = 0.109, p = 0.792) from the entrance and exit and ranged 78–585 mm FL, and 118–585 mm FL, respectively. Unspecked hardyhead were only sampled from the entrance and ranged 40–60 mm FL, whilst Australian smelt ranged 30–48 mm FL at the entrance and only one individual was sampled from the exit (39 mm FL). Golden perch from the entrance ranged 269–402 mm TL, and 206–451 mm TL from the exit, but sample sizes were too low for statistical comparison.

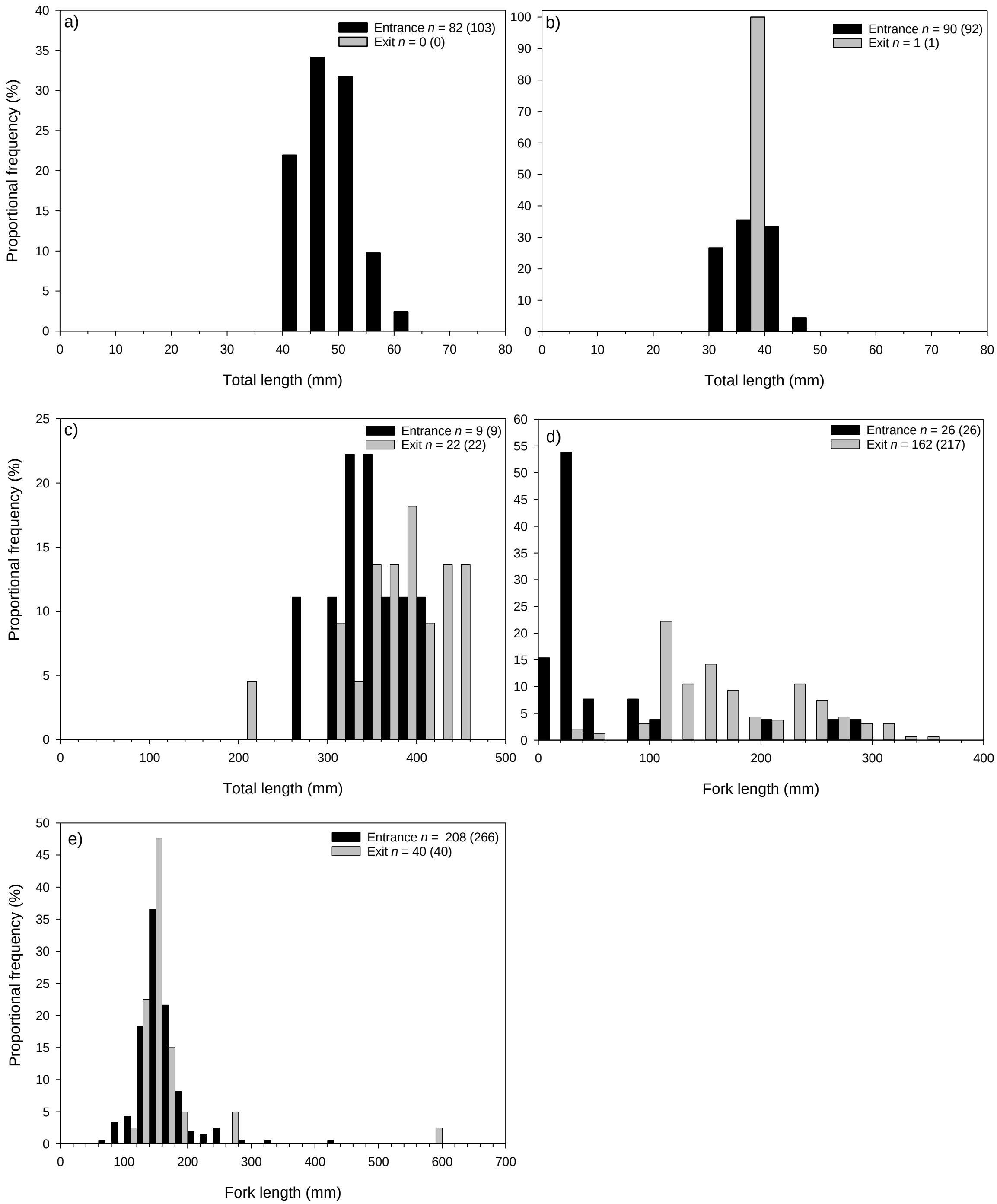

Figure 12. Length-frequency distributions of a) unspecked hardyhead, b) Australian smelt, c) golden perch, d) bony herring and e) common carp captured from the entrance (black bar) and exit (shaded bar) of the Denil fishway at Slaney weir in February 2017. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species.

Vertical-slot fishway

A total of seven species were sampled from the entrance of the vertical-slot fishway and six from the exit (Table 3). Significantly higher relative abundances of golden perch (*Pseudo-$F_{1, 11}$* = 350.07, $p < 0.004$) and Australian smelt (*Pseudo-$F_{1, 11}$* = 15.26, $p = 0.006$) were collected at the fishway exit than the entrance (Figure 13 and Table 3), but relative abundances of Unspecked hardyhead (*Pseudo-$F_{1, 11}$* = 3.25, $p = 0.124$) and common carp (*Pseudo-$F_{1, 11}$* = 0.13, $p = 0.783$) were not significantly different (Figure 13 and Table 3).

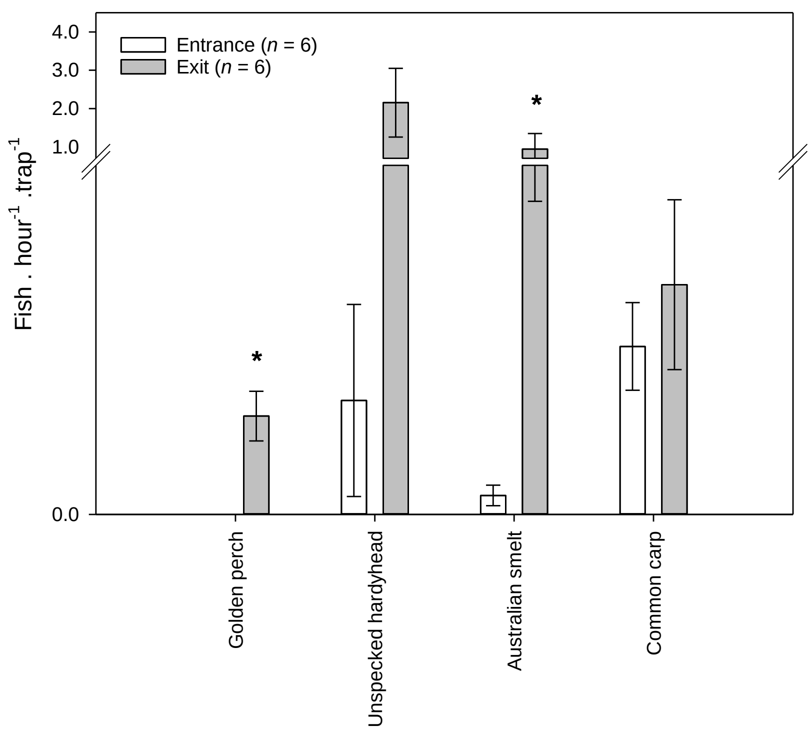

Figure 13. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (open bar) and exit (shaded bar) of the vertical-slot fishway at Slaney weir in February 2017. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of this fishway ranged 21–195 mm in length, whilst those that successfully ascended ranged 21–431 mm (Figure 14). Length-frequency distributions were similar between entrance and exit samples for unspecked hardyhead ($D_{27, 193}$ = 0.240, p = 0.11) and common carp ($D_{38, 51}$ = 0.192, p = 0.358). Golden perch were only collected at the fishway exit and ranged 178–431 mm, whilst Australian smelt ranged 34–42 mm at the entrance and 32–52 mm at the exit (Figure 14). Low entrance sample sizes for both species precluded statistical analysis.

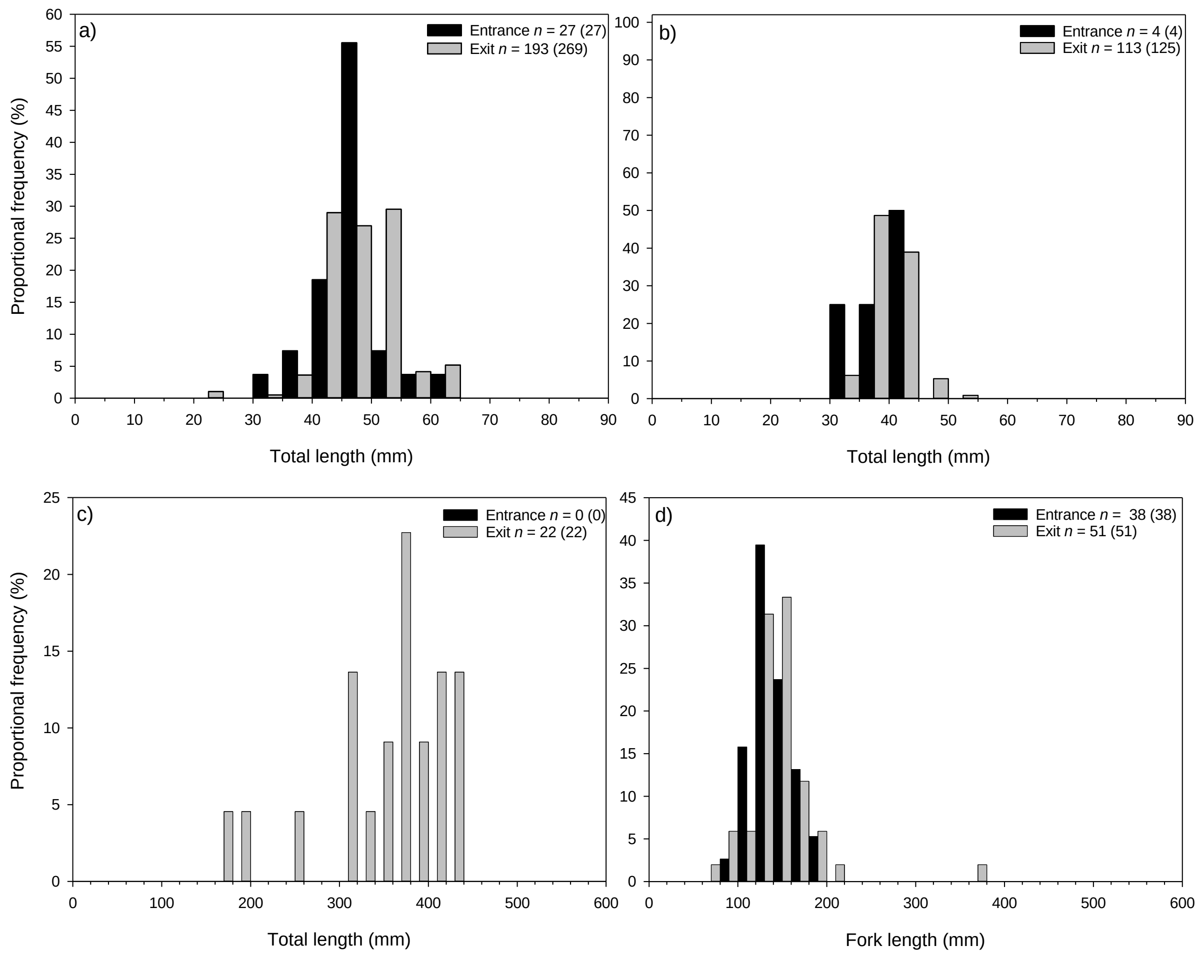

Figure 14. Length-frequency distributions of a) unspecked hardyhead, b) Australian smelt, c) golden perch and d) common carp captured from the entrance (black bar) and exit (shaded bar) of the vertical-slot fishway at Slaney weir in February 2017. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species.

3.3. Fish tracking

Murray cod movement

Total linear range

Over the period of regulator operation (10 August–10 November 2016), movements of radio-tagged Murray cod could be grouped into three distinct categories based on total linear ranges: 1) localised small-scale movement (<2 km), 2) medium-scale (2–10 km) movement within Chowilla and 3) broad-scale movement (>10 km) within Chowilla or the main channel of the River Murray, or between these habitats.

Sixteen Murray cod undertook localised small-scale (<2 km) movements around their initial detection location within Chowilla or the River Murray (Figure 15a). Murray cod undertaking such movements were both male (n = 7), female (n = 5), and of unknown gender (n = 4), and ranged in length, at time of capture, from 718–1210 mm TL. Four Murray cod (2 female, 1 male and 1 unknown gender) demonstrated little to no movement (e.g. <0.25 km) during regulator operations.

Twenty-two Murray cod undertook medium-scale (2–10 km) movements within Chowilla (Figure 15b). Fish moved both upstream and downstream, generally between Chowilla, Slaney, Little Slaney, Salt (between Slaney and Swifty's junction), Pipeclay, Boat and Swifty's Creeks. Murray cod undertaking medium-scale movements were both male (n = 13), female (n = 5) and of unknown gender (n = 4) and ranged in length at the time of capture from 885–1230 mm TL.

Sixteen Murray cod undertook broad-scale movements (>10km) within Chowilla (Figure 15c) or the main channel of the River Murray, or between these habitats. These movements were undertaken by males (n = 5) and females (n = 11), and ranged in length at time of capture from 514–1170 mm TL. The largest total linear range of a radio-tagged Murray cod was 37.5 km for an 825 mm TL female fish (Figure 15c).

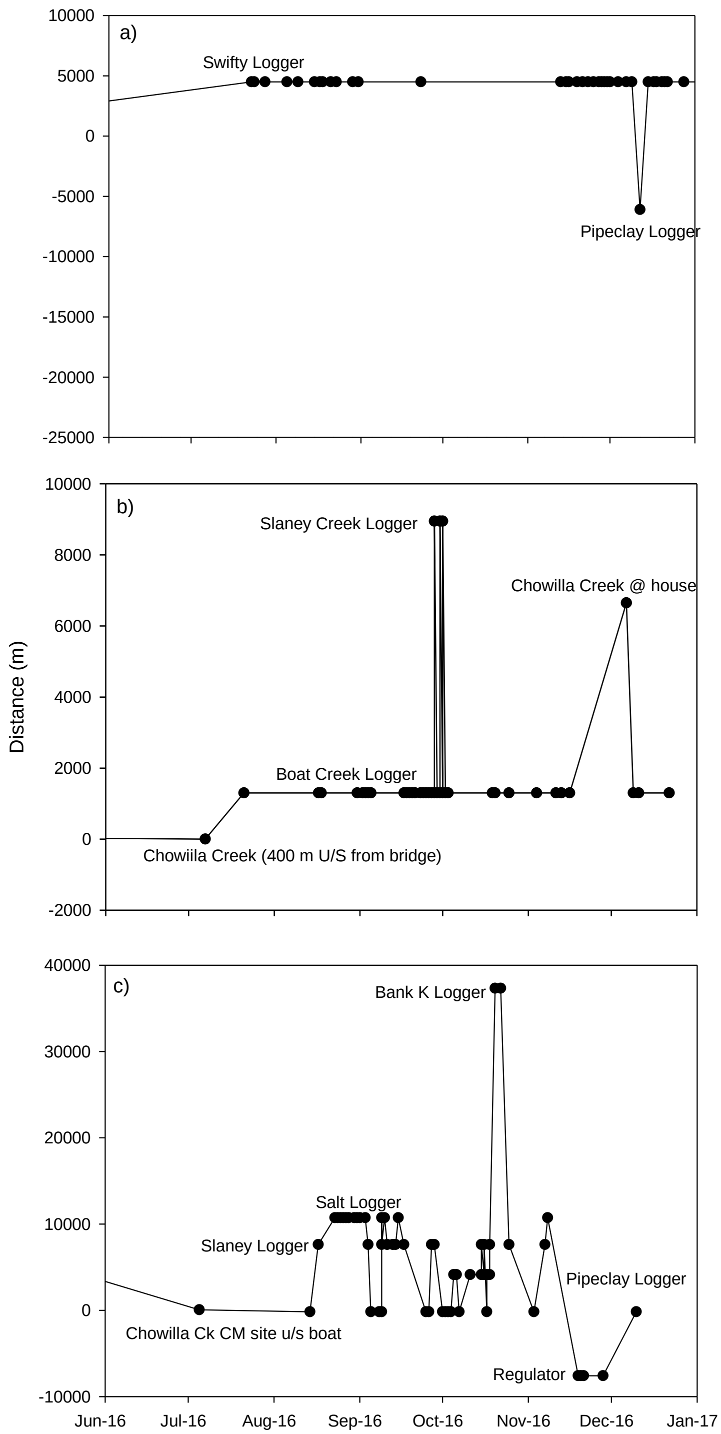

Figure 15. Examples of movement plots for individual Murray cod undertaking (a) localised small-scale movement (<2 km), (b) medium-scale movement within Chowilla (2–10 km) and (c) broad-scale (>10km) movement within Chowilla and the River Murray main channel. Negative values represent downstream movement and positive values upstream movement. Grey box depicts the period of regulator operation.

Female fish appeared to exhibit greater total linear ranges than male fish (Figure 16a), but there was no significant difference (*Pseudo-*$F_{1,\ 46}$ = 2.46, p = 0.113). In 2016, the magnitude of movement and differences between males and females was similar to that during regulator operations in 2014 (Figure 16b), but again differences between male and female fish were not significantly different (*Pseudo-*$F_{1,\ 24}$ = 2.16, p = 0.19).

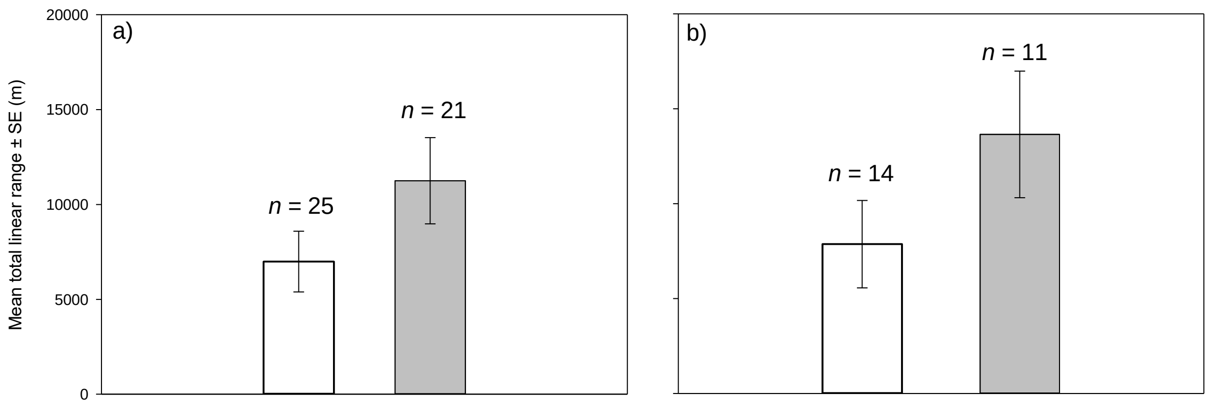

Figure 16. Total linear range (m, mean ± SE) of radio-tagged male (white bar) and female (grey bar) Murray cod during operation of the Chowilla Creek regulator in a) 2016 and b) 2014.

Interactions with the Chowilla Creek regulator

Six radio-tagged Murray cod were passively (remote loggers) and actively (manual tracking) located in the immediate vicinity (within 400 m) of the Chowilla Creek regulator during operation in August–November, 2016. Four fish were tracked moving downstream and approaching the regulator from upstream in the Chowilla system (via Chowilla Creek). All four reached the regulator, with two immediately returning back upstream (Figure 17a and b) and two remaining in the immediate vicinity upstream of the regulator for periods of 3 months (Figure 17c) and 1 month (Figure 17d), respectively, before returning back upstream.

Two fish approached the regulator from downstream, moving up Chowilla Creek (~1.4 km) from the River Murray main channel (Figure 17e and f). One fish appeared below the regulator in early September and remained immediately downstream (within 400 m) for just under a month before returning to the River Murray (Figure 17e). The second fish made similar movements, but after 3 months downstream of the regulator, this fish ascended the regulator vertical-slot fishway after multiple attempts, and moved up Chowilla Creek to the vicinity of Boat creek, where it remained for over a month before returning back down Chowilla Creek and was last detected at the Chowilla Creek regulator in late December 2016 (Figure 17f).

The four radio-tagged Murray cod that approached from upstream of the regulator, were one male and three female fish and ranged in length (at time of tagging) from 514–1170 mm for females and 675 mm for the male fish. The two radio-tagged Murray cod that approached from downstream of the regulator, were one male and one female that were 1005 mm and 855 mm in length (at the time of tagging), respectively. The male fish ascended the Chowilla Creek regulator vertical-slot fishway.

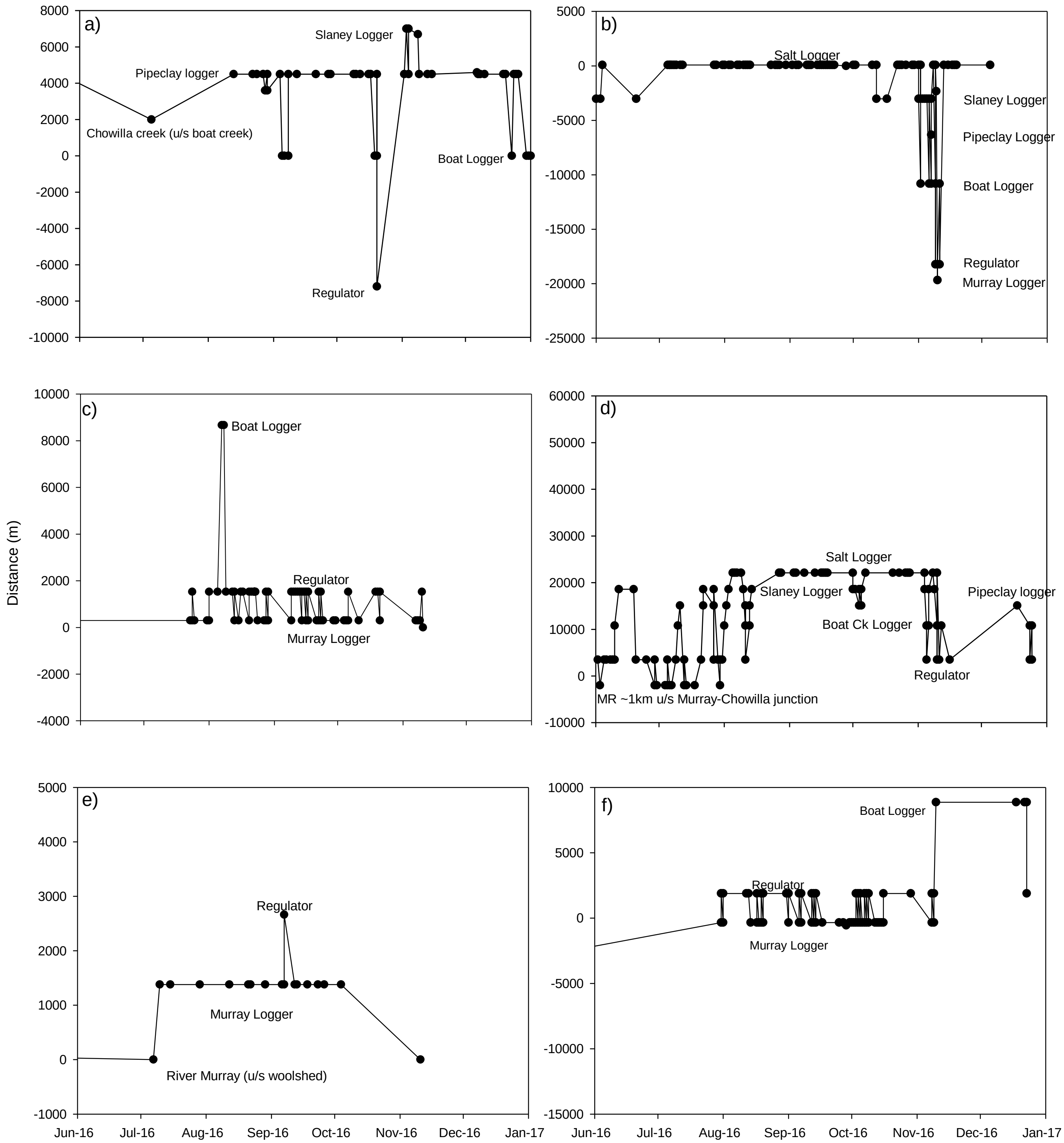

Figure 17. Movement plots for six Murray cod located in the vicinity of the Chowilla Creek regulator. Negative values represent downstream movement and positive values upstream movement. Grey box depicts the period of regulator operation for 2016.

Hydraulic characterisation of micro and meso-scale habitats

Meso-habitat scale

In May 2014, meso-scale hydraulic data were collected in two ‘cod reaches’ (Slaney Creek and Chowilla Creek upstream of the Boat Creek junction) during a period of entitlement flows (QSA = ~3,695 ML day^{-1}) and no regulator operation. Consequently, hydraulic comparisons during periods of regulator operation are limited to these reaches. In 2016, meso-scale hydraulic data were collected during a period regulator operation and moderate flow (QSA = ~34,830 ML day^{-1}) (September) and a period of no regulator operation and high flow (QSA = ~72,331 ML day^{-1}) (November).

In May 2014, discharge in Chowilla Creek ranged ~1800–2000 ML day^{-1} and water level at the regulator (open) was ~16.35 m AHD. During regulator operation in September 2016, discharge (maximum = 9,718 ML day^{-1}) and water levels (~3.4 m) within Chowilla Creek were substantially greater. Together, these actions increased the mean cross-sectional area of both Chowilla and Slaney Creeks by a factor of approximately 3.0–4.1, relative to conditions in May 2014 (Table 4). During no regulator operation, but high flows (~33,000 ML day^{-1}) in Chowilla Creek in November 2016, the mean cross-sectional area of both Chowilla and Slaney Creeks was increased by a factor of approximately 2.2 – 3.1, relative to conditions in May 2014 (Table 4).

Despite approximately a fivefold increase in discharge during operation of the regulator in September 2016, there were decreases in mean water velocity, vertical circulation, and horizontal circulation, in Chowilla Creek upstream of the Boat Creek junction relative to when the regulator was not in operation in May 2014 (Table 4). Alternatively, during no regulator operation, but high flows in November 2016, mean water velocity and vertical circulation increased, but horizontal circulation decreased, relative to no regulator operation in May 2014 (Table 4). In Slaney Creek in 2016, mean velocity, vertical circulation and horizontal circulation decreased substantially during regulator operations (September), but also during high flows (November), when compared to May 2014 (Table 4). During regulator operation in September 2016, water velocities were greatest in the River Murray main channel (Table 4).

Mean water velocity, and vertical and horizontal circulation across all cod reaches and conditions are presented in Figure 18. Decreases in water velocity (U, m s^{-1}), vertical circulation (M_3, s^{-1}) and horizontal circulation (M_4, s^{-1}) were evident during regulator operation in September 2016 when compared to no regulator and entitlement flows in May 2014 (Figure 18). During high flows and no regulator operation in November 2016, water velocities (U, m s^{-1}) and vertical circulation (M_3,

s^{-1}) were similar to those measured in May 2014, but horizontal circulation (M_4, s^{-1}) was substantially less (Figure 18).

Table 4. Summary of the hydraulic characteristics of 'cod' and 'non-cod' reaches within Chowilla during normal conditions (i.e. regulator not operating and under entitlement flows; QSA = ~3,695 ML day^{-1}) in May 2014, during regulator operation in September 2016 and during no regulator operation but high flows (QSA = ~72,331 ML day^{-1}) in November 2016. Details include mean discharge (Q, $m^3\ s^{-1}$), mean cross-sectional area (m^2), mean velocity (U, m s^{-1}), mean modified vertical circulation metric (M_3, s^{-1}) and mean modified horizontal circulation metric (M_4, s^{-1}).

Reach	Cod/non-cod	Mean Q ± SD ($m^3\ s^{-1}$)	Mean area ± SD (m^2)	Mean U ± SD (m s^{-1})	Mean M_3 ± SD (s^{-1})	Mean M_4 ± SD (s^{-1})
Regulator not operating under entitlement flows (May 2014)						
Slaney Creek	Cod	13.96 ± 0.67	34.94 ± 1.51	0.45 ± 0.04	0.35 ± 0.13	0.29 ± 0.07
Chowilla Creek u/s Boat Creek	Cod	20.54 ± 0.50	86.13 ± 12.28	0.29 ± 0.04	0.18 ± 0.03	0.13 ± 0.01
Regulator operating (September 2016)						
Little Slaney Creek	Cod	13.51 ± 1.73	90.54 ± 6.54	0.19 ± 0.021	0.13 ± 0.04	0.06 ± 0.01
Slaney Creek	Cod	19.24 ± 3.79	144.62 ± 26.95	0.18 ± 0.06	0.13 ± 0.06	0.05 ± 0.01
Pipeclay Creek	Cod	24.24 ± 3.61	238.34 ± 38.39	0.14 ± 0.02	0.14 ± 0.04	0.04 ± 0.01
Chowilla Creek u/s Boat Creek	Cod	40.23 ± 4.63	259.93 ± 24.71	0.20 ± 0.01	0.17 ± 0.02	0.08 ± 0.01
River Murray at Chowilla Junction	Cod	302.08 ± 61.61	555.88 ± 166.35	0.60 ± 0.06	0.18 ± 0.01	0.09 ± 0.01
Monoman Creek	Non-cod	11.13 ± 1.28	305.30 ± 19.32	0.05 ± 0.001	0.14 ± 0.01	0.05 ± 0.01
Chowilla Creek u/s regulator	Non-cod	80.14 ± 2.88	622.45 ± 52.67	0.15 ± 0.01	0.19 ± 0.01	0.09 ± 0.01
River Murray u/s Lock 6	Non-cod	279.36 ± 1.73	754.07 ± 22.01	0.40 ± 0.01	0.20 ± 0.02	0.08 ± 0.01
Regulator not operating under high flows (November 2016)						
Little Slaney Creek	Cod	19.19 ± 1.46	80.11 ± 1.69	0.30 ± 0.01	0.23 ± 0.03	0.11 ± 0.01
Slaney Creek	Cod	36.98 ± 2.09	108.63 ± 16.39	0.40 ± 0.09	0.24 ± 0.03	0.10 ± 0.001
Pipeclay Creek	Cod	45.09 ± 2.36	163.96 ± 16.27	0.35 ± 0.03	0.22 ± 0.03	0.06 ± 0.01
Chowilla Creek u/s Boat Creek	Cod	92.47 ± 4.82	195.49 ± 5.70	0.57 ± 0.02	0.24 ± 0.02	0.10 ± 0.02
Monoman Creek	Non-cod	44.68 ± 2.61	196.43 ± 13.60	0.26 ± 0.03	0.18 ± 0.04	0.06 ± 0.01
Chowilla Creek u/s regulator	Non-cod	166.75 ± 2.43	477.73 ± 29.23	0.38 ± 0.03	0.21 ± 0.02	0.08 ± 0.01
Chowilla Creek d/s regulator	Non-cod	160.75 ± 8.99	488.47 ± 15.66	0.36 ± 0.01	0.20 ± 0.02	0.10 ± 0.01
River Murray u/s Lock 6	Non-cod	422.36 ± 9.27	711.81 ± 17.13	0.64 ± 0.001	0.24 ± 0.02	0.11 ± 0.02

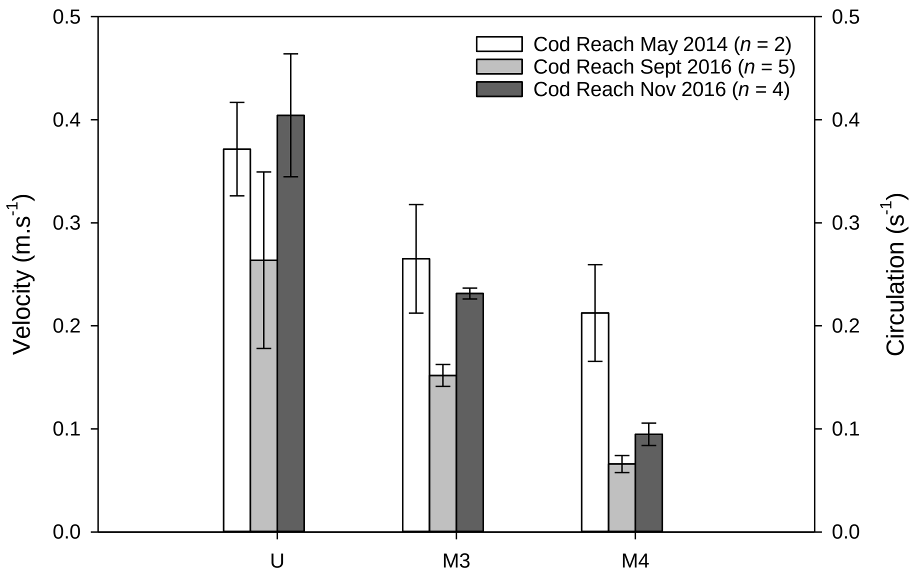

Figure 18. Mean (±SE) values of water velocity (U, m s^{-1}), the modified vertical circulation metric (M_3, s^{-1}) and modified horizontal circulation metric (M_4, s^{-1}) within Murray cod meso-scale habitats under normal conditions in May 2014 (i.e. regulator not operating and under entitlement flows; QSA = ~3,695 ML day^{-1}) and during regulator operations in September and no regulator operations but high flows (QSA = ~72,331 ML day^{-1}) in November 2016.

Micro-Habitat Scale

Hydraulic characterisation of Murray cod micro-habitats (0.1–10s m) was undertaken at nine sites where Murray cod were located in May 2014 and 8 sites where Murray cod were located during no regulator operation, but high flows in November 2016. Figure 19 presents an example of the graphic outputs of the velocity profiles from a site in Little Slaney Creek in 2016 (542-55). The fish at this site was located approximately 18 m from the left-hand bank in the 0 m transect. A substantial snag and steep sloping bank was present immediately upstream of the 0 m transect (Figure 19); this was characteristic of all sites assessed, with fish typically found in close proximity to large snags. The snag has a marked effect on both bathymetry and hydraulics, with a patch of static water bordering fast flowing water (>0.5 m s^{-1}) immediately downstream of the snag, which is persistent in the -5 and -10 m transects.

The hydraulic character of microhabitats utilised by Murray cod differed only slightly between no regulator operation under entitlement flows in May 2014 and no regulator operation, but high flows, in November 2016 (Table 5). Several sites were assessed in Slaney, Little Slaney, Salt and

Chowilla Creeks and a substantial increase in mean cross-sectional area at these sites in high flows in November 2016, relative to entitlement flows in May 2014, reflects the elevated water levels caused by greater discharge (Table 5). In May 2014 and November 2016, mean water velocity of Murray cod microhabitats was similar ranging 0.22–0.56 m s^{-1} and 0.25–0.52 m s^{-1}, respectively. Univariate PERMANOVA indicated that mean velocities (U, m s^{-1}) of Murray cod microhabitats during no regulator operation were similar during entitlement flows and high flows ($Pseudo\text{-}F_{1,\,16}$ = 0.0075, p = 0.929), as was vertical circulation (M_3) ($Pseudo\text{-}F_{1,\,16}$ = 0.3796, p = 0.555). Horizontal circulation (M_4), however, was significantly reduced at high flows ($Pseudo\text{-}F_{1,\,16}$ = 8.3485, p = 0.007) (Figure 20).

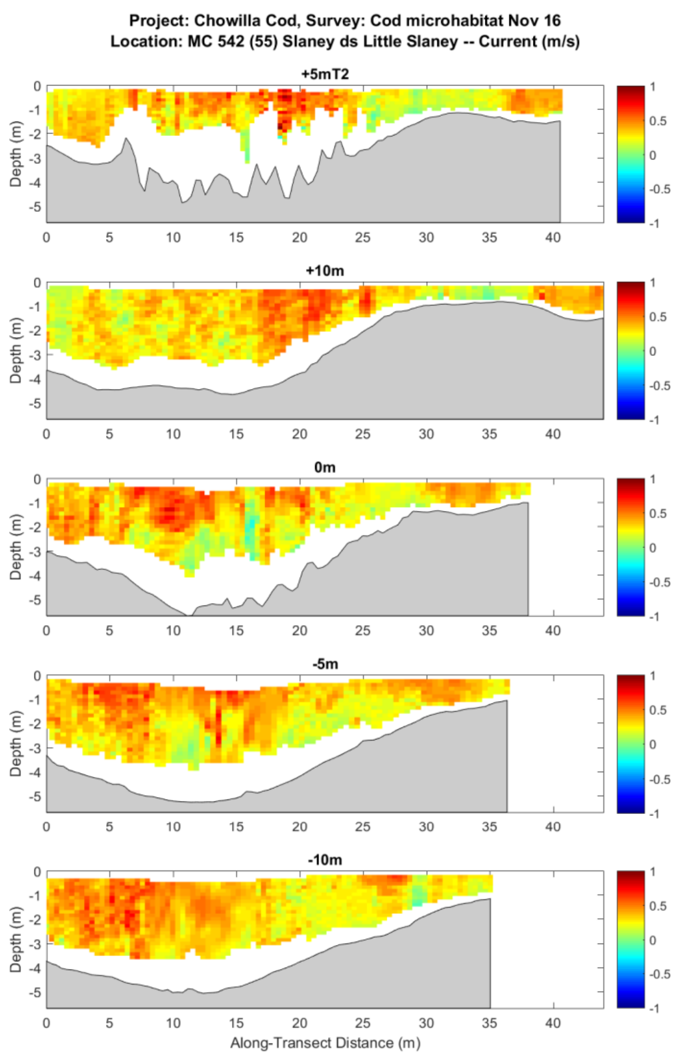

Figure 19. Cross-sectional velocity profiles generated for the -10, -5, 0, +5 and +10 m ADCP transects at a site on Little Slaney Creek where fish 542-55 was located in November 2016. The color index on the right axis represents water velocities (m s^{-1}), with red indicating higher velocities and blue indicating lower velocities.

Table 5. Summary of the hydraulic characteristics of individual Murray cod microhabitats within Chowilla during normal conditions (i.e. regulator not operating under entitlement flows; QSA = ~3,695 ML day^{-1}) in May 2014 and during no regulator operation but high flows (QSA = ~72,331 ML day^{-1}) in November 2016. Details include fish no., mean discharge (Q, m^3 s^{-1}), mean cross-sectional area (m^2), mean velocity (U, m s^{-1}), mean modified vertical circulation metric (M_3, s^{-1}) and mean modified horizontal circulation metric (M_4, s^{-1}).

Creek	Fish no.	Mean Q ± SD (m^3 s^{-1})	Mean area ± SD (m^2)	Mean U ± SD (m s^{-1})	Mean M_3 ± SD (s^{-1})	Mean M_4 ± SD (s^{-1})
Regulator not operating under entitlement flows (May 2014)						
Slaney Creek	542 (55)	14.35 ± 1.03	44.03 ± 4.30	0.37 ± 0.03	0.40 ± 0.06	0.32 ± 0.07
Slaney Creek	302 (50)	14.51 ± 0.35	34.33 ± 1.83	0.48 ± 0.02	0.26 ± 0.06	0.21 ± 0.05
Slaney Creek	342 (51)	14.66 ± 0.34	33.19 ± 1.78	0.51 ± 0.03	0.21 ± 0.03	0.18 ± 0.04
Slaney Creek	302 (52)	14.40 ± 0.74	30.20 ± 1.84	0.56 ± 0.02	0.33 ± 0.06	0.25 ± 0.04
Chowilla Creek (Pipeclay Island)	362 (25)	7.95 ± 0.19	33.20 ± 5.71	0.29 ± 0.05	0.31 ± 0.03	0.18 ± 0.03
Chowilla Creek (Pipeclay Island)	502 (51)	8.05 ± 0.23	29.84 ± 4.16	0.33 ± 0.04	0.31 ± 0.03	0.17 ± 0.03
Chowilla Creek	362 (53)	20.77 ± 0.55	95.48 ± 9.01	0.25 ± 0.02	0.15 ± 0.02	0.11 ± 0.01
Chowilla Creek	362 (24)	20.15 ± 0.85	74.32 ± 9.22	0.33 ± 0.03	0.22 ± 0.01	0.15 ± 0.04
Chowilla Creek	521 (55)	23.59 ± 1.08	123.08 ± 7.42	0.22 ± 0.01	0.06 ± 0.01	0.05 ± 0.00
Regulator not operating under high flows (November 2016)						
Slaney Creek	302 (52)	39.03 ± 1.16	117.49 ± 4.38	0.40 ± 0.01	0.21 ± 0.01	0.09 ± 0.01
Slaney Creek	342 (51)	30.88 ± 1.43	110.88 ± 2.97	0.35 ± 0.02	0.21 ± 0.02	0.09 ± 0.01
Slaney Creek	481 (52)	33.60 ± 1.79	108.64 ± 6.25	0.41 ± 0.03	0.23 ± 0.01	0.11 ± 0.01
Slaney Creek	542 (55)	31.92 ± 3.23	124.64 ± 6.95	0.32 ± 0.01	0.23 ± 0.02	0.12 ± 0.02
Little Slaney Creek	342 (53)	18.79 ± 0.92	77.76 ± 7.53	0.31 ± 0.03	0.25 ± 0.02	0.10 ± 0.01
Slaney Creek	481 (54)	27.63 ± 1.61	98.98 ± 5.88	0.37 ± 0.01	0.28 ± 0.04	0.11 ± 0.01
Chowilla Creek	302 (53)	109.48 ± 3.13	253.62 ± 11.37	0.52 ± 0.02	0.24 ± 0.01	0.11 ± 0.01
Salt Creek	362 (21)	34.45 ± 0.35	154.78 ± 6.09	0.25 ± 0.01	0.17 ± 0.05	0.06 ± 0.01

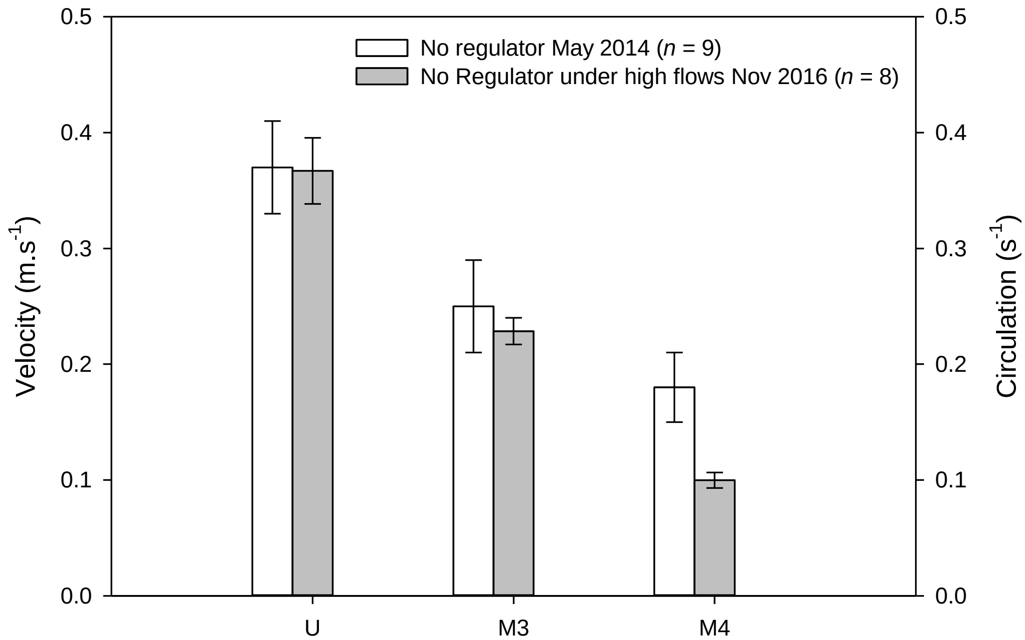

Figure 20. Mean (±SE) water velocity (U, m s^{-1}), modified vertical circulation metric (M_3, s^{-1}) and modified horizontal circulation metric (M_4, s^{-1}) within Murray cod micro-habitats under *normal* conditions in May 2014 (i.e. regulator not operating under entitlement flows; (QSA = ~3,695 ML day^{-1}) (white bars) and with no regulator under high flows (QSA = ~72,331 ML day^{-1}) in November 2016 (grey bars).

4. DISCUSSION

4.1. Fishway assessments

Barriers to fish movement lead to declines in fish populations by preventing dispersal and recolonisation, and restricting access to preferred habitats and spawning grounds (Gehrke *et al.* 1995). As such, fishways are commonly used to mitigate the impacts of barriers to fish movement in regulated rivers (Clay 1995). In 2014, integrated Denil and vertical-slot fishways were constructed on Slaney and Pipeclay weirs, with the objective of enabling the passage of fish between these creeks and the River Murray under all flows. The specific objective of this first component of the current study was to sample the entrance and exit of both fishway designs at Slaney and Pipeclay weirs to evaluate fishway use and passage efficiency, in regards to the abundance and size classes of species able to successfully ascend the fishways.

4.1.1. Fishway use

At Slaney and Pipeclay weirs, fish assemblages were significantly different between the Denil and vertical-slot fishways. These differences were primarily driven by greater relative abundances of three small-bodied species, unspecked hardyhead, Australian smelt and eastern gambusia at the vertical-slot fishways, and greater abundances of the large-bodied golden perch and medium-bodied bony herring at the Denil fishways. This result was expected given the Denil and vertical-slot fishways were specially designed for the passage of distinct size classes of fish: the vertical-slot fishway was designed to produce low internal velocities and turbulence (<32 W/m^3) and facilitate the passage of small-bodied fish (<100 mm TL), whilst the higher-gradient (1:10) and more turbulent Denil fishway was designed to facilitate the passage of medium-to-large-bodied species (>100 mm TL) (Mallen-Cooper and Stuart 2007). Medium- and large-bodied species did ascend the vertical-slot fishways, but greater abundances used the Denil fishways, and is likely attributed to higher water velocities at the entrance of these fishways (relative to the vertical-slot fishways), which in turn, result in higher levels of attraction of large-bodied fishes (Clay 1995).

4.1.2. Passage efficiency

The Denil fishways at Slaney and Pipeclay weirs facilitated the passage of golden perch and bony herring, but passage of the small-bodied species unspecked hardyhead, Australian smelt and eastern gambusia was obstructed. This was expected, given that the Denil fishways were specifically designed for fishes >100 mm in length. The large-bodied species common carp, had high passage efficiency at the Pipeclay weir Denil fishway, yet low passage efficiency at the

Slaney weir Denil fishway. This could be attributed to a higher abundance of juvenile carp (<120 mm FL) at Slaney Weir that were unable to successfully ascend the fishway. For all fish species, lengths ranged from 24 to 618 mm at the entrance and 39 to 640 mm at the exit, demonstrating that whilst putatively designed for fish >100 mm in length, Denil fishways can facilitate the passage of juveniles of some species, particularly those with strong swimming abilities (e.g. bony herring) (Mallen-Cooper and Stuart 2007).

Although designed primarily to facilitate the passage of small-bodied fishes, the vertical-slot fishways at Slaney and Pipeclay weirs demonstrated high passage efficiency for several small and large-bodied fishes (e.g. unspecked hardyhead, Australian smelt and golden perch). These same species were found in greater numbers at the exit than the entrance of the fishway, indicating successful ascent of the fishway, but potential entrance trap ‘shyness’ (aversion to the fishway entrance trap) caused by the trap being visible to fish entering the fishway. Similar observations have been made during entrance trapping at fishways throughout the MDB, especially for large-bodied species such as golden and silver perch (Baumgartner and Harris 2007). Consequently, the abundance of fish attempting to ascend the vertical-slot fishway has likely been underestimated for some species. Nonetheless, there were few differences in length frequency distributions between entrance and exit samples, suggesting little or no size-related obstruction to passage.

Both the Denil and vertical-slot fishways on Slaney and Pipeclay weirs are functioning as designed from a biological perspective, with fish >100 mm in length successfully ascending the Denil fishway, and fish <100 mm in length successfully utilising the vertical-slot fishway.

4.2. Murray cod movement patterns and habitat use

The Chowilla Creek regulator and ancillary structures have been constructed with the primary objective of artificially inundating the Chowilla floodplain to maintain or improve the condition of floodplain overstorey vegetation. The regulator is operated to increase water levels, backing up water to inundate the floodplain at riverine flows less than those that naturally cause overbank flooding. The regulator and ancillary structures are operated in accordance with guidelines for operation and risk mitigation outlined in an *Operations Plan* and an *Event Plan and Hazard Mitigation Strategy* (DEWNR, unpublished). This involves maintaining flow through the regulator and promoting water velocities ≥ 0.18 m s^{-1} within at least 75% of core Murray cod habitat (DEWNR, unpublished). Nevertheless, the regulator alters the hydrodynamics of lotic habitats and influences connectivity within and between fluvial and floodplain environments. As a consequence, operation of the regulator poses risks to riverine fishes, with the potential to impact on the movement and habitat use, and ultimately population dynamics of Murray cod (Mallen-Cooper *et al.* 2011, Koehn *et al.* 2014). To further understand the influence of regulator operations on the ecology of Murray cod in the Chowilla region, we analysed the movement patterns of existing radio-tagged Murray cod and characterized the hydraulic habitats utilised by radio-tagged Murray cod in Chowilla during regulator operation in 2016.

Over the period of regulator operation (10 August–10 November 2016), movements of radio-tagged Murray cod could generally be grouped into three distinct categories based on total linear ranges: 1) localised small-scale movement (<2 km), 2) medium-scale (2–10 km) movement within Chowilla and 3) broad-scale movement (>10 km) within Chowilla or the main channel of the River Murray, or between these habitats. These movements are similar to those that have previously been reported for radio-tagged Murray cod in Chowilla during entitlement flows (within-channel), overbank flooding and regulator operations (Leigh and Zampatti 2013, SARDI unpublished data). Murray cod exhibited high fidelity to specific regions in perennial anabranch habitats of Chowilla (e.g. Slaney Creek and Chowilla Creek immediately upstream of Boat Creek junction); these locations were characterised by flowing water and abundant large woody debris. Fish that undertook medium- and broad-scale movement moved between these specific meso-habitats and the main river channel.

In 2016, the Chowilla Creek regulator was operated concurrently with the spawning period of Murray cod in the lower River Murray (i.e. September–November) (Zampatti *et al.* 2011). As such, site fidelity and broader scale movements observed in this study could be related to reproductive behaviour. Based on fish length at the time of tagging, most of the 54 radio-tagged Murray cod tracked in the present study were likely reproductively mature (Rowland 1989). Female Murray cod exhibited greater total linear ranges than male fish. Male Murray cod establish a spawning site (potentially in late winter) and, after mating with a female, care for the eggs until hatching (Lintermans 2007). Females do not share parental care and are likely to move away from the spawning site and potentially mate with subsequent males (Rourke *et al.* 2009). Consequently, males are likely to be more sedentary and move over smaller ranges whilst caring for a brood, whilst females may remain active, and move over larger ranges whilst potentially searching for another mate.

Throughout the Murray and Darling rivers, Murray cod show an affinity for hydraulically diverse, flowing water (lotic) habitats, with abundant physical structure, particularly large woody debris (snags) (Boys and Thoms 2006, Leigh and Zampatti 2011, Koehn and Nicol 2014). In May 2014, when the Chowilla Creek regulator was not being operated and flows were at entitlement, radio-tagged Murray cod occupied hydraulically and structurally complex flowing water reaches (meso-habitats) with mean velocities in Chowilla Creek (immediately upstream of the Boat Creek junction) and Slaney Creek of 0.29 and 0.45 m s^{-1}, respectively. In November 2016 when the regulator was not in operation but high flows were present, mean velocities in these same regions were higher in Chowilla Creek (0.57 m s^{-1}) and similar in Slaney Creek. During regulator operation in October 2014 and September 2016, mean water velocities in the same regions were significantly reduced.

When no regulator was in place in May 2014, individual Murray cod occupied micro-habitats with mean velocities ranging 0.22–0.56 m s^{-1} across all sites, which was similar to no regulator operations with high flows in November 2016. Similarly, in the upper River Murray, Murray cod have been associated with mean velocities of 0.37 m s^{-1} (Koehn and Nicol 2014). Comparatively, in October 2014 when the regulator was in operation mean velocities at micro-habitats occupied by Murray cod decreased substantially. The impact of reduced water velocities and altered hydrodynamic on the ecology of Murray cod, particularly the drift and behaviour of early life stages, and in turn recruitment dynamics, remains unresolved.

4.2.1. Interaction with the Chowilla Creek Regulator

Chowilla Creek is fundamentally important for the movement of Murray cod between the River Murray and the lotic habitats of the Chowilla anabranch system. Seasonal movements of male and female fish occur in winter and spring, likely for the establishment of spawning sites and location of mates within the Chowilla system (Leigh and Zampatti 2013). Maintenance of this connectivity is considered imperative to sustaining Murray cod populations in the lower River Murray, particularly during periods of low flow (Zampatti *et al.* 2014). During operation of the Chowilla Creek regulator in 2016, six radio-tagged cod moved upstream (n = 2) or downstream (n = 4) within Chowilla Creek before reaching the regulator and being obstructed for periods of 1–3 months. Fish that approached from upstream, ultimately returned upstream, while only one of the fish that approached from downstream was able to locate and successfully ascend the regulator vertical-slot fishway after multiple attempts.

In the southern MDB, weirs can impede the downstream movements of large-bodied native fish such as Murray cod and golden perch (O'Connor *et al.* 2006). Radio-tagged Murray cod that approached the Chowilla Creek regulator from upstream and spent time immediately above the structure before retreating back upstream, indicate a reluctance to pass over the structure or an inability to find the vertical-slot fishway, which are not specifically designed for downstream passage.

The two fish that approached the regulator from downstream of the structure reappeared below the regulator for one and three months respectively before one fish retreated back to the River Murray whilst the other ascended the vertical-slot fishway. These fish were either feeding below the structure or attempting to move upstream into Chowilla. If these fish were attempting to move upstream, their consistent reappearance below the regulator, over an extended period of time (1–3 months) suggests that they may not have been able to effectively locate the vertical-slot fishway entrance. Fragmentation of longitudinal connectivity is a major ecological risk of the Chowilla Creek regulator and fishways could be effective in partly mitigating this impact (Baumgartner *et al.* 2014, Bond *et al.* 2014). As such, the hydraulic and biological function of the fishways on the Chowilla Creek regulator (and ancillary structures) should be assessed and any issues redressed as a matter of priority. In parallel, fishway attraction efficiency should be assessed using electronic tagging approaches (Cooke and Hinch 2013).

5. CONCUSIONS

The objectives of this study were to assess passage efficiency at the Slaney and Pipeclay fishways, and investigate Murray cod movement and the hydraulic characteristics of Murray cod habitats in association with the operation of the Chowilla Creek Regulator in 2016. Our study has shown that the integrated Denil and vertical-slot fishways at Slaney and Pipeclay weirs, provide efficient passage for the species and size ranges of fish for which they were designed. However, fishway attraction efficiency, i.e. the ability of upstream migrating fish to find the fishway entrances, remains untested. This study also revealed that the operation of the Chowilla Creek regulator may impede Murray cod movement in Chowilla Creek and simplify hydraulic complexity in core Murray cod habitats in Chowilla and Slaney Creeks. Whilst this may theoretically influence recruitment and population dynamics of Murray cod in the region, this remains to be empirically tested.

Future Research and Management

The following research and management priorities pertain to fishway function and the spatial ecology of Murray cod at Chowilla. They will assist with operation of the Chowilla Creek Regulator and ancillary structures, including mitigating risks of the regulator and ultimately to improving conservation outcomes for Murray cod and other fishes in the lower River Murray:

- Establishing and maintaining appropriate entrance conditions (hydraulics) at the Slaney and Pipeclay fishways, thus enabling fish to find and enter the fishways, is imperative to successful fishway function. Determining attraction efficiency at these fishways over a range of hydraulic/hydrological conditions, will assist with understanding fishway function and maximising fishway effectiveness at these sites.

- Installation of PIT readers on Slaney and Pipeclay fishways would enable further exploration of fishway function (including attraction efficiency) and the broader scale movement of fishes within Chowilla and between Chowilla and the River Murray.

- Ongoing monitoring of the demographics and abundance of Murray cod in the Chowilla region remains crucial. This would be bolstered by the allied monitoring of these pararmeters in a control region of the lower River Murray where Murray cod remain reasonably abundant, but are not influenced by regulator operation (e.g. in the River Murray downstream of Lock 4).

- A water velocity threshold of ≥0.18 m s^{-1} is currently used to maintain favourable hydraulic conditions for Murray cod. Data from recent investigations, however, indicate that a more biologically relevant threshold would be ≥0.30 m s^{-1}, in core Murray cod habitats throughout the Chowilla region.

- The hydraulic and biological function of the fishways on the Chowilla Creek regulator should be assessed. In parallel, fishway attraction efficiency could be investigated using electronic tagging approaches (e.g. combined PIT and radio tags).

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